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Book of Abstracts

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Plenary Lectures

Path-Independent Formability Formulation for Ductile Anisotropic Sheets

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In the common industrial sheet metal forming process, in which in-homogenous deformation under the plane stress condition is typically the case, sheets are so ductile that their forming fails more often than not after catastrophic strain localization, especially in the thinning mode, as a result of the boundary value problem of the constitutive law. In such a case, the measurement of the fracture criteria might be impractical and criteria to account for catastrophic strain localization replace the fracture criteria as a tool to evaluate sheet formability. The catastrophic strain localization, as a mathematical consequence under typical forming conditions rather than as a material property, is approximately deformation path-independent (or boundary condition independent) at room temperature as will be reviewed in this work for typical forming limit stretching and deep draw forming tests as well as their simplified models such as the M-K, Hill and Dorn.

Phase Field Modelling of Grain Boundary Motion Driven by Curvature and Stored Energy Gradients

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During thermo-mechanical processing, the strain energy stored in the microstucture of an FCC polycrystalline aggregate is generally reduced by physical mechanisms which rely, at least partially, on mechanisms such as dislocation cell or grain boundary motion which occur during recovery, recrystallisation or grain growth. The aim of this work is to develop a constitutive framework capable of describing the microstructural evolution driven by grain boundary curvature and/or stored energy during recrystallisation and grain growth. As recrystallisation processes depend primarily on the nature of the microstructural state, an accurate prediction of such phenomena requires that the microstructural heterogeneities which develop just before recrystallisation, such as dislocation cells and pile-ups, shear and twin bands, be properly described. The microstructural characteristics present in a polycrystal aggregate at the onset of thermal recrystallisation are first reproduced numerically. The constitutive behaviour of each grain in the aggregate is described using a dislocation mechanics-based crystallographic formulation. Different measures of stored internal strain energy are determined based on the dislocation density distribution in the aggregate.
The minimisation of stored and grain boundary energies provides the driving force for grain boundary motion. To describe the interface motion, a phase field model taking into account the stored energy distribution is formulated and implemented within the continuum framework. The coupling between the grain boundary kinematics and the crystal plasticity model is made through the dislocation densities and grain orientations. Furthermore, the parameters of the free energy are calibrated based on published Read-Shockley boundary energy data. To validate the proposed model, a polycrystalline Al aggregate is first cold deformed under plan strain conditions and then annealed. The predicted recrystallised material volume fraction evolution was found to have the same dependence on deformation levels and temperature as those reported in the literature.

Experimental and Numerical Simulation of Titanium Forming

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Driven by an increasing demand from aerospace industry, titanium and its alloys are becoming of prime importance in scientific research on thin sheets and tube forming. This is also reflected by the continuous transfer of the understanding and knowledge about metal behavior and their models from the automotive sector to the aeronautics areas: behavior model coupled with microstructure evolution, heat treatment, formability, numerical simulation of complex processes, etcIn this paper, we will illustrate this fact through some examples on strategies used for developing a precise and adequate behavior model for Titanium cold stamping. We will then assess the influence of operating conditions (choice of material, temperature, strain rate, initial geometries) to obtain a good final piece respecting the industrial requirements. Finally, using some numerical and experimental simulations of the process, we conclude with a discussion about the ability of some Titanium alloys for cold forming.

Innovation of Light Weight Technology

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In recent years, diverse efforts were made to introduce light weight technology in manufacturing, especially for sheet-based products. Light metallic materials including Al alloys and Magnesium alloys have been vastly used for light weight design of products. For heavy duty products relating to transportation such as automobiles, ships and high speed trains, etc., in addition to light metal alloys, advanced high-strength steels of thin gage have been used for achieving light weight more than ever. Either light metal alloy sheets or advanced high-strength steel sheets are not, however, amenable to forming at the room temperature due to forming defects occurring in the processes. Therefore, new innovative forming technologies have been introduced, especially for forming of advanced high-strength steel sheets. Hot press forming has widely been introduced in the automobile industries due to increased use of advanced high-strength steels. However, the introduction of hot press forming at the elevated temperature resulted in overuse of energy and environmental issues. Localized heating can be conveniently introduced to avoid the global heating of sheet metal blanks to form hard-to-form high-strength steels. Incremental forming can be also combined with localized heating in the incremental manner to avoid defects of hard-to-form materials such as advanced high strength steel sheets, magnesium sheets or aluminum alloy sheets. Shaped sheets such as channel-like profiles can be conveniently formed by combining localized heating and incremental forming resulting in defect-free products. Nowadays, the use of nonmetallic composites with fiber reinforced materials has been increasing such as including carbon or glass fiber reinforced plastics. Some tailored material properties could be obtained according to the requirement of products. Higher specific strength and higher specific stiffness can be also obtained by introducing innovative structural design of sheet-like materials, such as foamed sheets and structured sandwich sheets depending on the material requirement. Shaped sheets with channel-like cross sections are also widely used for specific product requirement. Especially, sandwich sheets with specially designed inner cores are treated with emphasis on innovative ultra-light weight design. Practical examples are explained for each category of light weight technology with relevant processing technologies. The merits and demerits of each category are compared and discussed between the categories.

Plasticity-damage couplings in Titanium

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At room temperature, titanium materials display deformation and failure properties that are quite different from that of typical materials with cubic crystalline structure (aluminium, steels, etc). Rolled or extruded products exhibit a strong anisotropy and very pronounced difference in yielding and work-hardening evolution between tension and compression loadings. In this paper, a macroscopic elastic/plastic model that accounts for the key features of the plastic deformation of Ti, in particular the distortion of the yield surface induced by texture evolution is presented. Comparison with data demonstrates that the model predicts with accuracy the plastic response for a variety of loading conditions. Furthermore, it is shown that the model can be extended such as to incorporate damage. In contrast to existing approaches, the plasticity-damage couplings are deduced and not postulated. Hence, all material parameters have a clear physical significance, being related to plastic properties that can be determined from few simple mechanical tests. The new model predicts that in titanium materials damage accumulation is strongly influenced by the anisotropy and asymmetry in plastic flow. Moreover, it is shown that under uniaxial tension, the porosity evolution should be much slower than in materials with plastic flow obeying the classical von Mises criterion, and that the succession of damage events leading to failure should also be markedly different.

Ductile damage at large plastic strains: models, numerical issues and transition to fracture

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The introduction of new effects, both in the plastic flow rule of the material and in the evolution laws for internal variables like damage, namely the importance of taking into account triaxiality and the influence of the third invariant of the deviatoric stress tensor in the modeling of mechanical behavior of metallic materials is here assessed. To solve mesh dependency associated with numerical implementation of strain softening laws a non-local approach of integral-type is used. A comprehensive assessment of several non-local models is carried out for different values of stress triaxiality and third invariant of the deviatoric stress tensor. A continuous-discontinuos model, based on the XFEM, in order to handle simultaneously large strains, damage localisation and crack propagation is discussed.

Formability

cleation and growth of the severely deformed region. From an analysis of the tensile test, the necking behavior is well predicted. Finally, analyses are carried out for various strain paths, and FLDs up to necking and fracture are predicted.

Hydroformability of 980MPa and 1180MPa Ultra-High Strength ERW Steel Tubes

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High strength steel tubes have attracted attention as materials for reducing auto body weight. However, there have been few reports on hydroforming using materials with nominal tensile strengths exceeding 980MPa. Therefore, free bulge forming tests and rectangular section bulge forming tests were carried out with electric resistance welded (ERW) tubes having nominal tensile strengths of 980MPa and 1180MPa. These steels are dual-phase steels consisting of martensite and ferrite. In the free bulge forming tests, the limiting bulging ratio (LBR) under axial feeding was 17% for the 980MPa material and 5% for the 1180MPa material. In the rectangular section bulge tests with a bulging ratio of 4%, it was possible to avoid rupture of the 1180MPa material at the heat-affected zone (HAZ) by applying axial feed loading or selecting the proper welded seam position. Under the same rectangular section bulging test conditions, forming of the 980MPa material without defects was possible regardless of the axial feeding condition and selection of the welded seam position.

Prediction of FLD of Sheet Metals based on Crystal Plasticity Model

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In some advanced sheet metal forming processes such as the incremental forming process, a local fracture strain after necking is very important. In order to accurately predict necking and fracture phenomena, a crystal plasticity model is introduced in the finite element analysis of tensile tests. A tensile specimen is modeled by many grains that have their own crystalline orientation. And each of the grains is discretized by many elements. Using this analysis, necking behavior of a tensile specimen can be predicted without any initial imperfections. A damage model is also implemented to predict sudden drops of load carrying capacity after necking and to reflect the void nucleation and growth of the severely deformed region. From an analysis of the tensile test, the necking behavior is well predicted. Finally, analyses are carried out for various strain paths, and FLDs up to necking and fracture are predicted.

Determining a Probabilistic Forming Limit Curve

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Forming Limit Curves are surrounded by uncertainty in particular the uncertainty surrounding the calculation of limit strains from experimental data. The position dependent method outlined in ISO12004-2 is known to make assumptions regarding the behavior of sheet metal at the onset of necking. Recent time dependent methods better utilize measured strain data from digital image correlation (DIC) techniques to determine the onset of localized necking. Both approaches generate a series of forming limit strains which require subsequent interpretation to produce a deterministic forming criterion. By acknowledging the inherent heterogeneous plastic deformation behavior of sheet metal, a new statistical approach to quantifying formability is proposed. Gaussian Mixture Models are used to characterize DIC-measured strain data and to determine both onset of localized necking and the size and location of the neck itself. By avoiding any pre-conceptions regarding the size or characteristics of the localized neck, a more realistic and robust probabilistic forming criterion is attainable.

Prediction of Localized Necking for Nonlinear Strain Paths Using the Modified Maximum Force Criterion (MMFC) and the Homogeneous Anisotropic Hardening Model (HAH)

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The reliable prediction of strain localization is a challenging task. It is generally known that in case of nonlinear strain paths the state of the art FLC cannot accurately predict the localization limit. The present paper aims to approach this problem using the MMFC criterion together with the novel HAH yield locus in order to define an adaptive FLC able to predict localization also in case of nonlinear deformation paths. Furthermore a reformulation of

the MMFC is proposed which natively accommodates anisotropy as well as anisotropic hardening effects and is solely based on the yield locus function and its first and second derivatives with respect to the stress tensor. The proposed method will be compared against especially devised experiments featuring optical measurements. An implementation into the finite element framework predicting necking in form of fringe plots is also introduced.

Forming Limits for Three-Dimensional Stress States and Nonlinear Loading Paths

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The formability of sheet metals is affected by material properties such as the strain hardening ability and strain rate sensitivity as well as process variables such as loading speed, temperature and friction. Much research has been carried out to understand the influence of these parameters on sheet formability with a view to improving the robustness of industrial forming processes. For instance, it has been shown that the existence of even moderate out-of-plane stresses can significantly affect the formability of sheet metals. And since many industrial forming processes are marked by non-negligible through-thickness stresses it is important to account for the normal stress in order to accurately predict forming limits. Another factor that has a very significant effect on sheet formability is the loading path. Indeed, non-linear strain paths cause the forming limit curve (FLC) to translate in principal strain space and therefore the actual FLC for a given location on a part may be quite different from the as-received FLC. Consequently, the virtual design of a forming process will only be reliable if the forming limits used to assess the forming severity of the part were determined with due consideration of the (non-linear) strain paths in each critical location of the part.

The FLC of sheet metals have often been predicted using the MK method which was proposed by Marciniak and Kuczynski (1967) and which models the inhomogeneity of the sheet material by a very shallow groove. Predictions of theoretical FLC using the MK method generally assume plane stress conditions, but in this work the MK analysis was modified to consider both the nonlinearity of the loading path and the presence of a through-thickness stress, simultaneously. Different magnitudes of prestrain were applied to a virtual sheet so as to simulate bi-linear strain paths and different values of the normal stress were applied for the prediction of the FLC. Published experimental FLC data obtained for different bilinear loading conditions were used to validate the theoretical work in both plane stress and general three-dimensional stress conditions. It was found that this modified MK model predicts FLC that correlate well with the limited experimental data.

The Bending-Affected Formability of Advanced High-Strength Steels

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During stamping of sheet metal, when material is drawn over a tight die radius along a long, cylindrical feature, splitting can occur over the radius or after the exit from the contact tangency point. This so-called shear fracture occurs at strains and stresses that cannot be predicted directly with conventional forming limit curves (FLC). Standard FLC-generating procedures rely on very gentle radii (R/t∼50-100) and quasi-static deformation, both of which are markedly different from the actual forming conditions.

Experimental and simulation work [1-3] has shown that shear fracture for typical advanced high strength steels (AHSS) occurs by plastic strain localization, not by fracture in the absence of such localization. Thus, it is a ductile process that may be understood and predicted by plasticity constitutive equations. Once localization begins (very near to the local maximum drawing load), fracture occurs with little additional punch travel, typically about 1mm (out of total punch travels of 20-100mm). The evidence for these critical conclusions will be reviewed.

Given this understanding, two simple methods are proposed to predict shear fracture in plane strain under applied sheet forming conditions: 1) a procedure to be applied in die-contact regions along cylindrical features, and 2) a procedure applicable to the flat or gently-curved regions on the exit side of such cylindrical features. Both analyses use a curve describing the limiting engineering stress in plane strain as a function of R/t. Such a curve can be obtained from measurements or simulations.

Analysis of Strain Paths of Sheared Edges during Hole Expansion Tests

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One of the limitations to the widespread use of advanced high strength steel (AHSS) sheets is the cracking of sheared edges during subsequent stretching operations, as nearly all stamped parts are sheared prior to sheet forming. Cracking at the edge occurs at levels below the conventional forming limit criteria. Understanding the strain path of the sheared edge during a hole expansion test should provide insight into the strain path of a sheared edge when it is stretched during production. As a result, experimental as well as finite element simulations are used for analyzing the strain path behavior of a sheared edge during hole expansion tests. The shearing process changes the global behavior in the sheet during a hole expansion, and the finite element results indicate that the strain paths for points near the edge of the hole during expansion are non-linear due to the presence of the shear affected zone (SAZ). These results are consistent with previously measured experimental values for the strain path.

Evolving texture-informed anisotropic yield criterion for sheet forming

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In this work we compare the predictions of the phenomenological anisotropic plane-stress plasticity model BBC2008, calibrated either classically by means of mechanical tests, or by crystal plasticity virtual experiments, to those of a HMS type model with continuous calibration of the same phenomenological model BBC2008. An industrial-grade aluminum alloy AA-6016 is chosen for the test case. Experimental part of the study includes tensile tests and deep drawing of cylindrical cups, preceded by measurements of crystallographic texture. It was found that the material exhibits a noticeable through-thickness gradient in terms of both the texture and plastic anisotropy. The classical calibration of the 16 parameters of BBC2008 was done from tensile experiments (yield stresses and Lankford coefficients) in directions every 15^o from the rolling direction and the biaxial yield stress and anisotropy coefficient. The initial texture for the HMS-BBC2008 model was determined from as received samples. The ALAMEL model was used to estimate polycrystal plasticity from texture information. Finally, the earing number and height profile was measured for experimentally drawn cups and compared to the results of macroscopic simulations, based on both the classically calibrated BBC2008 model and the continuously calibrated HMS-BBC2008 model.

Determination of Forming Limit Diagram for Tube Hydroforming Based on the Strain Rate Change Criterion

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Tube hydroforming (THF) is an attractive manufacturing process in automotive industry, and forming limit diagram (FLD) is a significant strategy to assess the formability of THF. In present study, a method of predicting the FLD for THF is developed based on finite element (FE) simulation with the strain rate change criterion (SRCC) as a failure criteria of identify localized necking. FE simulations under various linear loading paths are carried out to obtain the strain information. The equivalent strain rates at potential fracturing and its adjacent nodes are calculated and utilized with SRCC to distinguish the onset of fracturing in FE simulation. The fracture strains at the two nodes under various linear loading paths are abstracted for establishing FLD. Tube hydo-bulging experiments under the linear loading paths have been conducted to verify the prediction method of FLD, and the results show that this prediction method bears good agreement with experimental data.

Formability of 6xxx/5xxx/6xxx aluminum clad sheets fabricated by cold roll bonding

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6xxx/5xxx/6xxx aluminum clad sheets were fabricated by roll bonding at room temperature and the mechanical properties of the annealed sheets were examined. The bonding strength of the sheets increases with increasing a thickness reduction rate of roll bonding. After annealing, the sheets have a well bonded interface without a void and 2nd phase and the microstructure of the sheets consisted of fully recrystallized grains. Stress-strain curves show same strain hardening characteristics with core Al5023 alloy sheets. Meanwhile, the elongation of the sheets was higher than that of commercial Al6022 or Al5023 alloy sheet. The sheets showed very low tensile anisotropy due to different deformation characteristics of each layer in clad sheets. Finally, the sheet has the minimum earing after deep drawing test due to low plastic anisotropy. The experimental data were compared with numerical simulation results calculated by macroscopic anisotropy of each layer in the clad sheet. A phenomenological yield function, Yld2000, which accounts for the anisotropy of yield stress and r-value, was implemented into ABAQUS using the user subroutine UMAT. Cup drawing of the clad sheets was simulated using the FEM code. The profiles of earing were compared with the experimen-

tally measured results.

Forming Limits of Anisotropic Sheets with Non-Power-Law Hardening

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For aluminum alloys and some advanced high-strength steels, the tensile flow curve exhibits a tendency to saturate. The suitability of constitutive equations was analyzed for aluminum 6111-T4 and a general non-power-law hardening model was adopted in the derivation of forming limits incorporated material anisotropy with varying R-values. A bifurcation analysis was conducted for the left-hand-side FLD under the assumption of proportional loading and zero-extension necking orientation. Analytical results showed good correlation with Nakajima forming limit test data for aluminum sheets following Voce hardening law.

Effects of Equivalent Stress-Strain Curves on the Accuracy of Forming Limit Diagrams Using M-K Approach

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Post-necking hardening behaviour of metallic alloys plays an important role in calculating the limit strains during cup-drawing processes. Currently, numerical methods such as extrapolation from an experimental uniaxial tensile stress-strain data are used to capture post-necking behaviour in most of the contribution regarding sheet metal forming. However, these conventional methods do not always predict the correct post-necking hardening behaviour of materials; thus, higher or lower limit strains have been predicted during cup drawing processes. For example, Marciniak-Kuczynski (M-K) method, which is a common numerical method used to calculate the full forming limit diagrams (FLDs), has some limitations to accurately calculate FLDs for different post-necking hardening behaviours. In this work, it is proposed to use equivalent stress-strain data instead of a single uniaxial stress-strain curve to calculate the full FLD in a cup drawing process. M-K method coupled with a Taylor type rate dependant crystal plasticity formulation is used to calculate the limit strains in a poloycrystal of continuous cast AA5754 aluminum alloy. A representative volume element of 541 grains collected from EBSD data is considered for the analysis. The results show that using equivalent stress-strain data instead of a single uniaxial tensile stress-strain curve to calculate the full FLD is a reliable method to capture accurate post-necking behaviour in calculating limit strains using M-K method. In addition, since a correct post-necking hardening behaviour was chosen through this method, good agreement was observed between the experimental data and the results from the proposed method.

Numerical Analysis Considering Grain Size on Warm Forming of AZ31 Sheet

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Forming limit criteria is one of the important factors to predict failure on numerical analysis for sheet forming. A numerical analysis technique and forming limit considering grain size of AZ31 alloy sheet are proposed by experiment and FEM analysis. AZ31 alloy is generally recrystallized continuously and actively during warm and hot forming. Therefore, a large elongation is usually represented at an elevated temperature although low formability at room temperature. Dynamic recrystallization is an important factor of large elongation at an elevated temperature and has an effect on grain size of sheet during plastic deformation. The relationship was investigated by some formability testing and practical forming experiment since the formability is frequently related with grain size. And then an analysis method considering effect of grain size is studied for formability and failure prediction.

Prediction and Validation of Forming Limit Strains for Tube Hydroforming

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Earlier work has demonstrated through simulations that the forming limit strains of tubes during hydroforming and sheets during stamping of identical mechanical properties show significant differences. Typically, the forming limit strains were higher during hydroforming. In the present work, the forming limit strains is predicted by considering expansion of tubes by hydroforming process under different boundary conditions, so as to generate drawing and stretching

strain paths. The result were validated by carrying out tube expansion experiments on steel tubes and is found to be in agreement with simulation results. The effect of boundary condition on the evolution of microstructure is studied.

Prediction of Forming Limit Strains of Thin Foils using Shim

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Thin foils of metallic alloys find utility in metallic thermal protection systems, such as honeycomb structures. Understanding the formability of these thin foils becomes imperative so as to design accurate tooling and also to ensure mechanical robustness of the honeycomb structures during service. It has been found that, obtaining the precise limit strains of these foils directly using the conventional limiting dome test tooling is difficult, because of the excessive draw in and wrinkling that occurs during the punch travel, resulting in erroneous measurement or prediction of limit strains. To address this issue, the blank over blank stacking methodology was developed, which helped keep the draw-in and wrinkling at negligible and thus acceptable levels. Although the blank over blank stacking methodology offers a way to predict and measure limit strains, the same may not be accurate enough due to the effect the substrate properties may impose on the thin foil. To avoid this effect, a different methodology has been proposed herein, which uses a shim stacked over the blank to avoid draw in of these foil blanks and thus help accurate clamping of the blank between the die and blank holder. It is thus understood that either a critical local or global increase in the thickness of the blank material in and around the draw bead is essential to obtain effective clamping of foil and to avoid draw-in and wrinkling. Although, miniaturized hemispherical dome tests may be beneficial for obtaining limit strains as far as foils are concerned, the methodologies proposed herein provide a route to obtaining the same using available equipment, thus saving resources and time involved in development of new miniaturized testing devices. The forming limit strains of thin foils of IN 718 (inconel) alloy having a thickness of 50m, C263 (nimonic) alloy having a thickness of 100m and CP Ti (commercially pure titanium) having a thickness of 200m have been predicted using this methodology and have been compared to the predictions of the previously proposed blank over blank stacking method.

Design of Nonlinear Strain Path with Path Independent Polar Effective Plastic Strain (PEPS) Diagram for Beverage Can Expansion Process

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A path-independent Polar Effective Plastic Strain (PEPS) diagram was suggested by Stoughton and Yoon. It has been shown that the PEPS Diagram is an effective solution to problems having nonlinear effects, with advantages of the familiar strain-based diagram for linear loading, and without the strain-hardening limitations of the stress diagram. The PEPS diagram also has a one-to-one mathematical correspondence to the Stress-Based FLC. In the PEPS diagram, the nonlinear strain path effect is taken into account by considering the effective plastic strain and the incremental strain ratio. A new path is determined based on the magnitude of effective plastic strain radius and the direction to the new path connecting the origin. Expansion of beverage can used for heat exchanger has been processed with two different deformation paths: curling and expansion or expansion without curling. The PEPS diagram is utilized to explain the effect of the curling deformation on formability and how to improve the forming limit through nonlinear path design in the PEPS space. It has been found that the curling process improves the formability dramatically.

Determination of Forming Limit Diagrams with Digital Image Correlation Testing and Analysis

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Forming Limit Diagram (FLD) is a critical tool to assess the formability in sheet metal forming operations. Traditionally human judgment is used to determine the onset of localized necking when conducting Forming Limit Diagram tests by either Nakazima or Marciniak method. It is time consuming and results are more or less subjective. Recently, the Digital Image Correlation (DIC) technique emerges to be the preferred choice for sheet metal deformation analysis as forming limit strains can be obtained from processing the temporal and spatial fields of DIC data. However, the methodology to identify the onset of a localized neck in DIC analysis varies greatly and consensus has yet to be reached. In this presentation, a new method to identify the limit strain is proposed based on the physical phenomenon of the localized necking band and consistent results are obtained. The proposed method analyzes both the temporal and spatial fields of the strain data. Finite element analysis is also conducted to verify the developed methodology.

Development of an Interfacial Model for Forming of a Metal-Composite Material System

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This work presents a finite element model for the stamp forming simulation of Fiber-Metal laminate system consisting of glass fiber reinforced composite material layer sandwiched between two aluminium layers. A novel interfacial model was developed to analyze the role of the interface between the metal and composite layers. A one way coupled thermo mechanical model was used to study the effect of pre heating the material system to improve the formability. Comparison between the simulation and experiments were carried out for forming of rectangular cups. The results indicate that the interfacial model is effective in predicting the forming behavior of this advanced light weight material system.

Formability Analysis of Austenitic Stainless Steel-304 under Warm Conditions

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A warm deep drawing process of austenitic stainless steel-304 (ASS-304) of circular blanks with coupled thermal analysis is studied in this article. 65 mm blanks were deep drawn at different temperatures and thickness distribution is experimentally measured after cutting the drawn component into two halves. The process is simulated using explicit finite element code LS-DYNA. A Barlat 3 parameter model is used in the simulation, as the material is anisotropic up to 300°C. Material properties for the simulation are determined at different temperatures using a 5 T UTM coupled with a furnace. In this analysis constant punch speed and variable blank holder force (BHF) is applied to draw cups without wrinkle.

Finite Element Modeling and Prediction of Thickness Strains of Deep Drawing using ANN and LS-Dyna for ASS304

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Austenitic Stainless Steel (ASS) 304 sheets are increasingly used for making different parts because of their high corrosion-resistivity, good appearance and superior formability. However, austenitic phase gets transformed into martensite during forming, reveals its highly unstable nature. This transformation of austenitic phase to martensite is a function of strain, strain rate and temperature. To avoid this transformation, warm forming is useful, since the martensitic transformation decreases with increasing temperature [1-3]. The formability of a blank depends on various process parameters such as blank holding force, lubrication, punch and die radii, diepunch clearance, material properties and thickness of the sheet [4]. During deep drawing, if the process parameters are not selected properly, the blank is likely to develop defects.

Finite element simulations help to choose proper process parameters without actual experimentation. To obtain accurate solution during numerical simulation, proper selection of material model, which captures the material flow behavior, is required. And also adaptive meshing is taken into account for more accuracy [5]. ASS-304 sheet of 1 mm thickness is deep drawn using a cylindrical punch under the pure stretch boundary condition [6]. The temperature-dependent material model Mechanical Threshold Stress (MTS) was used to simulate the coupled thermo-mechanical finite element analysis of the deep drawing process. In this paper, the thickness strains of the drawn cup are predicted using FEM simulations and ANN. These are compared with the experimental results.

Experimental and Numerical Simulation Analytical Studies for Forming Limit of 2024 Aluminum Alloy on Synchronous Cooling Hot Sheet Metal Forming

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Due to 2024 aluminum alloy sheet usually exhibits poor formability at room temperature, the sheet forming for complex shaped part has many difficult problems. Synchronous cooling hot forming new process is implied to improve the formability of

lightweight materials such as 2024 aluminum alloy. In this paper, the forming limit on synchronous cooling hot forming new process have been investigated using the FE numerical simulation analysis. Square cup drawing and stamping processes were used to investigate the formability of 2024 aluminum alloy sheet. Forming limit at synchronous cooling hot forming could be predicted based on the FE method. The comparison of the numerical results with the experimental ones has shown that the forming limit and the necking site are successfully predicted by the simulation.

Numerical Methods & Multiscale modelling

The Implementation of Real Drawbead Model in a GPU-based Finite Element Code for Sheet Metal Forming

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Drawbeads are applied in the sheet forming process to improve the control of the material flow during the forming operation. However, modeling the exact drawbead geometry requires a large number of elements due to the small radii of the drawbead. The large number of elements will increase the calculation time for such finite element simulation drastically. In common sheet forming simulation systems these exact drawbeads are commonly replaced by equivalent drawbead models to overcome this problem of calculation time excess. But, many studies have demonstrated that the equivalent drawbead model cans not precisely simulation the blanks behavior when it passes the real drawbead. Modern GPU offers high computation power and increased memory bandwidth at a relatively low cost, and GPGPU techniques permitting them to be used in general purpose computing, including sheet forming simulation. In this paper the usage of exact drawbead models in a GPU-based parallel sheet forming simulation system is described. This GPU-based simulation system can obtain dozens of times speedup than CPU-based serial code with GTX 460 graphics card. Compare to use equivalent drawbead on common system, real drawbead can be adopted in this system without an increasing calculation time, and improve the quality and reliability of simulation results.

Multi Criteria Anisotropic Adaptive Remeshing for Sheet Metal Forming in FORGE®

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In this paper we present an innovative automatic adaptive anisotropic remeshing technique that has been introduced in the commercial FEM software FORGE. It enables the full 3D simulation of industrial applications of parts with a high aspect ratio such as sheets. An anisotropic mesh is generated in order to adapt to the part and tools geometries, and in order to minimize interpolation error on the velocity field and/or on any other user defined function (eg. temperature, strain). By minimizing the estimated error, the anisotropic adapted meshes provide a highly accurate solution, often better than those obtained on globally-refined isotropic meshes and at a much lower cost due to the small total number of nodes.

A Sheet Metal Forming Simulation of Automotive Outer Panels Considering the Behavior of Air in Die Cavity

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During a sheet metal forming process of automotive outer panels, the air trapped between a blank sheet and a die tool can become highly compressed, ultimately influencing the blank deformation and the press force. To prevent this problem, vent holes are drilled into die tools and needs several tens to hundreds according to the model size. The design and the drilling of vent holes are based on experts experience and try-out result and thus the process can be one of reasons increasing development cycle. Therefore the study on the size, the number, and the position of vent holes is demanded for reducing development cycle, but there is no simulation technology for analyzing forming defects, making numerical sheet metal forming process simulations that incorporate

the fluid dynamics of air. This study presents a sheet metal forming simulation of automotive outer panels (a roof and a body side outer) that simultaneously simulates the behavior of air in a die cavity. Through CAE results, the effect of air behavior and vent holes to blank deformation was analyzed. For this study, the commercial software PAM-STAMP^{TM}and PAM-SAFE^{TM}was used.

Systematic Study of Polycrystalline Flow during Tension Test of sheet 304 Austenitic Stainless Steel at room Temperature

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By systematic study the mapping of polycrystalline flow of sheet 304 austenitic stainless steel (ASS) during tension test at constant crosshead velocity at room temperature was obtained. The main results establish that the trajectory of crystals in the polycrystalline spatially extended system (PCSES), during irreversible deformation process obey a hyperbolic motion. Where, the ratio between the expansion velocity of the field and the velocity of the field source is not constant and the field lines of such trajectory of crystals become curved, this accelerated motion is called a hyperbolic motion. Such behavior is assisted by dislocations dynamics and self-accommodation process between crystals in the PCSES. Furthermore, by applying the quantum mechanics and relativistic model proposed by Muñoz-Andrade, the activation energy for polycrystalline flow during the tension test of 304 ASS was calculated for each instant in a global form. In conclusion was established that the mapping of the polycrystalline flow is fundamental to describe in an integral way the phenomenology and mechanics of irreversible deformation processes.

Locking and its Treatment for Nonlinear Isogeometric Analysis

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Isogeometric Analysis (IGA) has become very popular for the analysis of structures, fluids and fluid-structure interaction problems. IGA suffers from the same problems depicted by other numerical methods when dealing with constrained problems as those associated with handling of incompressibility or transverse shear effects on thin structures, giving rise to the well-known locking problems. In this work, some methodologies to alleviate locking problems in IGA will be presented. They include an analysis of the subspace of the constrained fields underlying the numerical solution and include projection techniques to extrapolate those field representations at points associated with reduced Gaussian integration rules. The basis functions used are grounded on Non-Uniform Rational B-Splines (NURBS), which are very popular on the solid modeling (CAD) community. The extension of the proposed locking remedies to nonlinear isogeometric analysis is also considered.

Numerical Simulation for the Magnetic Force Distribution in Electromagnetic Forming of Small Size Flat Sheet

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It is essential to calculate magnetic force in the process of studying electromagnetic flat sheet forming. Calculating magnetic force is the basis of analyzing the sheet deformation and optimizing technical parameters. Magnetic force distribution on the sheet can be obtained by numerical simulation of electromagnetic field. In contrast to other computing methods, the method of numerical simulation has some significant advantages, such as higher calculation accuracy, easier using and other advantages. In this paper, in order to study of magnetic force distribution on the small size flat sheet in electromagnetic forming when flat round spiral coil, flat rectangular spiral coil and uniform pressure coil are adopted, the 3D finite element models are established by software ANSYS/EMAG. The magnetic force distribution on the sheet are analyzed when the plane geometries of sheet are equal or less than the coil geometries under fixed discharge impulse. The results showed that when the physical dimensions of sheet are less than the corresponding dimensions of the coil, the variation of induced current channel width on the sheet will cause induced current crowding effect that seriously influence the magnetic force distribution, and the degree of inhomogeneity of magnetic force distribution is increase nearly linearly with the variation of induced current channel width; the small size uniform pressure coil will produce approximately uniform magnetic force distribution on the sheet, but the coil is easy to early failure; the desirable magnetic force distribution can be achieved when the unilateral placed flat rectangular spiral coil is adopted, and this program can be take as preferred one, because the longevity of flat rectangular spiral coil is longer than the working life of small size uniform pressure coil.

Evolutionary Optimization for Conditions of Variable BHF for Springback Reduction in AHSS-Mild Steel TWB

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In this study, the advanced high strength steels (AHSS)/mild steel TWB sheet is applied to the U-draw bending springback under non-constant blank holding force (BHF). On both sides of the blank, two different BHF-punch stroke are applied. A systematic approach to obtain optimal BHF-stroke profiles is proposed. The optimal condition would require satisfying two conflicting objectives simultaneously: (1) minimize springback deformation and (2) minimize the forming severity, leading to a Pareto-optimal problem. The optimization procedure consists of the following steps: sampling design, finite element (FE) simulations, metamodeling, and finally the calculation of a Pareto-frontier. PAM-STAMP® FE software is employed in this study. The generated outputs of FE simulations on some statistically significant sampling points are then used for the construction of metamodels of optimum accuracy and complexity, which, in turn, were used to evaluate the output for any set of inputs, replacing the computing intensive FE simulations. A novel genetic algorithms based multi-objective optimization technique is applied for optimization. Yet far to be completely removed, springback in TWB can be appreciably reduced using the proposed approach of variable BHF control.

Atomistic Simulation of Dislocation Nucleation and Segregation under Adhesive Contact of a FCC Metal with a Stepped Coating

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Coating and oxide layers are commonly observed on crystal surfaces, which are naturally formed in some metals in atmospheric environment or artificially coated for engineering applications. No matter how perfect the coating layer is prepared, there exist some amounts of nanoscale roughness on its surface. Nanoscale asperities of material surfaces may play a key role in the evolution of surface plasticity through dislocation activities under frictional contact loadings. In this study, atomistic simulation with the Large-scale Atomic/Molecular Massively Parallel Simulator (LAMMPS) was performed for the adhesive contact of a rigid flat indenter on a carbon diamond film on a face-centered cubic copper crystal, in which nanoscale roughness was modeled with a surface step. The atomic interaction between the flat indenter and the carbon film was modeled with Lennard-Jones potential, of which parameters was varied to tailor the adhesion energy between the flat indenter and the carbon film. As the indenter is compressed against the carbon film with a surface step, dislocations are nucleated from the step and emitted into the copper substrate. Depending on the Burgers vectors and glide planes, the nucleated dislocations are segregated near the surfaces or in the bulk of the copper substrate. This dislocation nucleation and segregation phenomenon may effectively explain the effect of protective coatings on surface microplasticity.

Hierarchical multi-scale modeling of texture and substructure for FE simulations of multi-stage forming processes

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Advances in multi-scale modeling are pushed by the desire to incorporate physical phenomena into simulations on a much larger length scale. Current authors have developed a multi-scale model for ferritic steel. We consider the development of the intragranular dislocation substructure (on the so-called micro scale) as well as the crystallographic texture (on the meso scale) and the evolution of texture under the constraint of nearest neighbor grain-to-grain interaction. The homogenized response (on the macro scale) is hierarchically coupled to a highly flexible anisotropic material model designed for efficient large-scale FE simulations. During plastic straining, this hierarchical multi-scale (HMS) model predicts changes in texture and grain substructure. The latter manifests itself in macroscopic hardening. These microstructural evolutions are effectively considered in the FE environment through adaptive identification of the HMS model.
In the current study, we propose a quadratic approximation of the macroscopic hardening. The hardening approximation is re-identified after (a) a critical amount of monotonic deformation along the strain path applied in identification, or (b) a change in strain path. The investigated case study is a two-stage forming process: equibiaxial stretching followed by uniaxial tension. Firstly, we compare the multi-scale model directly to experimental flow stress curves in both

stages, confirming a reasonable reproduction of the transient hardening that is observed after the change in strain path. Secondly, a one-element FE simulation of the two-stage process illustrates the capability of the HMS model to reproduce the underlying multi-scale model in a computationally efficient way.

Neutron Diffraction Study of Martensite Phase in Stainless Steel

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Neutron diffraction technique is very powerful tool in understanding the information of microstructures in higher advanced steels used for industrial applications. Neutrons make it possible to measure non-destructively in bulk sample with various sample environments such as furnace, loading devices, pressure cells and magnetic fields. In some cases, X-ray, TEM and APT are complementarily used to get the local information in the sample. In this presentation, the quantitative analysis of and the partitioning of the martensite phase induced by thermal and mechanical process in stainless steels by neutron scattering techniques carried out at HANARO will be introduced.

Smoothed variable-node finite elements - Next generation CAE approach

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The meshfree approach leads to the extension of the trial function space of finite elements, linking to the new finite element formulation called Smoothed Finite Element Method, which is based upon the gradient smoothing. This enables one to overcome some shortcomings of the conventional finite element method in that it provides a flexible adjustment in deploying nodal points, yielding smoothed variable-node finite elements. The smoothed variable node finite elements turn out to be extremely powerful in dealing with a class of complex problems entailing evolving interface and discontinuity as well as multi-scale problems. In this presentation, we discuss the strong points of this approach in conjunction with its application to some of the representative challenging problems: first, crack propagation in microstructured materials, containing numerous inclusions or voids; second, quasicontinuum application for nanoindentation; third, elastic analysis of a polycrystalline body containing complex interfaces. In addition, to explore possible extension to the applications for elastic-plastic deformation, the performance of the new approach for elastic-plastic problems is compared with that of the existing finite element approach.

FE Simulation of Magnesium Alloy Microstructure Evolution in Tension

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Finite element (FE) simulation of microstructure evolution was performed in the current work. The flow stress curve for FE simulation was obtained from tensile test which was carried out at room temperature. Samples were machined from a rolled sheet of AZ31B magnesium alloy. Simplified micro scale models were developed in order to study the influence of the round inclusion and twin-like inclusion on the material fracture behaviour. It was shown that fracture initiation point is dependent on the yield stress of the inclusion. Finally, polycrystalline model including ten grains of similar sizes was developed. The triple junction points were recognized as sites of fracture initiation.

Numerical Modeling of Size Effect in Micro Hydromechanical Deep Drawing

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A modeling of tribological size effects in micro deep drawing (MDD) and micro hydromechanical deep drawing (MHDD) is a main focus in this study. The inner and outer pockets in which the different friction coefficients can be applied at different lubrication conditions are considered on the blank surface. The ratio of the area of outer pockets to inner pockets is changed with the decrease in the size. The low friction coefficient at the outer pockets is assumed in MHDD by considering the lubrication effect of fluid medium. The numerical analysis is performed under six lubrication conditions. The analytical results of punch force-stroke curves are in good agreement with the experimental values. The friction force decreases in MHDD with the decrease in the size although it increases in MDD. The friction coefficient at die shoulder significantly influences the friction force due to high contact pressure in MHDD.

Materials Optimization - Manufacturing Assembly and CAE & Structure Concurrent Engineering With Hot and Cold Formed Tailored Solutions

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CAFÉ requirements lead to the need of lightweight designs. The BIW is offering a significant opportunity to reduce weight. Consequently, BIW engineers need to change existing grades, gages, and geometry, this under given cost constraints.
Virtual Prototyping makes sure that component manufacturing and assembly processes yield the designed specifications, tolerances and crash performance. ESI GROUP aims at providing all necessary tools for virtual prototyping of lightweight constructions designed and assembled with tailored solutions. This paper outlines what is needed for realistic virtual prototyping, and the status of the simulation solution. Validated realistic engineering examples are used to illustrate the capabilities in the field of virtual die design, forming, quenching, cooling channel engineering, assembly, and product performance.

Simulation of Cylindrical Cup Drawing of AZ31 Sheet Metal with Crystal Plasticity Finite Element Method

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As a light-weight structural material, magnesium alloys show good potential in improving the fuel efficiency of vehicles and reducing CO2 emissions. However, it is well known that polycrystalline Mg alloys develop pronounced crystallographic texture and plastic anisotropy during rolling, which leads to earing phenomenon during deep drawing of the rolled sheets. It is vital to predict this phenomenon accurately for application of magnesium sheet metals. In the present study, a crystal plasticity model for AZ31 magnesium alloy that incorporates both slip and twinning is established. Then the crystal plasticity model is implemented in the commercial finite element software ABAQUS/Explicit through secondary development interface (VUMAT). Finally, the stamping process of a cylindrical cup is simulated using the developed crystal plasticity finite element model, and the predicting method is verified by comparing with experimental results from both earing profile and deformation texture.

Numerical Analysis of Spiral Roller of Chain-die Former

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Chain-die Forming is a novel sheet metal forming technology developed recently. It effectively minimizes the redundant deformation during forming in order to reduce residual stresses to very small values even to zero in product, which is impossible to be achieved through conventional roll forming. Better quality of products therefore can be expected with the development of this new technology. This article is to use FEM to analyze the stresses developed in the spiral roller which is one of the key elements in a Chain-die former. In order to optimize the design of Chain-die former, the results of equivalent stress have been collected and analyzed to understand the capability of the spiral roller. Maximum working load as an important index therefore can be determined. The comparison between spiral roller and simple hollow roller is also discussed.

Hierarchical Multi-Scale modeling of magnesium alloys: from crystal level to macroscopic shear testing

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Magnesium alloys have gained more importance in recent years as lightweight materials for the automotive industry, owing to their low density and relatively high strength. However, the plastic behavior of hexagonal closed packed (HCP) alloys is anisotropic and complicated, which still challenges both engineers and computer models that simulate sheet forming processes. This is because of the crystallographic texture and the complex deformation mechanisms that involve not only crystallographic slip, but also twinning, which may lead to abrupt changes in plastic anisotropy. Moreover, HCP materials typically exhibit directional hardening effects. To capture these three factors, one may employ a predictive physics-based model that operates at the micro-scale. On the other hand, sheet forming processes are conducted at the macro-scale, which implies that a macroscopic model needs to be enriched with accounting for relevant micro-scale phenomena.

In this paper we present an extension to the Hierarchical Multi-Scale (HMS) model described in [1]. The enhanced HMS model allows one to predict the evolution of plastic anisotropy that is associated with the evolution of crystallographic texture in HCP materials. The model consists of three main components: (I) a macroscopic finite element (FE) model, (II) a microscale model that provides the constitutive behavior and the evolution of state variables at integration points of the FE model, and (III) a plastic potential function that is systematically recalibrated by means of the micro-scale model and is exploited by the FE model. A Taylortype crystal plasticity code [2] is used as the micro-scale model to simulate the large strain behavior of HCP metals. We consider crystallographic slip and deformation twinning as the principal deformation mechanisms. Plastic anisotropy in the FE part of the HMS model is described by means of the Facet plastic potential [3]. We demonstrate that the Facet potential can accurately reproduce complicated and highly asymmetric yield loci of magnesium. Moreover, discrete equiwork surfaces predicted by the crystal plasticity can be reliably used for constructing the Facet potential. Hardening of the material is predicted by the microscale model (II) and reproduced in (I) by means of incrementally reconstructed low order polynomials.

In the current paper, we apply this approach to study a shear testing of AZ31B magnesium alloy. It is shown that the HMS model is capable of predicting the spatial distribution of several micro-scale quantities of interest in the whole macroscopic sample, including the crystallographic texture, the activity of deformation mechanisms (crystallographic slip and deformation twinning), the volume fraction of twins, as well as the hardening behavior. We also quantitatively compare results of simulations that account for texture evolution to those that assume constant plastic anisotropy throughout the deformation process.

The Coupled Thermo-Mechanical-Microstructural Finite Element Modeling Of Hot Stamping Process In 22MnB5 Steel

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In this study, a coupled thermo-mechanical-microstructural finite element model based on the subroutine of commercial software ABAQUS is developed to predict the hot stamping process in 22MnB5 steel. The JohnsonMehlAvramiKolmogorov type model with Scheil additivity rule and KoistinenMarburger model are adopted to simulate the diffusional phase transformation and diffusionless one respectively. During the calculation of temperature and stress/strain field, the contributions of microstructure evolution, e.g. transformation latent heat, transformation strain, and transformation plasticity are taken into account, which give more insight of the material response. The model allows to evaluate the transient stress and strain distributions, the final microstructure constituent and the final distortion of the sheet part during the press quenching process. The effect of transformation plasticity on the geometry precision and the residual stress are discussed.

Incremental sheet forming

Evaluation of the Dimensional Accuracy in Single Point Incremental Forming

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Incremental Sheet Forming (ISF) is a forming process widely used to obtain small batches or prototypes. By improving forming strategies, the process can be used in a wide range of applications. However, this technology still presents some drawbacks. The dimensional accuracy between the 3D CAD model and the final product is one of the key challenges for this technique. The springback phenomenon during the incremental forming process is an important reason for the lack of accuracy. In order to study the mechanism of this phenomenon, the geometry of the sheet metal was measured in two different stages of the conventional production chain. First, the geometry of the sheet metal part was acquired after the forming stage, without be released from the blank holder. Then, the final geometry was achieved after the cutting process from the original sheet. A 3D scanning system was used to measure and inspect the springback phenomenon of each step. A reverse method is proposed to design the new tool path for compensation of the springback.

Application of a Shear-Modified GTN Model to Incremental Sheet Forming

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This paper investigates the effects of using a shear-modified Gurson-Tvergaard-Needleman model, which is based on the mechanics of voids, for simulating material behavior in the incremental forming process. The problem chosen for analysis is a simplified version of the NUMISHEET 2014 incremental forming benchmark test. The implications of the shear-modification of the model specifically for incremental sheet forming processes are confirmed using finite element analysis. It is shown that including the shear term has a significant effect on fracture timing in incremental forming, which is not well reflected in the observed tensile test simulations for calibration. The numerical implementation and the need for comprehensive calibration of the model are briefly discussed.

Numerical Simulation of a Conical Shape Made By Single Point Incremental

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The Single Point Incremental Forming (SPIF) is a manufacturing process in which a sheet is deformed by using a relative small tool without the need of dies. The current work aims the application of the adaptive remeshing technique developed for shell and extended to 3D brick elements in general, and specifically to RESS (Reduced Enhanced Solid-Shell) formulation. The study will be focused on NUMISHEET 2014 benchmark: a cone shape made by SPIF process. The purpose is to use the developed tools to predict the deformed shape and tool-load histories.

Single-Point Incremental Forming of 2024-T3 Aluminum Alloy Sheets

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Many aluminum alloy sheet metal parts with complex geometry in airplane are often formed by drop hammer forming with intermediate annealing and then heat treated into T temper. The manufacturing cost is very high because of a number of forming and heat treatment steps. Incremental sheet forming can form complex parts because of larger forming limit than conventional stamping. So the research that the part is formed directly from T temper aluminum alloy sheet using incremental sheet forming is very attractive. 2024-T3 is the aluminum alloy used mostly in aerospace manufacturing. Single-point incremental forming experiments with 2024-T3 are carried to form cone shape parts. In this work, the formability of 2024-T3 aluminum alloy sheets in single-point incremental forming was preliminarily studied. Effect of tool diameter and wall angle on the formability were investigated. It is found that the surface roughness can be reduced and the forming depth of the cone shape part can be increased by increasing the tool diameter.

Geometrical and FEA Study on Millipede Forming

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Millipede Forming is an innovative sheet metal forming approach that has been proposed and developed in Australia. U-channels, Z-channels or tubular products can be made by Millipede Forming. While a strip moves through an optimal transitional surface between the entry to exit of a forming stand, the redundant longitudinal membrane strain can be significantly reduced compared to the conventional roll forming, which is the essential principle to obtaining high quality products. The incremental forming process studied has demonstrated major advantages on space efficiency, power consumption and materials sensitivities. The purpose of this study is to investigate the effects of main geometrical parameters and their optimization, in order to minimize the redundant longitudinal strains into elastic to avoid the redundant plastic deformations at flange during forming. In this study, a mild-steel U-channel sample with 10 mm flange width, fabricated by Millipede Forming in a forming length of 200 mm has been studied. Theoretical longitudinal membrane strains at profiles edge of different transitional surfaces and downhill pass are also analyzed. The results showed that obtaining an optimal transitional surface is essential and necessary in controlling the peak longitudinal strain to an acceptable amount and that by increasing downhill pass, longitudinal strain can be significantly reduced. The optimized transitional surface and downhill pass flow were simulated by Abaqus, and the peak longitudinal strain was finally less than 0.2% through a very short forming length of 200 mm. The results prove that Millipede Forming can achieve a better product quality in a much shorter forming distance than conventional roll forming.

An Analytical Approach for Investigation of the Incremental Sheet Forming Process

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Incremental sheet forming (ISF) is a highly versatile and flexible process for rapid manufacturing of complex sheet metal parts. The characteristic of localized deformation is significantly different from conventional sheet metal forming process. Although many studies have been performed to investigate the ISF deformation process, the understanding of the deformation mechanism is still limited. In most of the analytical methods, membrane approach has been employed, in which one of the most important factors, the bending effect was ignored. In this paper, an analytical model has been developed in which the localized deformation region is divided into sub deformation zones. In each deformation zone, the state of stress and strain is analyzed through the thickness direction so the bending effect can be considered. Using the proposed model, the localized deformation and the fracture mechanism in ISF process are studied in detail. In addition, experimental validation has also been implemented to support the obtained analytical results.

Numerical Simulation of High Speed Incremental Forming of Aluminum Alloy

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Filice Luigino, Gagliardi Francesco

University of Calabria

In this study, an innovative process is analyzed with the aim to satisfy the industrial requirements, such as process flexibility, differentiation and customizing of products, cost reduction, minimization of execution time, sustainable production, etc. The attention is focused on incremental forming process, nowadays used in different fields such as: rapid prototyping, medical sector, architectural industry, aerospace and marine, in the production of molds and dies. Incremental forming consists in deforming only a small region of the workspace through a punch driven by a NC machine. SPIF is the considered variant of the process, in which the punch gives local deformation without dies and molds; consequently, the final product geometry can be changed by the control of an actuator without requiring a set of different tools. The drawback of this process is its slowness. The aim of this study is to assess the IF feasibility at high speeds. An experimental campaign will be performed by a CNC lathe with high speed to test process feasibility and the influence on materials formability mainly on aluminum alloys. The first results show how the material presents the same performance than in conventional speed IF and, in some cases, better material behavior due to the temperature field. An accurate numerical simulation has been performed to investigate the material behavior during the high speed process substantially confirming experimental evidence.

Influence Of Laser Assisted Single Point Incremental Forming On The Accuracy Of Shallow Sloped Parts

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Inwards bulging of the bottom is a typical geometric inaccuracy in shallow sloped Single Point Incrementally Formed (SPIF) parts. In this work, the effect of applying a localized heated spot moving synchronously with the forming tool on the geometrical accuracy of shallow sloped parts has been studied. To investigate the bulging of the bottom the results of an experimentally validated three-dimensional elasto-plastic finite element model have been utilized. These results have been used to identify the contact zone between the tool and the sheet, during Laser Assisted Single Point Incremental Forming (LASPIF) process. Moreover, a three-dimensional transient heat transfer model was formulated to identify optimum process parameters for the heating process. FE modeling results have been validated by temperature field measurements obtained from IR camera observations and a good agreement between the experimental data and the model has been observed. Based on the selected process parameters different relative positioning strategies between the tool position and the dynamically heated spot have been selected. Geometrical accuracies and the process forces have been measured and the best forming strategy has been identified accordingly.

Stress-Based Predictions of Formability and Failure in Incremental Sheet Forming

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This research investigates the deformation mechanism in incremental sheet forming (ISF) with relation to necking and failure. A strain-based forming limit criterion is widely used in sheet-metal forming industry to predict necking. However, this criterion is strictly valid only when the strain path is linear throughout the deformation process. Where the

strain path in ISF is often found to be severely nonlinear throughout the deformation history. Therefore, the practice of using a strain-based forming limit criterion often leads to erroneous assessments of formability and failure prediction. On the other hands, stress-based forming limit is insensitive against any changes in the strain path and hence it is used to model the necking and fracture limits. Simulation model is evaluated for a single point incremental forming using AA 6022-T4E32 and checked the accuracy against experiments.

Fast Simulation of Asymmetric Incremental Sheet Metal Forming

Markus Bambach

RWTH Aachen University

Asymmetric incremental sheet forming (AISF) is a flexible manufacturing process for the production of low volumes of sheet metal parts. In AISF, a sheet metal part is formed gradually by the localized plastic deformation produced by a CNC controlled, ball-headed forming tool. The local plastic deformation under the tool leads to a number of challenges for numerical process simulation. Previous work indicates that implicit finite element (FE) methods are at present not efficient enough to allow for the simulation of AISF for industrially relevant parts, mostly due to the fact that the moving contact requires a very small time step. Finite element methods based on explicit time integration can be sped up using mass or time scaling to enable the simulation of large-scale sheet metal forming problems. However, AISF still requires dedicated adaptive methods to further reduce the calculation times. In this paper, an adaptive remeshing strategy based on a multi-mesh method is applied to the simulation of incremental sheet forming and combined with subcycling to further reduce the calculation times. For the forming example considered, it is shown that savings in CPU time of up to 80% are possible with good accuracy.

Effect of Relative Tool Position on the Geometric Accuracy of Accumulative DSIF

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This paper investigates the effect of relative tool position on geometric accuracy of a new Accumulative Double-Sided Incremental Forming (ADSIF) process which has been proven to improve both geometric accuracy and formability compared to other Incremental Sheet Forming (ISF) methods. ADSIF uses two independently moving, small hemispherically ended tools on both sides of a completely peripherally clamped sheet to form it to a desired shape. The study is motivated by the experimental observation that the relative positioning of the tools in ADSIF affects the formed geometry of the sheet deformation in the tool-sheet contact zone. A simplified Finite Element Analysis is combined with metamodeling techniques for rapid prediction of correct tool positioning required to achieve a desired geometry. Subsequently, full FEA simulations are performed to establish the level of accuracy of the simplified FEA simulation.

Tool Path Influence on Electric Pulse Aided Deformation during Incremental Sheet Metal Forming

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Titanium and its alloys are difficult to form at room temperature due to their high flow stress. Super plastic deformation of Ti alloys involves low strain rate forming at very high temperatures which need special tooling which can withstand high temperatures. It was observed that when high current density electric pulse is applied during deformation it reduces the flow stress through electron-dislocation interaction. This phenomenon is known as electro-plasticity. In the present work, importance of tool configuration to enhance the formability without much resistive heating is demonstrated for Incremental Sheet Metal Forming (ISMF). Tool configuration is selected to minimize the current carrying zone in DC pulse aided incremental forming to enhance the formability due to electro plasticity and the same is demonstrated by forming two pyramid shaped components of 30° and 45° wall angles using a Titanium alloy sheet of 0.6 mm thickness. Load measurement indicated that a critical current density is essential for the electro-plasticity to be effective and the same is realized with the load and temperature measurements.

Materials characterisation and experimental testing methods

Augmented Use of Standard Mechanical Testing Measurements for Sheet Metal Forming: Digital Image Correlation for Localized Necking

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Standard test methods are often well developed to perform specific measurements with frequent updates as measurement technologies mature. Digital image correlation (DIC) is a prime example of a widely used research tool that could replace existing measurement techniques applied in various standard tests. This broad applicability has led to new insights and misunderstandings. In this work, the DIC pattern and processing parameters are investigated to measure shape and displacements on necked samples. Uncertainties of the measured shapes and displacements are determined on unstrained, but 3D surfaces. Large correlation subsets are found to degrade the ability to interrogate even slight grooves in the generally flat surface. Even with optimized patterns and subset sizes, it is difficult to measure vertical (out of plane) displacements $<10\mu$m, due to uncertainties.

Measurement of the Forming Limit Stress Curve Using a Multi-Axial Tube Expansion Test with a Digital Image Correlation System

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A servo-controlled tension-internal pressure testing machine with an optical 3D deformation analysis system (ARAMIS) was used to measure the multi-axial plastic deformation behavior of a high-strength steel sheet for a range of strain from initial yield to fracture. The testing machine is capable of applying arbitrary principal stress or strain paths to a tubular specimen using an electrical, closed-loop servo-control system for axial force and internal pressure. Tubular specimens with an inner diameter of 44.6 mm were fabricated from a high-strength steel sheet with a tensile strength of 590 MPa and a thickness of 1.2 mm by roller bending and laser welding. Several linear and non-linear stress paths in the first quadrant of the stress space were applied to the tubular specimens in order to measure the forming limit curve (FLC) and forming limit stress curve (FLSC) of the as-received test material, in addition to the contours of plastic work and the directions of plastic strain rates. The contours of plastic work and the directions of plastic strain rates measured for the linear stress path experiments were compared with those calculated using selected yield functions in order to identify the most appropriate yield function for the test material. Moreover, a Marciniak-Kuczyski type (M-K) forming limit analysis was performed using the most appropriate yield function. The calculated and measured FLC and FLSC were compared in order to validate the M-K approach. The path-dependence of the FLC and FLSC was also investigated.

Mechanical Weld Zone Characterization for the Numerical Simulation of Forming Friction Stir Welded Aluminum Blanks

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In order to predict the warm formability of friction stir welded aluminum sheets, a new approach for the mechanical characterization at elevated temperature is presented in this paper. Based on warm tensile test and biaxial tensile test local properties of base material and weld nugget material were determined by using specimens with reduced measuring areas. Special characterization specimens are designed according to the weld zone dimensions and numerically optimized to guarantee homogeneous stress distribution. Identified material parameters were used to build up local material models based on approximated flow curves and an anisotropic yield function. The ability of predicting the formability performance of welded sheets was finally evaluated by the validation of numerical simulations with experimental results in dome stretching tests.

Cyclic Tension Compression Testing of AHSS Flat Specimens with Digital Image Correlation System

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ThyssenKrupp Steel USA

A cyclic tension-compression testing program was conducted on flat specimens of TPN-W780 (Three

Phase Nano) and DP980 (Dual Phase) Advanced High Strength Steels (AHSS). This experimental method was enabled utilizing an anti-buckling clamping device performed in a test machine, and the surface strains along the thickness edge are measured with a three-dimensional Digital Image Correlation (DIC) system. The in-plane pre-strain and reversed strain values, at specified strain rates, are investigated to observe the potential plastic flow and the nonlinear strain hardening behavior of the materials. The validity of the test results is established with the monotonic tension tests, to substantiate the true stress-strain curves corrected for the frictional and biaxial stresses induced by the clamping device. A process method for analyzing the correction using a macro script is shown to simplify the output of the true stress-strain results for material model calibration. An in progress study to validate the forming and spring-back predictive capabilities of a calibrated TPN-W780 complex material model to an actual stamping of an automotive component will demonstrate the usefulness of the experimental cyclic test method. Suggestions to improve the testing, strain analysis and calibration of the model parameters are proposed for augmented use of this test method.

Advances in Post-necking Flow Curve Identification of Sheet Metal through Standard Tensile Testing

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The standard tensile test is still the most common material test to identify the hardening behavior of sheet metal. When using standard equipment and well-known analytical formulas, however, the hardening behavior can only be identified up to the point of maximum uniform elongation. Several methods which deal with the problem of extended flow curve identification of sheet metal through a tensile test have been proposed in the past. This paper gives an overview of the four classes of methods to identify post-necking hardening behavior of sheet metal through tensile testing. In addition, identification methods from the first (average values across the neck), second (Bridgeman correction, modified Siebel and Schwaigerer correction) and third class (special case of the VFM) are used to identify the post-necking hardening behavior of DC05. Finally, these results are used to assess the validity of the different methods.

In-Situ Stress Analysis with X-Ray Diffraction for Yield Locus Characterization of Sheet Metals

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A main problem in the field of sheet metal characterization is the inhomogeneous plastic deformation in the gauge regions of specimens which causes the analytically calculated stresses to differ from the sought state of stress acting in the middle of the gauge region. To overcome this problem, application of X-Ray diffraction is analyzed. For that purpose a mobile X-ray diffractometer and an optical strain measurement system are mounted on a universal tensile testing machine. This enables the recording of the whole strain and stress history of a material point. The method is applied to uniaxial tension tests, plane strain tension tests and shear tests to characterize the interstitial free steel alloy DC06. The applicability of the concepts of stress factors is verified by uniaxial tension tests. The experimentally obtained values are compared with the theoretical values calculated with crystal elasticity models utilizing the orientation distribution functions (ODF). The relaxation problem is addressed which shows itself as drops in the stress values with the strain kept at a constant level. This drop is analyzed with elasto-viscoplastic material models to correct the measured stresses. Results show that the XRD is applicable to measure the stresses in sheet metals with preferred orientation. The obtained yield locus is expressed with the Yld2000-2D material model and an industry oriented workpiece is analyzed numerically. The comparison of the strain distribution on the workpiece verifies the identified material parameters.

Correlation between Macro-scale Uniaxial Tension and Nano-scale Indentation in Duplex Low-density Steel

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Recently, many researches have been performed to develop many kinds of advanced high strength steels (AHSSs), in order to reduce the weight of automotive parts. Especially, the interests on the low-density steels with maintaining high strength and toughness are emerging in automotive applications, and many

kinds of low-density steel have been developed lately. Among the low-density AHSSs, duplex low-density steels containing the substitutional light elements are highlighted for the outstanding strengthductility balance. These duplex steels, which composed of ferrite and metastable austenite, show complex deformation behavior which arises from the interactions among the different microstructural constituents. To ensure the reliable design in alloy and process of the duplex low-density steels, it is necessary to understand the influence of intrinsic behavior of their microstructural constituents including plastic yielding and deformation-induced martensitic transformation (DIMT) of metastable austenite on their macro-scale deformation behavior.
In this study, the dual-scale correlation between macro-scale tensile test and nano-scale indentation of a duplex low-density steel containing 5 mass% of aluminum was carried out, in order to explain the dramatic difference of macro-scale tensile behavior in two specimens obtained under specific heat treatment conditions, despite of the same chemical composition and almost similar microstructures. First, the intrinsic mechanical properties of each phase were measured by nano-indentation, and the maximum shear stress at elasto-plastic transition for each phase in both specimens was determined. The effect of grain size on the yielding was considered to evaluate the substantial initial yield stress of each phase from the view point of nano-indentation scale with the combination of Hall-Petch relationship. In addition, the mechanical stability of metastable austenite was investigated by in-situ electron backscattered diffraction (EBSD). Based on above approaches, the dramatic difference of macroscopic tensile behavior such as yield strength, yield point phenomenon and strain hardening in two specimens was successfully explained.

Effect of kinematic stability of initial orientation on deformation heterogeneity and ductile failure in duplex stainless steel during uniaxial tension

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The crystal plasticity finite element method (CPFEM) was used to investigate the effect of the kinematic stability of the initial orientations on deformation heterogeneity and ductile failure of ferrite and austenite phases in duplex stainless steel (DSS) during uniaxial tension. The individual stress-strain relationships of ferrite and austenite phases in DSS were evaluated via in-situ neutron diffraction in combination with the CPFEM. A CPFEM based on the representative volume elements (RVEs) of a unit cell of DSS with a regular bamboo structure demonstrated that the kinematic stability of the initial orientations significantly affected the deformation heterogeneity and ductile failure in the constituent phases in RVEs during uniaxial tension. The regions susceptible to ductile failure were identified as being in the austenite phase near the phase boundaries of ferrite and austenite.

Development Of A Benchmark Factor To Detect Wrinkles In Bending Parts

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The rotary draw bending process finds special use in the bending of parts with small bending radii. Due to the support of the forming zone during the bending process, semi-finished products with small wall thicknesses can be bent. One typical quality characteristic is the emergence of corrugations and wrinkles at the inside arc. Presently, the standard for the evaluation of wrinkles is insufficient. The wrinkles distribution along the longitudinal axis of the tube results in an average value [1]. An evaluation of the wrinkles is not carried out. Due to the lack of an adequate basis of assessment, coordination problems between customers and suppliers occur. They result from an imprecision caused by the lack of quantitative evaluability of the geometric deviations at the inside arc. The benchmark factor for the inside arc presented in this article is an approach to holistically evaluate the geometric deviations at the inside arc. The classification of geometric deviations is carried out according to the area of the geometric characteristics and the respective flank angles.

Characterization of a Dual Phase Steel Using Tensile and Free Bending Tests

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Accurate material characterization is needed for good simulation and process design and to achieve high quality standards in the automobile industry. Previous studies have shown that the material behaviour near the yield point is strongly affected by residual stress and recent investigations have revealed that tensile test data does not reflect well the effect of residual stresses. A test procedure promising a higher sensitivity to residual stress is the free bending test. In this work the difference between material data generated using the tensile test is compared with that obtained from a pure bending for a cold rolled Dual Phase high strength steel. Tensile tests and bending tests were performed on specimens oriented in the rolling, diagonal and transverse directions and material anisotropy and hardening studied. The results show that there are significant differences in material hardening and anisotropy between the material data generated by the tensile test and that obtained using the bending testing.

Investigation on the Tensile Behavior of Fiber Metal Laminates based on Self-Reinforced Polypropylene

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Mechanical tests have been carried out to accurately evaluate the tensile properties of fiber metal laminates (FMLs). The FMLs in this paper comprised of a layer of self-reinforced polypropylene (SRPP) sandwiched between two layers of aluminum alloy 5052-H34. In this study, nonlinear tensile and fracture behavior of FMLs under the in-plane loading conditions has been investigated with numerical simulations and theoretical analysis. The numerical simulation based on finite element modeling using the ABAQUS/Explicit and the theoretical constitutive model based on a volume fraction approach and a modified classical lamination theory, which incorporates the elastic-plastic behavior of the aluminum alloy are used to predict the mechanical properties such as stress-strain response and deformation behavior of FMLs. In addition, through comparing the numerical simulations and the theoretical analysis with experimental results, it was concluded that a numerical simulation model adopted describes with sufficient accuracy the overall tensile stress-strain curve.

An Evaluation Technique for Forming Limit Strains of Zircaloy-4 and Zirlo Sheets Based on FEA Solutions

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In this study, we determine the forming limit strains (FLS) for zircaloy-4 and zirlo. First, we obtain true stress-strain curves for the two materials by the weighted-average method. Then we experimentally evaluate FLSs by limit dome height (LDH) tests. Theoretical forming limit curves (FLC) are obtained using regressed stress-strain relations, and it is shown that they are in a good agreement with experimental data. Further, we establish an FE model for determining FLSs. The LDHT model is used for the region between uniaxial and plane strain ($\varepsilon_2 < 0$); for the section $\varepsilon_2 \geq 0$, we use a biaxial tensile model and apply various displacement ratios. As experimental FLSs the presumed strain obtained by Gaussian regression is taken, while as analytical FLS we take the real strain at the point of local thinning. The analytical FLSs are shown to be in a good agreement with experimental and theoretical values.

Characterizing the Heterophase Interface Character Distribution (HICD) of the Cu-Nb Multilayer Composites Using EBSD

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A method for characterizing the full five parameter heterophase interface character distributions (HICD) using two-dimensional electron back-scatter diffraction (EBSD) images is presented. Especially, Cu–Nb interfaces in both physical vapor-deposited (PVD) pure Cu–Nb and accumulative roll-bonded (ARB) alloyed Cu–Nb multilayer composites are characterized. The analysis shows that the Cu–Nb interface relationships between various misorientations in the PVD pure Cu–Nb differ from those with corresponding misorientations in the ARB alloyed Cu–Nb, which indicates that these interfaces are preferentially selected depending on the manufacturing processes. Interestingly, the measured ARB textures along the interface also differ from the theoretical rolling textures for each bulk single phase metal, suggesting that during ARB layer refinement these interfaces have some influence on slip activity by constraining grain deformation or through the kinetics of dislocationinterface interactions.

Accurate Parameter Identification for Crystal Plasticity Finite-Element Analysis in a Magnesium Alloy Sheet

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A new procedure of parameter identification for crys-

tal plasticity finite-element analysis in a rolled Magnesium alloy sheet was proposed. The procedure consisted of the following four steps; (1) the parameters for basal slip are estimated to achieve a fit with the initial yield stress under uniaxial tension, (2) a ratio between the parameters for the prismatic slip and the pyramidal-2 slip is estimated to achieve a fit with the evolution of Lankford value, (3) with keeping the ratio, the parameters for the prismatic slip and the pyramidal-2 slip as well as those of basal slip are adjusted to achieve a fit with the stress-strain curve under uniaxial tension, and (4) the parameters for the twinning are estimated to achieve a fit with the stress-strain curve under uniaxial compression. Using the conventional parameters, the evolution of Lankford value was surprisingly larger than that of the experiment although the stress-strain curve was in good agreement with the experimental result. On the other hand, when the newly-identified parameters were used, both the stress-strain curve and the evolution of Lankford value were in good agreement with the experimental results, showing that the proposed procedure gave more accurate parameters.

Material characterization and continuum modeling of AZ31B and ZEK100 magnesium alloy sheet

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Wrought magnesium alloys are attractive for automotive industry applications due to their low density and high specific strength. However, commercial magnesium alloys, such as AZ31B sheet usually have poor formability at room temperature due to limited activity of slip systems. Additionally, due to the twinning deformation mechanism activated in specific loading directions, magnesium alloys exhibit an asymmetric stress-strain response in uniaxial tension and compression tests. The formability of magnesium alloys can be improved by deforming at elevated temperatures; however, warm forming requires more complex tooling setup which increases the cost of the forming operation. Alternatively, the formability can be improved by the addition of rare-earth elements such as Ce, Nd, Y and Gd, for example, which have been shown to weaken the basal texture.

The aim of this work is to compare and identify the effect of initial crystallographic texture on the mechanical response of commercial AZ31B-O and rare-earth ZEK100 magnesium alloy sheets in light of known deformation mechanisms operating at different orientations and strain rates. Tensile and compression testing was performed on AZ31B and ZEK100 sheets along different directions to characterize the material response under a wide range of temperature (23-250oC) and strain rate (0.001s-1-1000s-1). A digital image correlation system (DIC) was used to capture the evolution of plastic strain during the deformation. Three point bend tests were also performed on the AZ31B samples and surface strain on the tensile surface of the bend was measured using the DIC method. The instantaneous R-values and their evolution with respect to the plastic strain were measured from the tensile and compressive DIC data. The ZEK100 sheet exhibits strong in-plane anisotropy both in tension and compression as the orientation changes from the RD to TD. The low to high strain rate experiments reveal a significant orientation dependence of the strain rate sensitivity of ZEK100. In contrast, the rate sensitivity of AZ31B, while pronounced, does not depend upon loading direction. In the RD, the rate sensitivity of ZEK100 is manifest in significant changes in yield strength, but only mild changes in hardening rate. In contrast, along the TD, the yield strength is not affected by strain rate, while the hardening rate increases significantly with strain rate. This behavior is attributed to different deformation mechanisms being activated at different strain rates depending on the load path, sheet orientation and texture. As temperature is increased, the degree of anisotropy and asymmetry is reduced for both alloys.

An evolving asymmetric/anisotropic continuum-based approach, adopting Cazacu-Plunkett-Barlat (CPB) yield surfaces, is proposed to model the complex behavior of magnesium alloys at room and elevated temperatures. The model shows that the material response of AZ31B at room temperature is highly anisotropic and asymmetric; while a minor asymmetry between uniaxial tension and compression results is predicted at elevated temperature, consistent with experimental data. The proposed material model is used to simulate 3-point bending experiments on AZ31B and predict both the load-displacement response as well as the distribution of strains on the outer bend radius. The results of the simulation using the new evolving continuum model compare well with experimental data over predictions using other material models such as classical von Mises and non-evolving CPB based models.

Acquisition Of Material Properties In Production For Sheet Metal Forming Processes

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In past work a measurement system for the in-line acquisition of material properties was developed at IVP.

This system is based on the non-destructive eddy-current principle. Using this system, a 100% control of material properties of the processed material is possible. The system can be used for ferromagnetic materials like standard steels as well as paramagnetic materials like Aluminum and stainless steel. Used as an in-line measurement system, it can be configured as a stand-alone system to control material properties and sort out inapplicable material or as part of a control system of the forming process. In both cases, the acquired data can be used as input data for numerical simulations, e.g. stochastic simulations based on real world data.

Cruciform Specimen Design and Validation for Constitutive Identification of Sheet Metal

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Accurate material models are imperative for successful simulations of sheet metal forming. Calibrating these models can benefit significantly from biaxial experimental data, for example by testing cruciform specimens under biaxial tension. While this technique allows for significant flexibility in the strain paths that can be investigated, a major limitation is the difficulty of accurately determining the stresses in the test section. We propose a cruciform specimen design that allows for direct and accurate determination of stresses from remote load and local strain measurements. The specimen has a test section of reduced thickness; sharp radii and step transitions between the arms and the test section; and laser-cut slots in the four arms. Using finite element analysis, we show that these features result in a uniform stress field inside the test section, with the exception of a thin boundary layer between the arms and the test section. Furthermore, we show numerically that this specimen design can very accurately recover the hardening behavior and the yield surface of the material for strains exceeding 15% for a dual-phase steel (DP590), depending on the loading path. While very accurate for constitutive identification, this design cannot be used to assess the forming limits of sheet metal as failure initiates at the thin boundary layer at the periphery of the test section.

The micromechanical deformation behaviors of hot-rolled 590DP steel during hole-expansion test

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The crystal plasticity finite element method (CPFEM) was used to study the effect exerted by the crystallographic orientation and spatial distribution of the constituent phases in 590DP steel during hole-expansion. The individual crystallographic orientations and spatial distributions for ferrite and martensite phases in 590DP steel was characterized using phase identification method that was based on the image quality(IQ) EBSD data. By a direct mapping of the microstructure into finite element meshes, the CPFEM captured the effect of the microstructure heterogeneity on the hot spots for void formation and micro-crack propagation in 590DP steel during hole-expansion. The void formation mechanisms as well as micro-crack propagation were analyzed through hierarchical scanning electron microscope (SEM) observations at the hole edge. An isotropic elasto-plastic FEM was also used to simulate the micromechanical deformation behaviors of 590DP steel during hole-expansion without considering the crystallographic orientation of the constituent phases. The simulation results demonstrated that the initial crystallographic orientation of the constituent phases significantly affects the hot spots for void formation and micro-crack propagation in 590DP steel during hole-expansion.

Characteristics of the Aluminum Alloy Sheets for Forming and Application Examples

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In this paper, the characteristics and application examples of aluminum alloy sheets developed for automotive parts by Sumitomo Light Metal are described. For the automotive closure panels (ex., hood, back-door), an Al-Mg-Si alloy sheet having an excellent hemming performance was developed. The cause of the occurrence and the propagation of cracks by bending were considered to be the combined effect of the shear bands formed across several crystal grains and the micro-voids formed around the second phase particles. By reducing the shear band formation during bending by controlling the crystallographic texture, the Al-Mg-Si alloy sheets showed an excellent hemming performance. For the automotive outer panels (ex., roof, fender, trunk-lid), an Al-Mg alloy sheet, which has both a good hot blow formability and excellent surface appearance after hot blow forming was developed, and hot blow forming technology was put to practical use using this developed Al-Mg alloy

sheet. For automotive heat insulators, a high ductile Al-Fe alloy sheet was developed. The heat insulator, which integrated several panels, was put into practical use using this developed Al-Fe alloy sheet. The textured sheet was often used as a heat insulator in order to reduce the thickness of the aluminum alloy sheet and obtain good press formability. The new textured sheet, which has both high rigidity and good press formability for heat insulators, was developed by FE analysis.

Development of Measurement Method of Draw Bead Parameters for CAE Analysis

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In this study, a new identification procedure for the simulation parameters of the equivalent draw bead model was proposed. In this method, the blank holding force was gradually reduced during the draw bead test and the variations in the draw bead restraining force and die clearance were measured continuously. The lifting force at which the die clearance started to increase was also obtained from the variation in die clearance. As an application example, a square cup drawing process was simulated using the parameters identified by this procedure. The results of wrinkles on a flange were in good agreement with experimental results. Moreover, we proposed an alternative method to identify the parameters solely using the CAE analysis.

Numerical and Experimental Investigation forMagnetic Pulse Forming of AZ31 Magnesium Alloy Sheet

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Magnetic pulse forming (MPF) is a high speed forming process, which can significantly improve the formability of AZ31 magnesium alloy material at room temperature.An electromagnetic field model, in which the electric circuit and magnetic circuit are coupled, is established by finite element analysis software ANSYS/MULTIPHYSICS. The magnitude and distribution of magnetic force is obtained through the coupling model. Based upon the obtained magnetic force and constitutive model established at high strain rate, 3D deformation analysis modelsforfree bulging with and without an Al drive sheetare performed by ANSYS/LS-DYNA.The distribution of magnetic flux density, magnetic pressure, and thickness fieldare analyzed and discussed.The results showed that the Al drive sheet could eliminate the depression at the bottom of the formed sheet. The predicted profiles and thicknessin typical sections of the partwere validated by experiments, which demonstrated that the established numerical model could successfully simulate the related MPF process.

3-D mesoscale, spatial characterization of ultrasonic additive manufactured AA 6061

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Two different techniques for 2-Dimensional characterization of the microstructure of metals namely, Electron Backscatter Diffraction (EBSD) and Energy-Dispersive X-ray Spectroscopy (EDS), are used in conjunction with Focused Ion Beam (FIB) tomography and a microstructural quantification module, in order to examine the morphology, texture and interconnectivity of phases and grains in a 50x50x35 um volume of ultrasonic additive manufactured AA 6061. First, 3-D EBSD/EDS data is acquired via the careful selection of FIB-milling parameters and by using a lateral as well as z-depth resolution of 0.2 μm. Second, the tomographic data is reconstructed using a novel procedure that uses the information from the elemental maps of the spectroscopy data to modify the EBSD data at voxels belonging to phases other than the aluminum matrix and then performs region growing based on mis-orientation of grains. This enables the reconstruction of different inter-metallic phases that would otherwise be un-indexable owing to poor EBSD patterns due to ion-beam-induced damage. Third, a microstructural quantification module is used to quantify the texture and morphology in the three dimensional model. The distributions of calculated structural parameters such as grain orientation, mis-orientation, and, size and shape of grains and phases, are reported along with results from an analysis of the spatial distribution of secondary phase particles. The exchange of information between EBSD and EDS data realized via the reconstruction process enables us to overcome the limitations of each of the individual characterization techniques, such as material issues during FIB-assisted surface preparation and distortion of elemental maps due to stage drift. In contrast to conventional characterization techniques that provide image-based, qualitative information along with a morphological measure such as grain size, the approach developed in this study

provides a tool that enables high-fidelity 3-D, textural and chemical characterization of real microstructures of metal alloys and provides detailed quantitative information about the structural parameters and their distributions. This information can be used to develop high fidelity models for use in predictive simulations. The approach is a step towards achieving complete exchange of information between characterization methods used at the micro-scale and, is a contribution to the bigger goal of developing integrated tools for materials characterization across multiple scales, as motivated in [1].

Comparison of Determination of Biaxial True Stress True Strain Curves by the Use of Plane Strain Compression Test and Bulge Test

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The true stress-strain curve of the common uniaxial tensile test delivers data only within the uniform elongation. Beyond the instability point, the flow curve is usually extrapolated by different the mathematical approaches. Due to the different mathematical approaches, the extrapolated flow curve shows different curve shapes. A more accurate extrapolation can be achieved with the help of a different test, which enables an experimental determination of true stress - true strain curves at higher strain values. In this paper the biaxial true stress - true strain curves determined with the aid of a newly developed plane strain compression test for thin sheets are presented and compared with the results of the bulge test for the same material.

Constitutive Modelling

Effect of Tensile Twins on the Subsequent Plastic Deformation in Rolled Mg-3Al-1Zn Alloy

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The $\{10\bar{1}2\}$ tensile twins influence plastic flow of magnesium alloys for the subsequent plastic deformation since it contributes to grain refinement and texture hardening between the twinned and untwined regions. This paper investigates the variation of plastic flow of the rolled Mg-3Al-1Zn alloy which is compressed with a small plastic strain at the room temperature to induce the twins in the initial specimen. Subsequent tension and compression along the rolling and transverse direction are conducted with the twin induced specimens in order to examine the effect of the initial tensile twins.

Effect of Temperature Dependent Material Properties on Electromagnetic Forming Behavior

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Electromagnetic forming (EmF) is kinds of high velocity impulse forming technologies using Lorentzs force induced by high intensity pulsed electromagnetic field for electrically conductive metals. It has been known that due to extremely high strain rates in comparison to traditional quasi static forming processes, the formability can be improved and the springback can be reduced for several metals. In this study, an effect of temperature dependent material properties on the formability and springback was investigated to consider temperature rise due to Joule heat. EmF experiments were presented for two aluminum alloy sheets having 1.0mm thickness for both, AA1050-H and AA5J32-O. Electromagnetic forming system (EmFS) with maximum energy capacity of 120kJ was used and the spiral type coil and open die cavity were utilized to freely form the targeted hemi elliptical protrusion. In order to analyze the effect of temperature dependent material properties on the formability and springback, the numerical simulations for EmF were performed with considering the variations of elastic modulus and flow curve in range from room temperature to 100^{o}C.

Tailored Work Hardening Descriptions in Simulation of Sheet Metal Forming

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In the previous decades much attention has been given on an accurate material description, especially for simulations at the design stage of new models in the automotive industry. Improvements lead to shorter design times and a better tailored use of material. It also contributed to the design and optimization of new materials. The current description of plastic material behaviour in simulation models of sheet metal forming is covered by a hardening curve and a yield surface. In this paper the focus will be on modelling of work hardening for advanced high strength steels considering the requirements of present applications. Nowadays work hardening models need to include the effect of hard phases in a soft matrix and the effect of strain rate and temperature on work hardening. Most material tests to characterize work hardening are only applicable to low strains whereas many practical applications require hardening data at relatively high strains. Therefore, physically based hardening descriptions are needed allowing reliable extensions to high strain values.

Variation of Yield Loci in Finite Element Analysis by Considering Texture Evolution for AA5042 Aluminum Sheets

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Yield function has various material parameters that describe how materials respond plastically in given conditions. However, a significant number of mechanical tests are required to identify the many material parameters for yield function. In this study, an effective method using crystal plasticity through a virtual experiment is introduced to develop the anisotropic yield function for AA5042. The crystal plasticity approach was used to predict the anisotropic response of the material in order to consider a number of stress or strain modes that would not otherwise be evident through mechanical testing. A rate-independent crystal plasticity model based on a smooth single crystal yield surface, which removes the innate ambiguity problem within the rate-independent model and Taylor model for polycrystalline deformation behavior were employed to predict the materials response in the balanced biaxial stress, pure shear, and plane strain states to identify the parameters for the anisotropic yield function of AA5042.

A New Representation of Linear Transformation Tensor for the Description of Plastic Subsequent Anisotropy

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Defining material coefficients of anisotropic yield function as scalar functions of equivalent plastic strain is usually employed to model subsequent anisotropic behavior of metallic sheet. However, it might be difficult to take into account the influence of strain path change with this method. In this paper, a new representation of linear transformation tensor within the isotropic equivalent plasticity theory [Karafillis, A., Boyce, M., 1993. A general anisotropic yield criterion using bounds and a transformation weighting tensor. J. Mech. Phys. Solids 41, 1859-1886.] is proposed in order to consider the influence of strain path change on subsequent anisotropy. To illustrate the capability of suggested representation, a numerical example about subsequent anisotropy is presented.

Study on Stress-Strain Response of Multi-Phase TRIP Steel under Cyclic Loading

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The stress-strain response of multi-phase TRIP590 sheet steel is studied in cyclic loading condition at room temperature based on a cyclic phase transformation model and a multi-phase mixed kinematic hardening model. The cyclic martensite transformation model is proposed based on the shear-band intersection, where the repeat number, strain amplitude and cyclic frequency are used to control the phase transformation process. The multi-phase mixed kinematic hardening model is developed based on the non-linear kinematic hardening rule of per-phase. The parameters of transformation model are identified with the relationship between the austenite volume fraction and the repeat number. The parameters in Kinematic hardening model are confirmed by the experimental hysteresis loops in different strain amplitude conditions. The responses of hysteresis loop and stress amplitude are evaluated by tension-compression data.

An Alternative Approach for Modeling Strength Differential Effect in Sheet Metals with Symmetric Yield Functions

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An alternative approach is proposed to utilize symmetric yield functions for modeling the tension-compression asymmetry commonly observed in hcp materials. In this work, the strength differential (SD) effect is modeled by choosing separate symmetric plane stress yield functions (for example, Barlat Yld 2000-2d) for the tension i.e., in the first quadrant of principal stress space, and compression i.e., third quadrant of principal stress space. In the second and fourth quadrants, the yield locus is constructed by adopting interpolating functions between uniaxial tensile and compressive stress states. In this work, different interpolating functions are chosen and the predictive capability of each approach is discussed. The main advantage of this proposed approach is that the yield locus parameters are deterministic and relatively easy to identify when compared to the Cazacu family of yield functions commonly used for modeling SD effect observed in hcp materials.

The Strain Path Dependence of Plastic Deformation Response of AA5754: Experiment and Modeling

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This work presents modeling of experiments on a balanced biaxial (BB) pre-strained AA5754 alloy, subsequently reloaded uniaxially along the rolling direction and transverse direction. The material exhibits a complex plastic deformation response during the change in strain path due to 1) crystallographic texture, 2) aging (interactions between dislocations and Mg atoms) and 3) recovery (annihilation and rearrangement of dislocations). With a BB pre-strain of about 5%, the aging process is dominant, and the yield strength for uniaxially deformed samples is observed to be higher than the flow stress during BB straining. The strain hardening rate after changing path is, however, lower than that for pre-straining. Higher degrees of pre-straining make the dynamic recovery more active. The dynamic recovery at higher strain levels compensates for the aging effect, and results in: 1) a reduction of the yield strength, and 2) an increase in the hardening rate of re-strained specimens along other directions. The yield strength of deformed samples is further reduced if these samples are left at room temperature to let static recovery occur. The synergistic influences of texture condition, aging and recovery processes on the material response make the modeling of strain path dependence of mechanical behavior of AA5754 challenging. In this study, the influence of crystallographic texture is taken into account by incorporating the latent hardening into a visco-plastic self-consistent model. Different strengths of dislocation glide interaction models in 24 slip systems are used to represent the latent hardening. Moreover, the aging and recovery effects are also included into the latent hardening model by considering strong interactions between dislocations and dissolved atom Mg and the microstructural evolution. These microstructural considerations provide a powerful capability to successfully describe the strain path dependence of plastic deformation behavior of AA5754.

Measurement and Material Modeling of Biaxial Work-Hardening Behavior for Pure Titanium Sheet

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Biaxial tensile tests of a commercial pure titanium sheet (JIS #1) were performed using a servo-controlled multiaxial tube expansion testing machine developed by one of the authors [Kuwabara, T. and Sugawara, F., Multiaxial tube expansion test method for measurement of sheet metal deformation behavior under biaxial tension for a large strain range, Int. J. Plasticity, 45 (2013), 103-118]. Tubular specimens with an inner diameter of 54 mm were fabricated by roller bending and TIG welding the as-received test material with a thickness of 0.5 mm. Several linear stress paths in the first quadrant of the stress space were applied to the tubular specimens to measure the contours of plastic work and the directions of the plastic strain rates for an equivalent plastic strain range of $0.05 < \varepsilon_0^p < 0.30$. It was found that the shapes of the work contours significantly changed with an increase in and that the Yld2000-2d yield function could reproduce the differential work hardening behavior of the test material by changing the material parameters and the exponent as functions of ε_0^p.

Combination Of The Strain Dependent Yld2000 Model With An Extended HAH Model

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Because of the complex forming behavior of sheet materials, a good mathematical description is one of the keys in order to obtain reliable simulation results. Considerable efforts were made in the fields of crystal plasticity, which helps to deeply understand materials

deformation behavior. However, these kind of models so far cant be used for industrial applications because they usually are numerically to costly. Today, becaus eof their simplicity and the relatively small experimental effort for the parameter fitting, most often models are used, that only capture the initial anisotropy of materials. If deformations take place along nonlinear strain pathes, the stress responses of these models are not accurate anymore. This is eventually manifested in a widley differing strain distribution within the part as well as in a non-correct springback behavior. To overcome these limitations, a combination of the strain dependent Yld2000 model and an extended version of the HAH model is proposed in this work. As a result of this combination, a model which is able to capture all the major anisotropic hardening effects is obtained. In the following, the model is described in detail and its abilities are demonstrated.

Strain Rate-dependent Flow Stress Curves in the Large Deformation Range

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This paper deals with the construction method of the flow stress curve at various strain rates in the large deformation range. The hydraulic bulge test is carried out for EDDQ and 590DP steel sheets in order to obtain equi-biaxial flow stress curves according to the punch speed. By using the measured curves, the stress data at various plastic strains is fitted by Cowper-Symonds model in order to analyze the strain rate sensitivity and determine the stress value at the designated strain rate. Equi-biaxial flow stress curves at various strain rates are constructed by fitting the determined stress value with Swift model with respect to the plastic strain. Finally, equi-biaxial flow stress curves are converted into uniaxial flow stress curves by using Yld2000-2d yield function. A suggested procedure can be utilized to construct the uniaxial flow stress curves at various strain rates in the large deformation range.

Modeling of Anisotropic Hardening of Sheet Metals

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To describe the evolution of anisotropy of sheet metals, in terms of both r-values and stresses, the present paper proposes anisotropic hardening models, where the shape of yield surface changes with increasing plastic strain. In this framework of modeling, any types of yield functions are able to be used. The evolution of anisotropy is expressed by updating the yield function as an interpolation between two yield functions defined at two different effective plastic strains. In this paper, two types of interpolation models, i.e., nonlinear interpolation model and piecewise interpolation model are presented. These models are validated by comparing the experimental data on 3003-O aluminum sheet (after Hu, Int J Plasticity 23, 620-639, 2007). To describe the Bauschinger effect, the combined anisotropic-kinematic hardening model is formulated based on Yoshida-Uemori kinematic hardening model.

Gurson-type Elastic-Plastic Damage Model Based on Strain-Rate Plastic Potential

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Ductile damage is generally described by stress-space analytical potentials. In this contribution, it is shown that strain rate potentials, which are exact conjugate of the stress-based potentials, can be equally used to describe the dilatational response of porous metals. This framework is particularly appropriate for porous materials with matrix described by complex yield criteria for which a closed-form expression of the stress-based potential is not available. Illustration of the new approach is done for porous metals containing randomly distributed spherical voids in a von Mises elasto-plastic matrix. Furthermore, a general time integration algorithm for simulation of the mechanical response using this new formulation is developed and implemented in Abaqus/Standard. The proposed model and algorithm are validated with respect to the Abaqus built-in GTN model, which is based on a stress potential, through the simulation of a tensile test on a round bar.

Application of Crystal Plasticity and Evolutionary Yield Functions for Modeling of Forming Processes

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Crystal plasticity relates the plastic behavior of crystalline materials to their microstructures. It can be used as a computational tool for the analysis of metal

forming processes, microcrack initiation, crack propagation, fatigue, creep, texture design, calculation of damage parameters, FLD diagrams, and evolutionary coefficients of yield functions. In order to describe the plastic deformation by the crystallographic glide, three objectives must be met; 1) determination of active slip systems, 2) determination of shear rate on active slip systems, and 3) overcoming the problem arising from non-uniqueness of active slip systems in an arbitrary strain path. Using an optimization technique, single crystal yield functions were developed to meet the above objectives, and to serve as a constitutive model for the forming analysis of polycrystalline metals. In the first part of the presentation, I will present the rate-independent, dual mixed (DM) and combined constraints crystal plasticity (CCCP) models which were implemented into ABAQUS as a UMAT. These models require as input the initial texture of the metal (from OIM), the appropriate active slip systems, and the hardening parameters for each slip system. As output, these models calculate the total plastic deformation, shear rate for each slip system, and the texture evolution. Currently, the hardening for each slip system is calculated using a phenomenological hardening model accounting for self and latent hardenings. However, progress made toward implementing other hardening models, including a dislocation density based model to calculate slip resistances for each slip system will be discussed. In order to perform macroscale FE simulation of metal forming problems, Taylors assumption is invoked where each grain is assumed to undergo the same deformation rate. To accurately represent the plastic behavior of a polycrystalline metal, currently as many as 50-100 grain orientations are considered at each FE integration point. The accuracy and efficiency of DM and CCCP constitutive models were recently verified by simulating the bulging and hydroforming of a 6061-T4 aluminum tube [2010], bulging of a niobium sheet, and the shear deformation of a tin solder joint [2012]. In the second part of the presentation, I will discuss a new approach in which the anisotropy coefficients of phenomenological yield functions are evolved as a function of parameters such as temperature and the effective plastic strain to account for the deformation induced anisotropy of the metal. Such yield functions have been developed for warm forming of aluminum [2007], and niobium sheet [2007]. Crystal plasticity is also being used to calculate the forming limit diagram (FLD). A plan is currently underway to develop evolutionary yield functions for multi-phase, advanced high strength steels (AHSS).

The Effects of Single Crystal Hardening Models on the Predictions of Sheet Metal Formability

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Simulations of sheet metal formability with numerical models based on crystal plasticity theory are becoming popular as computational resources keep on improving. Even though the kinematics of crystal plasticity theory is well known for some time, researchers still focus on the development of advanced hardening models, at single crystal level, that can accurately capture experimentally observed deformation mechanisms. In the first part of this paper, the effects of various single crystal hardening models on the initiation and propagation of localized deformation is discussed. It is demonstrated that, the choice of the hardening model can significantly affect the localized deformation pattern, especially when complex strain paths are considered. In the final part of this paper, a new crystal plasticity based hardening law is proposed to predict material response under complex strain paths. The model is calibrated with experimentally measured microstructural features during deformation. The new hardening law, in contrast to existing laws, can be completely determined from a uniaxial tension stress-strain curve with very few free parameters. The model accounts for hardening due to interactions with forest dislocations as well as with dislocation cells. The interaction with dislocation cells is estimated by using backstress effect. Furthermore, the new formulation employs the so-called Nye tensor to evolve the dislocation cell size and an efficient computational framework is implemented in the numerical model. The new model is calibrated with experimental uniaxial tension data for the aluminum alloy 5754. The predicted stress-strain curve and microstructural response of the material along various strain paths are compared to experimental measurements. The new model presents much better predictions compared to other various existing hardening laws in the literature. This model allows us to examine the inhomogeneous distribution of slip arising from microstructural features as well as from strain paths and provides a powerful tool to investigate the onset of diffuse and localized necking (shear banding) observed during sheet metal forming operations.

A Study of 6th-Order Polynomial Type 3D Yield Function and Its Application

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Recently, Yoshida et al. proposed a 6th-order polynomial type 3D yield function (Yoshida model) with user friendly parameter identification scheme ([1]). This yield function has some advantages. One of the advantages is high flexibility to describe anisotropic properties. Besides, it does not need additional parameters to apply for 3D (solid) FE analysis. Authors implemented this model into commercial FEM code LS-DYNA via the user material subroutine. In this study, this yield function is applied for simulation of earing evolution of AA5042 during drawing and ironing processes and good results are obtained. As the reason for high accuracy, anisotropic properties are discussed.

Planar Anisotropy Evaluation of New CaO-added Al5052 Alloy Sheet with Plane Stress Yield Functions

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An obstacle to broader implementation of aluminum alloys in transportation industries is the superior formability of less costly steel alloys. Enormous potential benefits in mass reduction for fuel economy improvements with light weight, nonferrous alloys have stimulated novel approaches to forming complex aluminum components. In this paper, planar anisotropy of the new Al50552 alloy containing a calcium(Ca)-based compound, which is so-called Eco Al5052, was evaluated experimentally. The planar anisotropy was then modeled with three plane stress yield criteria of different complexity and theory bases, i.e., Hill48, Yld89 and Yld2000. The results indicate that different yield models distinctly affect the interpolation accuracy of the planar anisotropic behaviors. Yld2000 criterion exhibit better agreement with experimental data than those from Hill48 and Yld89 criteria since it has great extensibility due to the larger number of the mechanical parameters incorporated.

On the Influence of the Yield Parameters Identification Procedure in Cylindrical Cups Earing Prediction

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This work presents a study concerning the deep drawing process of a cylindrical cup, following the process conditions defined on the BENCHMARK 1 - Earing Evolution During Drawing and Ironing Processes, of NUMISHEET 2011 [1]. The deep drawing operation is analyzed for an AA5042 aluminum alloy, which orthotropic behavior is described using the Cazacu and Barlat, 2001 yield criterion [2]. The constitutive parameters were determined based on the experimental data obtained from tensile tests, with different orientations to the rolling direction, disk compression test and the equibiaxial tension test, using DD3MAT in-house code. An analytical approach that relates the earing profile with the ones of both r -values and yield stresses [3,4] is used to understand the influence of the identification procedure on the analytically and numerically predicted earing profile. The numerical simulations of the forming process were performed using DD3IMP in-house code. The analysis shows that, although earing is generally assumed as being coupled to the r-values profile, it is also important that the yield criterion captures the relative differences of the yield stress profile.

Experiment and Numerical Simulation on Cross-die Forming of SUS304 Metastable Austenitic Stainless Using a Modified Johnson-Cook Model

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True stress-strain curves of SUS304 metastable austenitic stainless steel at various strain rates were fitted by a modified Johnson-Cook material model. The effect of blank-holder force on Cross-die forming of SUS304 stainless steel was studied. The forming process was also simulated by the software Marc based on this model. Major strain distribution, thickness distribution and load-displacement were compared between experiment and simulation. The results indicated the modified Johnson-Cook model could well predict the deformation behavior of SUS304 stainless steel. The martensitie volume fraction at different positions of the formed part was in good agreement with what can be expected.

Stress-strain responses under continuous strain path changes based on HAH model

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In this work, an approach was proposed to describe the plastic behavior of a steel sheet under continuous strain path change from plane strain tension to simple shear. A recently developed anisotropic hard-

ening model, which is based on a homogeneous yield function, the so-called HAH model [1,2], was applied to model experiments conducted on mild steel [3,4]. The HAH model was implemented in the user material subroutine (VUMAT) of ABAQUS/Explicit [5]. The FE simulations were conducted to reproduce a set of experiments in which continuous strain path changes were imposed. Six different rates of transition from plane strain to simple shear were investigated. The prediction results captured a transient hardening behavior that depends on the rate of strain path change, in agreement with the experiments. In particular, anisotropic hardening features during the shear deformation stage, such as Bauschinger-like effect and stress overshooting, were well described.

Anisotropy Effect on the Stress-Based Fracture Forming Limit Diagram Using a Modified LouHuh Ductile Fracture Criterion

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This paper is concerned with the anisotropy effect on the stress-based fracture forming limit diagram using a modified LouHuh ductile fracture criterion. In sheet metal forming process, a usage of advanced high-strength steels (AHSSs) has been remarkably increasing for the lightweight car body and good formability. It is, however, unable to evaluate the formability of AHSS with the conventional forming limit diagram during complex forming processes since it is obtained by assuming the proportional loading path and AHSS shows sudden fracture involving little amount of necking. The stress-based fracture forming limit diagram was constructed using a modified LouHuh ductile fracture criterion in order to evaluate the formability of AHSS accurately. The anisotropy effect on the fracture strain is also evaluated to reflect the material behavior of sheet metals in constructing the criterion for the prediction of onset of the fracture. The constructed stress-based fracture forming limit diagrams deal with the stress state ranging from pure shear to equi-biaxial tension with the variation of orientation of sheet metals. It is clearly observed that the stress-based fracture forming limit diagrams are varied with the change of orientation of sheet metals.

Use of an Hyperelasto-hysteresis behavior law for deep drawing simulation

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For the numerical simulation of sheet metal forming processes, appropriate hardening model and plastic yield criterion that properly describe material behavior at large strain is needed. An accurate description of the mechanical behavior is very important, especially for springback analysis. In this paper, an original hyperelasto-hysteresis behavior law is presented. Contrary to classical constitutive model, based on the decomposition of deformation, this model assumes the decomposition of stress. The total stress is expressed as the addition of two partial stresses, the first being hyperelastic while the second one is related to hysteresis of elastoplastic type [1-4]. In this study, the partial hyperelastic stress tensor is calculated from the hyperelastic potential proposed by Favier [5]. This potential is expressed as function of three invariants of the Almansi strain tensor: the relative variation of volume V, the intensity of the deviatoric portion of the deformation tensor and the Lode angle.The hysteresis is described by an incremental model of hypoelastic type according the relation:
$\dot{\sigma} = 2\mu\bar{D} + \beta\Phi\Delta_R^t\bar{\sigma}$
and an algorithm to manage discrete memory points $\Delta_R^t = \sigma - \sigma_R$ introduced by P. Guélin [1]. $\bar{D}$ is the deviatoric strain rate tensor. More details can be found in references [5,6]. Eight parameters independent of the temperature are used in this model, including four parameters involved in the hyperelastic potential and four parameters of the hysteresis scheme.
The aim of this paper is to investigate the capability of this original hyperelasto-hysteresis model, to represent the behavior of an aluminum alloy during a forming process and springback evolution using the split-ring test. The studied material is a 5000 series Al-Mg alloy, AA5754-0. It is often used in the automotive industry for inner body panels.
Mechanical testings are performed through uniaxial tensile tests and monotonic shear tests [7] Figure 1 presents the comparison between the numerical identification with the hyperelasto-hysteresis behavior law and the experimental results for a shear test and a tension test. The comparison with typical experimental data for this aluminium alloy shows the possibilities of the hyperelasto-hysteresis model.
The hyperelasto-hysteresis model is introduced into an User MATerial subroutine, used by the commercial Abaqus software, by a specific technic [8].
To show the relevance of this model, the numerical results obtained with this model are compared with the experimental results of the deep drawing process of a cylindrical cup. The punch-force evolution during deep drawing and thickness distribution obtained numerically are compared with experimental ones provided in [9]. Finally, the split-ring test is used to evaluate the springback phenomenon. This test consists in cutting a ring specimen from a full drawn cup and then to split the ring longitudinally along a radial plane. The difference between the ring diameters, before and after splitting, gives a direct measure of the springback phenomenon, and indirectly, of the amount of residual stresses in the drawn cup. A comparison between the numerical results for the

ring opening with the hyperelasto-hysteresis model and the experimental ones are analyzed.

Effect of Pre-Straining on the Evolution of Material Anisotropy in Rolled Magnesium Alloy AZ31 Sheet

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The large strain Elastic Visco-Plastic Self-Consistent (EVPSC) model and the recently developed Twinning and De-Twinning (TDT) model are applied to study the mechanical behavior of rolled magnesium alloy AZ31 sheet. Three different specimen orientations with tilt angles of 0^o, 45^o and 90^o between the rolling direction and longitudinal specimen axis are used to study the mechanical anisotropy under both uniaxial tension and compression. The effect of pre-strain in uniaxial compression along the rolling direction on subsequent uniaxial tension/compression along the three directions is also investigated. It is demonstrated that the twinning during pre-strain in compression and the detwinning in the subsequent deformation have a significant influence on the mechanical anisotropy. Numerical results are in good agreement with the experimental observations found in the literature.

Constitutive Model of AZ31B Sheet at Various Pre-strains and Temperatures

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Due to their high specific strength, vibration absorption capability, and excellent corrosion resistance, Mg alloys have been potential alternative to other lightweight materials in the automotive industry. Mg alloys are known to have unique mechanical properties; i.e., yielding asymmetry, anisotropy, unusual hardening behavior at room temperature. Usually, Mg alloy sheets have inferior formability at room temperature, but the formability increases when the temperature increases. Moreover, the asymmetry and anisotropy become less significant due to the activation of non-basal slip systems at higher temperature. Utilizing this unique properties, the forming of Mg alloy sheets has been frequently conducted at the temperature of 200^oC or higher, at which twinning effect is less dominant. However, the forming process at elevated temperature lowers production speed due to the additional heating and cooling stages. To resolve this problem, studies on technology that maximizes the formability of Mg alloy sheets at lower temperature have been widely conducted. In this paper, the response of AZ31B Mg alloy sheets under tension-compression cyclic loading at different pre-strains and temperatures was measured experimentally. Then a practical hardening model was developed to reproduce the measured stress-strain responses, which can be applied to the simulation of sheet metal forming of Mg alloy sheets.

Fracture and damage

Modified Mohr-Coulomb Fracture Model for Anisotropic Sheet Materials Under Limited Triaxial Stress Conditions

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This paper reviews recent work of the authors to model necking and fracture for anisotropic materials, which requires consideration of the stress conditions that vary through the thickness of the sheet, and in particular, taking into consideration the conditions at individual integration points. Although the prior work adequately addresses the roll of triaxial stress conditions on necking, the fracture model developed in the prior work was limited in its application to analysis of plane-stress conditions. In this work, a fracture model is developed for application to a limited range of triaxial stress conditions, in which the through-thickness shear stresses are assumed to be negligible, but the normal stress is allowed to be non-zero. The model is extended in a way that reduces to the prior anisotropic fracture model under plane stress conditions, but includes the contribution of a triaxial stress condition in a way that retains the desired features of the Mohr-Coulomb Model.

New Ductile Fracture Criterion in Sheet Metal Forming at a Wide Range of Strain Rates

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This paper introduces a new ductile fracture criterion derived from the fracture mechanism of void generation, coalescence, and shear linking. The ductile fracture criterion covers a wide range of stress states including the pure shear and compression. The criterion is also extended to the three dimensional stress state for ductile fracture of bulk materials. Experiments have been conducted to evaluate fracture strains of auto-body steels as well as 4130 steel, OFHC copper and Ti6Al4V sheets over a wide range of strain rates ranging from $0.001\mathrm{s}^{-1}$ to $1700\mathrm{s}^{-1}$. The fracture tests were carried out with three types of the in-plane shear, dog bone and grooved specimens as well as the tension specimen with a circular hole to trace the strain paths on the conditions of the in-plane shear, uniaxial tension and plain strain. The fracture strain and the strain path were measured using 2-D DIC method on the surfaces of specimens to construct fracture loci of the Lou-Huh ductile fracture criterion with the variation of the strain rate. The fracture loci constructed demonstrates interesting results to show variation of the loci with the variation of the strain rate. The SEM experiments were conducted for investigation of the microstructure of the fractured surface to seek the reason of difference in the fracture loci with the variation of the strain rate.

Forming Limits in The Hole-Flanging Process by Coupled and Uncoupled Damage Models

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The aim of this work is to identify the limits of the hole-flanging process under different conditions. A 3D finite element model was developed to predict failure in hole-flanging process for sheet aluminium alloys. The GursonTvergaardNeedleman (GTN) coupled damage model and the Bao-Wierzbicki (BW) uncoupled damage model were used. The parameters of both coupled and uncoupled models were identified by inverse analysis based on uniaxial tensile test. Experiments were conducted to analyse the types of failure that appear during the process. Numerical results were compared with experimental datas to check the validity of both models in predicting failure during the hole-flanging process. The comparative study showed that the GTN model predicts more accurately almost all types of failure while fracture occurrence can be only predicted by the BW model.

Hardness-Based Plasticity and Fracture Model for Quench-Hardenable Boron Steel (22MnB5)

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A comprehensive strain hardening and fracture characterization of different grades of boron steel blanks has been performed, providing the foundation for the implementation into the modular material model (MMM) framework developed by Volkswagen Group Research for an explicit crash code. Due to the introduction of hardness-based interpolation rules for the characterized main grades, the hardening and fracture behavior is solely described by the underlying Vickers hardness. In other words, knowledge of the hardness distribution within a hot-formed component is enough to set up the newly developed computational model. The hardness distribution can be easily introduced via an experimentally measured hardness curve or via hardness mapping from a corresponding hot-forming simulation. For industrial application using rather coarse and computationally inexpensive shell element meshes, the user material model has been extended by a necking/post-necking model with reduced mesh-dependency as an additional failure mode. The present paper mainly addresses the necking/post-necking model.

Prediction of Edge Failure of Dual Phase 780 Steel Subjected to Hole Expansion

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University of Waterloo

The edge failure of a dual phase steel, DP780, under hole expansion (stretch flange) deformation conditions is examined. In order to assess the effect of damage processes without the presence of notches due to shearing, machined holes with a smooth edge condition were expanded with a conical punch. Images of the expansion as well as punch loaddisplacement were recorded during the tests. The GISSMO damage based failure criteria was implemented in a finite element model to predict the load-displacement of the punch and the initial crack formation. This failure criteria was calibrated using the effective plastic failure strain versus triaxiality data obtained from a set

of uniaxial and notched tensile samples. The predicted punch load-displacement curve was found to be in agreement with observations including the load drop at the onset of failure. The predicted peak load of 23.4kN compared favorably to the observed peak of 24.4kN. The model predicted a hole expansion ratio of 53.4% and compared well to the experimentally observed ratio of 51.0% ±10.0% .

Characterizing the Stretch-Flangeability of Hot Rolled Stretch Flangeable Steels

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Hole expansion tests are commonly used to characterize the edge stretching limit of a material. Traditionally, a conical punch is used to expand a punched hole until a through-thickness crack appears. However, many automotive stretch flanging operations involve in-plane edge stretching that is best captured with a flat punch. In this paper, hole expansion tests were carried out on two different hot-rolled stretch-flangeable steels: HR-SF 590 and HR-SF 780 using both flat and conical punches. The fracture mechanisms for both punch types were investigated using scanning electron microscopy (SEM).

Application of MMC Model on Simulation of Shearing Process of Thick Hot-rolled High Strength Steel Plate

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Shear operation is widely used as the first step in sheet metal forming to cut the sheet or plate into the required size. The shear of thick hot-rolled High Strength Steel (HSS) requires large shearing force and the sheared edge quality is relatively poor because of the large thickness and high strength compared with the traditional low carbon steel. Bad sheared edge quality will easily lead to edge cracking during the post-forming process. This study investigates the shearing process of thick hot-rolled HSS plate metal, which is generally exploited as the beam of heavy trucks. The Modified Mohr-Coulomb fracture criterion (MMC) is employed in numerical simulation to calculate the initiation and propagation of cracks during the process evolution. Tensile specimens are designed to obtain various stress states in tension. Equivalent fracture strains are measured with Digital Image Correlation (DIC) equipment to constitute the fracture locus. Simulation of the tension test is carried out to check the fracture model. Then the MMC model is applied to the simulation of the shearing process, and the simulation results show that the MMC model predicts the ductile fracture successfully.

Analysis of Failure of Resistance Spot Welding for Advanced High Strength Steel

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For the evaluation of the failure performance of the similar spot welded joints under static loading conditions, characterization procedure was proposed utilizing numerically inverse calibration method. TRIP (Transformation induced plasticity steel) 980 and DP (Dual Phase steel) 980 sheets were considered as base materials. In order to characterize the mechanical properties, for the spot weld joints were performed simple tension tests based on the newly developed miniature simple tension test method, while for the base sheets were performed those following standard methods. Considering the hardening behaviors and failure properties of the base sheets and weld nuggets, numerical simulations for the lap-shear tension test were performed and compared with experiments.

Modeling Failure For Nonlinear Strain Paths With CrachFEM

A. Heath, H. Gese, G. Oberhofer, H. Dell

MATFEM Partnerschaft Dr. Gese & Oberhofer

This paper describes a general technique for simulating sheet failure under complex deformation. Separate failure risks are calculated for unstable necking and ductile fracture modes associated with void growth and shear banding. Necking is detected by a multi-scale method which considers sheet inhomogeneity, strain hardening, Bauschinger effects, strain rate sensitivity and the multi-axial stress-state in the neck. The model is easily calibrated from uniaxial test data and can be combined with a mesh-independent treatment of post-necking deformation. Ductile fracture risks are based on damage tensors calculated as integrals of the effective plastic strain weighted by the stress state. The tensorial formulation accounts for fracture strain recovery following load reversal. Model parameters can be evaluated with standard testing machines using tailored specimens. The failure methodology is realized in the software module MFGenYld+CrachFEM, which can be

coupled to all major explicit FEM codes.

Numerical Models for the Prediction of Failure for Multilayer Fusion Al-Alloy Sheets

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Initiation and propagation of cracks in monolithic and multi-layer aluminum alloys, called Fusion, is investigated. 2D plane strain finite element simulations are performed to model deformation due to bending and to predict failure. For this purpose, fracture strains are measured based on microscopic pictures of Nakajima specimens. In addition to, micro-structure of materials is taken into account by introducing a random grain distribution over the sheet thickness as well as a random distribution of the measured yield curve. It is shown that the performed experiments and the introduced FE-Model are appropriate methods to highlight the advantages of the Fusion material, especially for bending processes.

Experimental and Numerical Investigation of fracture with an advanced Gurson model

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In this paper, damage and fracture in ferritic and ferrito-pearlitic steels sheet are studied. The plasticity and damage of the material are analyzed through classical tests (tensile tests, monotonic and Bauschinger shear tests, plane strain tests) plus a selection of notched specimens. Two approaches are used: the first one is through microscopic measurements, to obtain the porosity around the crack. The second is using numerical simulations with an extended version of the Gurson model, comprising plastic anisotropy, kinematic hardening and void growth. As the post-necking behavior is known for being sensitive to the material parameters, type of element and mesh size, a sensitivity analysis on the neck geometry will be carried out to evaluate the robustness of the method. The model is validated by comparing the neck geometry, force/displacement curves and porosity distributions with experimental observations. The results provide an important insight into the ductile and brittle fracture of the material, useful for future applications (viz. sheet metal forming, which usually lies in the low triaxiality level) and current extensions of Gurson model (void nucleation and coalescence, shear).

Comparative Study between Phenomenological and Micro Void Based Ductile Fracture Models for Metal Sheets Application

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Recent research has shown that metal ductile fracture strains are dependent on both stress triaxiality (the normalized hydrostatic pressure) and Lode angle parameter (related to the normalized third deviatoric stress invariant). In this paper, a comparative study is conducted on the phenomenological and micro void based ductile fracture models in the 3-D space of stress triaxiality, Lode angle parameter, and the equivalent strain to fracture. The selected phenomenological ductile fracture models include Cockcroft-Latham (C-L), Modified Mohr-Coulomb (MMC), and Pressure Modified Maximum Shear (PMMS). The selected micro void based models are Gurson-Needlman-Tvergaard (GNT) and Gurson-Nahshon-Hutchinson (GNH) and Nielsen-Tvergaard (N-T) models. These models are then calibrated from the three sets of experimental data of metal sheets, TRIP 690 and TRIP 780 steel sheets and AZ31B-H24 magnesium sheets. The experimental data include basic uniaxial testing (dogbone, notched and central hole specimens), and the advanced bi-axial testing with shear/ tensile loading and bi-axial tension. The predicting capabilities of these models are compared in both 3D fracture loci and 2D plane stress fracture envelopes. Guidelines of using these models are also discussed.

Prediction of Formability for Non-linear Deformation History using Generalized Forming Limit Concept (GFLC)

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The prediction of formability is one of the most important tasks in sheet metal process simulation. The common criterion in industrial applications is the Forming Limit Curve (FLC). The big advantage of FLCs is the easy interpretation of simulation or measurement data in combination with an ISO standard for the experimental determination. However, the conventional FLCs are limited to almost linear and unbroken strain paths, i.e. deformation histories with non-linear strain increments often lead to big differ-

ences in comparison to the prediction of the FLC. In this paper a phenomenological approach, the so-called Generalized Forming Limit Concept (GFLC), is introduced to predict the localized necking on arbitrary deformation history with unlimited number of non-linear strain increments. The GFLC consists of the conventional FLC and an acceptable number of experiments with bi-linear deformation history. With the idea of the new defined Principle of Equivalent Pre-Forming every deformation state built up of two linear strain increments can be transformed to a pure linear strain path with the same used formability of the material. In advance this procedure can be repeated as often as necessary. Therefore, it allows a robust and cost effective analysis of beginning instability in Finite Element Analysis (FEA) for arbitrary deformation histories. In addition, the GFLC is fully downwards compatible to the established FLC for pure linear strain paths.

Modeling of Shear Ductile Fracture Considering a Changeable Cut-off Value for Stress Triaxiality

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A macroscopic ductile fracture criterion is proposed based on micro-mechanism analysis of nucleation, growth and shear coalescence of voids from experimental observation of fracture surfaces. The proposed ductile fracture model endows a changeable cut-off value for the stress triaxiality to represent effect of micro-structures, the Lode parameter, temperature, and strain rate on ductility of metals. The proposed model is used to construct fracture loci of AA 2024-T351. The constructed fracture loci are compared with experimental data covering wide stress triaxiality ranging between 0.5 and 1.0. The comparison suggests that the proposed model can provide a satisfactory prediction of ductile fracture for metals from compressive upsetting tests to plane strain tension with slanted fracture surfaces. Moreover, it is expected that the proposed model reasonably describes ductile fracture behavior in high velocity perforation simulation since a reasonable cut-off value for the stress triaxiality is coupled with the proposed ductile fracture criterion.

Rate-dependent Hosford-Coulomb Fracture Initiation Model for Advanced High Strength Steel Sheets

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Basic plasticity and fracture experiments are performed at low ($\sim 10^{-3}$/s), intermediate ($\sim 10^{0}$/s) and high strain rates ($\sim 10^{3}$/s) on specimens extracted from DP590 and TRIP780 steel sheets. Finite element simulations are carried out on all experiments to determine the evolution of the stress state, strain, strain rate and temperature at the location of fracture initiation within the specimen. A plasticity model, with Johnson-Cook type rate and temperature-dependency and combined Swift-Voce strain hardening, is used to describe the viscoplastic response of the tested materials. To account for the important effect of thermal softening without solving the thermal field equations, the incremental change in temperature is computed using a strain rate dependent weighting function that differentiates between isothermal and adiabatic conditions. The calibration and validation of the plasticity model for the tested advanced high strength steels demonstrates the models ability to describe the post-necking response of tensile specimens (notched and central hole) with great accuracy over a wide range of strain rates and at very large strains (Fig. 1a). It is found that the material ductility increases substantially as a function of the loading speed, with increases of up to 50% from low to high speeds of loading. An extended Hosford-Coulomb fracture initiation model is proposed which accounts for the effects on the stress triaxiality, Lode angle parameter and strain rate on fracture (Fig. 1b).

Stamping Failure Analysis of Advanced High Strength Steel Sheet Based on Non-uniform Local Deformation through Thickness

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The phenomenon Shear fracture is often observed in the stretch-bending process of stamping over small radius with advanced high strength steels (AHSS). It occurs parallel to and near the die radius in the stretch-bending test. Since traditional Forming Limit Diagram (FLD) is unable to describe this type of failure, experimental and simulation works were constructed in this paper to investigate and predict the shear fracture. Fracture experiments were carried out through a stretch-bending test system, and failure mode was observed. There is no obviously thinning at the shear fracture surface. Further research shows that the initial crack of shear fracture occurs at the outer layer of specimen at die radius position. Finite element (FE) models were built for stretch-bending test with 3D element. The non-uniform local deformation through thickness corresponding to bending position was obtained and analyzed. Cockcroft & Latham fracture criterion is used. The outer layer of specimen at bending position reaches the critical fracture state firstly, which agrees well with experiments. Different fracture criteria are also compared and selected to determine this fracture. Results show that based on the non-uniform local deformation, the initial crack location of shear fracture at small radius can be effectively predicted by fracture criteria related to the maximum principle stress.

Validation of Formability of Laminated Sheet Metal for Deep Drawing Process using GTN Damage Model

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In this study, we studied formability of PET/PVC laminated sheet metal which named VCM (Vinyl Coated Metal). VCM offers various patterns and good-looking metal steel used for appliances such as refrigerator and washing machine. But, this sheet has problems which are crack and peeling of film when the material is formed by deep drawing process. To predict the problems, we used finite element method and GTN (Gurson-Tvergaard-Needleman) damage model to represent damage of material. We divided the VCM into 3 layers (PET film, adhesive and steel added PVC) in finite element analysis model to express the crack and peeling phenomenon. The material properties of each layer are determined by reverse engineering based on tensile test result. Furthermore, we performed the simple rectangular deep drawing and simulated it. The simulation result shows good agreement with drawing experiment result in position, punch stroke of crack occurrence. Also, we studied the fracture mechanism of PET film on VCM by comparing the width direction strain of metal and PET film.

Roll forming

Sensitivity Analysis of Roll Load, Torque and Material Properties in the Roll Forming Process

Buddhika Abeyrathna, Bernard Rolfe, Peter Hodgson, Matthias Weiss

Deakin University

Advanced High Strength Steel (AHSS) and Ultra High Strength Steel (UHSS) are increasingly used in the current automotive industry because of their high strength and weight saving potential. As a sheet forming process, roll forming is capable of forming such materials with precise dimensions, however a small change in processing may results in significant change in the material properties such as yield strength and hardening exponent from coil to coil or within the same coil.

This paper presents the effect of yield strength and the hardening exponent on roll load, torque of the roll forming process and the longitudinal bow. The roll forming process is numerically simulated, and then the regression analysis and Analysis of Variance (ANOVA) techniques are employed to establish the relationships among the aforementioned parameters and to determine the percentage influence of material properties on longitudinal bow, roll load and torque.

Mechanism of Cut End Deformation of Hat Shape Channel Steel by Roll Forming

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The hat-channel steel is channel with a bottom horizontal web and two vertical (web) with outward flange fabricated by roll forming. Roll formed hat channel will flair in (closing) at front end and flair out (opening) at tail end when cut off into component and this is called cut end deformation. The mechanism of pipe end deformation after cut-off hat channel in length was investigated by experimentation and finite element (FE) analysis. Residual shear stress in the longitudinal direction and in-plane shear stress at the edge become owning to outer and inner elements. The upper part of flange will have opposite reverse bending deformation with the lower part of flange. Opposite direction of residual twisting moment occurs at the upper part and lower part of flange. These stress and moments offset each other making the cut end deformation small at cutting edge.

Effect of Temper Rolling on Final Shape Defects in a V-section Roll Forming Process

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Roll forming is a continuous process in which a flat strip is shaped to the desired profile by sequential bending in a series of roll stands. Because of the large variety of applications of roll forming in the industry, Finite Element Analysis (FEA) is increasingly utilized for roll forming process design. Bending is the dominant deformation mode in roll forming. Sheet materials used in this process are generally temper rolled, roller- or tension- leveled. These processes introduce residual stresses into the material, and recent studies have shown that those affect the material behavior in bending. In this study a numerical model of the temper rolling (skin passing) process was used to determine a residual stress distribution in a dual phase, DP780, steel strip. A 5-stand roll forming process for the forming of a V-section was modeled, and the effect of various thickness reduction levels in the temper rolling process on the final shape defects was analyzed. The results show that a small thickness reduction in the temper rolling process decreases the maximum bow height but the final springback angle increases. It is also shown that reasonable model accuracy can be achieved by including the residual stress information due to temper rolling as initial condition in the numerical modeling of a roll forming process.

Numerical Investigation about the Effect of Increasing the Number of Forming Passes on the Quality of AHSS Roll Formed Products

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Over recent years, roll forming has gained an increasing interest for the manufacture of structural components made of Advanced High Strength Steel (AHSS) sheets. It is an incremental forming technique where the material is bent into the desired shape by feeding it through a number of roll forming stands. Springback is a major concern in forming of AHSS, and springback is lower in roll forming when compared to that in single step and multi-step bending. Some experimental studies suggest that this is may be due to the incremental nature of the roll forming process. In this study the effect of forming passes/steps on springback is numerically analyzed for DP 780 by means of FEA Abaqus standard. The cyclic hardening characteristics of DP780 were determined by the pure bending test. The hardening model generated from bend data set was imported into Abaqus. The effect forming pattern on the springback was analyzed by forming a V-section shaped profile (15 mm forming radius). The numerical results show that there is a reduction in springback with increasing number of forming passes in the roll forming process, and that this may be the result of straining experienced by the sheet during the multi-step roll forming. This study seems to provide a greater insight into understanding the nature of springback with the forming passes and process design.

Numerical Simulation of X90 UOE Pipe Forming Process

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The UOE process is an important technique to manufacture large-diameter welding pipes which are increasingly applied in oil pipelines and offshore platforms. The forming process of UOE mainly consists of five successive operations: crimping, U-forming, O-forming, welding and mechanical expansion, through which a blank is formed into a pipe in a UOE pipe mill. The blank with an appropriate edge bevel is bent into a cylindrical shape by crimping (C-forming), U-forming and O-forming successively. After the O-forming, there is an open-seam between two ends of the plate. Then, the blank is welded by automatic four-electrode submerged arc welding technique. Subsequently, the welded pipe is expanded with a mechanical expander to get a high precision circular shape. The multiple operations in the UOE mill make it difficult to control the quality of the formed pipe. Therefore, process design mainly relies on experience in practical production. In this study, the UOE forming of an API X90 pipe is studied by using finite element simulation. The mechanical properties tests are performed on the API X90 pipeline steel blank. A two-dimensional finite element model under the hypothesis of plane strain condition is developed to simulate the UOE process according to data coming from the workshop. A kinematic hardening model is used in the simulation to take the Bauschinger effect into account. The deformation characteristics of the blank during the forming processes are analyzed. The simulation results show a significant coherence in the geometric configurations comparing with the practical

manufacturing.

The Study on Deformation Characterization in Micro Rolling for Ultra-thin Strip

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The demand for miniaturized parts and miniaturized semi-finished products is increasing. Metal forming processes cannot be simply scaled down to produce miniaturized micro parts and microforming processes have the capability of improving mass production and minimizing material waste. In this study, experimental and theoretical investigations on the micro rolling process have proven that the micro rolling deformation of thin strip is influenced by size effects from specimen sizeon flow stress and friction coefficient. The analytical and finite element (FE) models for describing the size effect related phenomena for SUS 304 stainless steel, such as the change of flow stress, friction and deformation behaviour, are proposed. The material surface constraint and the material deformation mode are critical in determination of material flow stress curve. The identified deformation and mechanics behaviours provide a basis for further exploration of the material deformation behaviour in plastic deformation of micro scale and the development of micro scale products via micro rolling.

Study on Design Parameters of Flexible Roll Forming Process for Atypical Skin Structure

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The conventional die forming process using a die and press machine tool has been generally applied for the manufacture of three-dimensional curved sheet metal for skin structure. However, it is still difficult to make this conventional die forming process economically efficient because of the additional production cost caused by the development and management of the forming apparatus. For these reasons, many investigations of flexible forming technologies have been carried out to replace the conventional die forming process with alternative forming processes. Nevertheless, these alternative forming processes still do not provide sufficient solution for a skin structure because of some defects such as dimples and wrinkles on sheet metal. It can also cause economic losses incurred by additional machining to outside of the forming region on the sheet metal. In this research, new sheet metal forming process for atypical skin structure, called the flexible roll forming (FRF) process, is proposed to resolve the problems on both existing alternative processes and the conventional die forming process. This proposed process utilizes adjustable punches and two flexible rollers as forming tools. The initial blank, which inserted between flexible rollers, is formed to atypical skin structure by rotation of the roller. The curvatures of flexible rollers are adjusted by different lengths of the punches. It is also equipped with motors that can supply torque to punch module and flexible rollers. In contrast to the existing processes for atypical skin structure, the blank size of this process is unrestricted in the longitudinal direction just as with the typical roll forming process. Furthermore, this process does not cause production cost incurred by the additional machining and some defects. In this paper, the procedure of the FRF process for atypical skin structure is presented. The design parameters on modeling for finite element simulations are also verified by describing atypical skin structure.

Springback

Springback Analysis of Ultra High Strength Steel

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It is an inevitable trend in the automotive industry to apply more and more high strength steels and even ultra-high strength steels. Even though these materials are more difficult to process the development time of forming tools must be reduced. In order to keep the development time under control, simulation tools are used to verify the forming process in advance. At Aoi Machine Industry a project has been executed to accurately simulate springback of ultra-high strength steels in order to reduce the tool tryout time. In the first phase of the project the simulation settings were optimized based on B-Pillar model A made of Dual Phase 980. In the second phase, it was verified with B-Pillar model B whether these simulation settings were usable as general setting. Results showed that with the right settings it is very well possible to accurately simulate springback of ultra-high strength steels. In the third phase the project the stamping of a B-Pillar of Dual Phase 1180 was studied.

Investigation into Springback Characteristics of Two HSS Sheets during Cold V-bending

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Considering the safety and the light-weight structure, there is an increasing requirement of high strength steel (HSS) sheets in the automotive industry. The high-precise prediction of the springback depends on constitutive equations and their corresponding material parameters. In order to investigate the springback of HSS sheets, DP590 and B280VK, their constitutive behaviors were analyzed based on the sheet tension tests. With respect to the constitutive equation, the Voce model is more proper to two hot-rolled steels, DP590 and B280VK, than the Swift model. Two steels are all saturated hardening, and the degree of hardening decreases with the strain. The cold v-banding tests of two HSS sheets were carried out for evaluation of springback characteristics. Results of v-bending experiments showed that the springback angle increases with the bending along 45°, 90° and 0° to the rolling direction of steel in turn.

An Experimental Device for Cyclic Tension and Compression Tests

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A novel clamping device that prevents the sheet metal from being buckled in the compression test was developed in the present study. The thickness change of sheet metal during the compression test was taken into consideration for the determination of the clamping gap that makes the cyclic tension and compression test can be conducted with the use of only one single specimen. To accommodate for sheet metal with different thicknesses, an empirical formula that suggests the relation between the sheet thickness and the clamping device gap was also established. The efficiency of the developed clamping device was validated by both the finite element analysis and the cyclic tension and compression tests conducted in the present study, with the material constants used in the Yoshida-Uemori model being determined as well.

Biaxial Unloading and Springback Behavior of Dual-Phase DP590 Steel using Cruciform Specimens

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The unloading behavior of a dual-phase steel (DP590) from a biaxial state of stress was probed using a newly-designed cruciform specimen. The specimen was designed to develop uniform and relatively large plastic strains (over 15% equivalent logarithmic plastic strain) in the gage section, before failure. Nine radial loading paths in the 1st quadrant of the plane stress space were probed. The experiments involved repeated loading and unloading up to failure. At every unloading, the initial response was found to agree with the linear, orthotropically elastic response of the undeformed material. This first linear response was followed by a second one, at a reduced slope. Beyond that, the recorded response was fully non-linear. The same sequence of events was observed during each reloading. The biaxial non-linear strain recovery components ε_x^{nl} and ε_y^{nl} were measured to be on average approximately 11% of the elastic strains ε_x^e and ε_y^e, respectively. This ratio was found to increase with plastic deformation. Subsequently, these biaxial experiments were used to calibrate the Yld2000-2D yield function.

Analysis of Hardening Behavior of Sheet Metals by a New Simple Shear Test Method Taking into Account the Bauschinger Effect

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Sogang University

In this study we establish a process to predict hardening behavior considering the Bauschinger effect for zircaloy-4 sheets. When a metal is compressed after tension in forming, the yield strength decreases. For this reason, the Bauschinger effect should be considered in FE simulations of spring-back. We suggested a suitable specimen size and a method for determining the optimum tightening torque for simple shear tests. Shear stress-strain curves are obtained for five materials. We developed a method to convert the shear load-displacement curve to the effective stress-strain curve with FEA. We simulated the simple shear forward/reverse test using the combined isotropic/kinematic hardening model. We also investigated the change of the load-displacement curve by

varying the hardening coefficients. We determined the hardening coefficients so that they follow the hardening behavior of zircaloy-4 in experiments.

Simulation of Springback and Microstructural analysis of Dual Phase Steels

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With increasing demand for weight reduction and better crashworthiness abilities in car development, advanced high strength Dual Phase (DP) steels have been progressively used when making automotive parts. The higher strength steels exhibit higher springback and lower dimensional accuracy after stamping. This has necessitated the use of simulation of each stamped component prior to production to estimate the parts dimensional accuracy. Understanding the micro-mechanical behaviour of AHSS sheet may provide more accuracy to stamping simulations.This work can be divided basically into two parts: first modelling a standard channel forming process; second modelling the micro-structure of the process. The standard top hat channel forming process, benchmark NUMISHEET93, is used for investigating springback effect of WISCO Dual Phase steels. The second part of this work includes the finite element analysis of microstructures to understand the behaviour of the multi-phase steel at a more fundamental level. The outcomes of this work will help in the dimensional control of steels during manufacturing stage based on the materials microstructure.

Robust Process Design and Springback Compensation of a Decklid Inner

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Springback compensation is one of the key topics in current die face engineering. The accuracy of the springback simulation, the robustness of method planning and springback are considered to be the main factors which influences the effectiveness of springback compensation. In the present paper, the basic principles of springback compensation are presented firstly. These principles consist of an accurate full cycle simulation with final validation setting and the robust process design and optimization are discussed in detail via an industrial example, a decklid inner. Moreover, an effective compensation strategy is put forward based on the analysis of springback and the simulation based springback compensation is introduced in the phase of process design. In the end, the final verification and comparison in tryout and production is given in this paper, which verified that the methodology of robust springback compensation is effective during the die development.

Springback Simulation and Springback Compensation of an Aluminum Outer Panel

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. In the present paper, the main factors which influence the accuracy of springback simulation are discussed, and the optimized parameters, which aim at obtaining an accurate springback simulation, and the full cycle simulation, which aims at the closest boundary condition between simulation and practice, are discussed. As a verification and comparison, an experimental part, Aluminum hood outer, is used and some good results are achieved. Based on the result of the springback verification, the minimum clamping concept for springback compensation is discussed and the compensation strategy is determined according to the springback behavior in different operations. Moreover, the springback in the car position and in the inspection tool is compared and a methodology of springback compensation without gravity is put forward. In the end, the basic principles of the rebuilding of class A surface is discussed and the comparison of geometrical deviation of the final part in tryout is given in this paper.

Springback Compensation Algorithm For Tool Design In Creep Age Forming Of Large Aluminum Alloy Plate

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The creep unified constitutive equations, which was built based on the age forming mechanism of aluminum alloy, was integrated with the commercial finite element analysis software MSC.MARC via the

user defined subroutine, CREEP, and the creep age forming process simulations for 7055 aluminum alloy plate parts were conducted. Then the springback of the workpiece after forming was calculated by ATOS Professional Software. Based on the combination between simulation results and calculation of springback by ATOS for the formed plate, a new weighted springback compensation algorithm for tool surface modification was developed. The compensate effects between the new algorithm and other overall compensation algorithms on the tool surface are compared. The results show that, the maximal forming error of the workpiece was reduced to below 0.2mm after 5 times compensations with the new weighted algorithm, while error rebound phenomenon occurred and the maximal forming error cannot be reduced to 0.3mm even after 6 times compensations with fixed or variable compensation coefficient, which are based on the overall compensation algorithm.

Springback Assessment Based on Level Set Interpolation and Shape Manifolds in Deep Drawing

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In this paper, we introduce an original shape representation approach for automatic springback characterization. It is based on the generation of parameterized Level Set functions. The central idea is the concept of the shape manifold representing the design domain in the reduced-order shape-space. Performing Proper Orthogonal Decomposition on the shapes followed by using the Diffuse Approximation allows us to efficiently reduce the problem dimensionality and to interpolate uniquely between admissible input shapes, while also determining the smallest number of parameters needed to characterize the final formed shape. We apply this methodology to the problem of springback assessment for the deep drawing operation of metal sheets.

The Effectiveness of FE Model for Increasing Accuracy in Stretch Forming Simulation of Aircraft Skin Panels

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In the aerospace industry, stretch forming has been used to form the outer surface parts of aircraft, which are called skin panels. Empirical methods have been used to correct the springback by measuring the formed panels. However, such methods are impractical and cost prohibitive. Therefore, there is a need to develop simulation technologies to predict the springback caused by stretch forming. This paper reports the results of a study on the influences of the modeling conditions and parameters on the accuracy of an FE analysis simulating the stretch forming of aircraft skin panels. The effects of the mesh aspect ratio, convergence criteria, and integration points are investigated, and better simulation conditions and parameters are proposed.

Application of plastic forming simulation to aircraft parts

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It is important to establish the techniques to manufacture the parts for aircraft structures at lower cost in the recent aircraft industry. To reduce the tool cost, large-sizing and die-less manufacturing processes are being applied for aircraft sheet metal parts. Simulation technologies are useful for obtaining a better understanding and solutions of these large and complex plastic forming processes. In this paper, several examples of applying simulation technologies to main plastic forming (hydro pressure forming, stretch forming and roll forming) for aircraft parts are described.
Hydro pressure forming can reduce the number of dies by applying hydraulic pressure with the use of rubber pad as shown in Fig.1. While the merit lies in its ability to eliminate a female die, its often the cases that we require hand straightening caused by unavoidable issues such as the occurrence of wrinkle and incomplete forming. The effectiveness of high pressure and rubber pad hardness is evaluated by simulation for defining the specification of new hydroforming press investment.
Stretch forming can also reduce the number of dies. Stretch forming has complicated jaws at two sides (Fig.2), so it is impossible to simulate by conventional software preprocessor. Software preprocessor developments of this process and a simulation example are described. Sheet stringer parts are made by roll forming (Fig.3). This process uses many rollers; therefore a lot of forming conditions exists. The effect of each forming condition cannot be obtained without simulation because a huge amount of forming tests is needed to investigate. An example to demonstrate the relationship between die clearance and deformation of parts with the use of simulation is reported.

FEM Simulation on Rotating Piercing Process of Double-Layer Clad Sheet with Coulomb Friction

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This study proposes a new piercing technology with rotating punch on the double-layer clad sheet; it carries out an FEM simulation on rotating piercing process using DEFORM-3D commercial software. Frictions among the punch, the blank holder, the dies and the double-layer clad sheet material are assumed as Coulomb friction, but can be different. The surface of the inner diameter, the effective stress, the effective strain, velocity field, damage, burr and the shearing force can be determined form the FEM simulation. In this study, effects of various piercing conditions such as the clearance, the punch nose angle, the frictional factor, the rotating angular velocity, the shearing force, and burr on shearing characteristics are explored effectively to realize the feasibility of FEM model.

Innovative forming methods

Analysis of Local Warm Forming of High Strength Steel using Near Infrared Ray Energy

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The automotive industry has been pressed to satisfy more rigorous fuel efficiency requirements to promote energy conservation, safety features and cost containment. To satisfy this need, high strength steel has been developed and used for many different vehicle parts. The use of high strength steels, however, requires careful analysis and creativity in order to accommodate its relatively high springback behavior. An innovative method, called local warm forming with near infrared ray, has been developed to help promote the use of high strength steels in sheet metal forming. For this method, local regions of the work piece are heated using infrared ray energy, thereby promoting the reduction of springback behavior. In this research, a V-bend test is conducted with DP980. After springback, the bend angles for specimens without local heating are compared to those with local heating. Numerical analysis has been performed using the commercial program, DEFORM-2D. This analysis is carried out with the purpose of understanding how changes to the local stress distribution will affect the springback during the unloading process. The results between experimental and computational approaches are evaluated to assure the accuracy of the simulation. Subsequent numerical simulation studies are performed to explore best practices with respect to thermal boundary conditions, timing, and applicability to the production environment.

Numerical and Experimental Evaluation of Laser Forming Process for the Shape Correction in Ultra High Strength Steels

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In this paper, laser forming characteristics in ultra high strength steel with ultimate strength of 1200MPa are investigated numerically and experimentally. FE simulation is conducted to identify the response related to deformation and characterize the effect of laser power, beam diameter and scanning speed with respect to the bending angle for a square sheet part. The thermo-mechanical behaviors during the straight-line heating process are presented in terms of temperature, stress and strain. An experimental setup including a fiber laser with maximum mean power of 3.0 KW is used in the experiments. From the results in this work, it would be easily adjustment the laser power and the scanning speed by controlling the line energy for a bending operation of CP1180 steel sheets.

Effect of Electric Current on Hardness of Metal for Electrically Assisted Manufacturing

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Electrically assisted manufacturing is one of promising manufacturing processes for the improved ductility and the decreased spring back effect on plastic working. Most researches have focused on the tensile test, compressive test, and flexural test with different electric current density, types of electric currents, and types of materials. Many applications of forg-

ing, rolling and sheet metal forming with electrical assistance have been introduced. However, hardness change by electric current is also important for plastic working of the surface. Surface texturing is widely used for many functional surfaces. In this research, we tried to confirm the effect of electric current on hardness of metals. The hardness was decreased by the electric current as we expected. The electric current density passing through the surface is different according to the position, so the amplitude of electric current, the positions of two electrodes, and the measurement position were studied by experiments. With experimental results, the guidelines for electrically assisted surface texturing were suggested.

Study on Stretching Effect of Multiple Die Forming Technology

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The multiple die forming (MDF) technology is suitable for flexible manufacturing, and it affords several advantages including its applicability to various forming processes such as single-curved surface forming, and double-curved surface forming. In sheet metal forming process, the elastic recovery has become a problem. Therefore, the stretch forming process is applied MDF technology to reduce elastic recovery effect. Numerical simulation is carried out for a saddle-type surface forming using ABAQUS. Every simulation case performs spring-back analysis to find elastic recovery effect after forming simulation. In this simulation, urethane pads are defined based on a hyperelastic material model as a cushion for the smoothness of forming surface. The elastic recovery deformation behavior is also investigated to consider the exact result after the last forming process, and then, the actual experiments are performed to confirm the formability of this forming process. By comparing the simulation and the experimental results, the tendency of the decreased amount of elastic recovery from the application of stretch process is verified. Consequently, it is confirmed that the multiple die stretch forming process has the capability and feasibility of being used to manufacture the curved surfaces of sheet metal.

Forming an Age Hardenable Aluminum Alloy with Intermediate Annealing

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A method to improve formability of aluminum sheet alloys by a two-stage stamping process with intermediate annealing was developed for a non-age hardenable Al-Mg alloy where the annealing heat treatment provided recovery of cold work from the initial stamping and recrystallization of the microstructure to enhance the forming limits of the material. This method was extended to an age hardenable, Al-Mg-Si alloy, which is complicated by the competing metallurgical effects during heat treatment including recovery (softening effect) vs. precipitation (hardening effect). An annealing heat treatment process condition was discovered wherein the stored strain energy from an initial plastic deformation can be sufficiently recovered to enhance formability in a second deformation; however, there is a deleterious effect on subsequent precipitation hardening. The improvement in formability was quantified with uniaxial tensile tests as well as with the forming limit diagram. Since strain-based forming limit curves (FLC) are sensitive to pre-strain history, both stress-based FLCs and polar-effective-plastic-strain (PEPS) FLCs, which are path-independent, were used to evaluate the forming limits after preform annealing. A technique was developed to calculate the stress-based FLC in which a residual-effective-plastic-strain (REPS) was determined by overlapping the hardening curve of the pre-strained and annealed material with that of the simply-annealed-material. After converting the strain-based FLCs using the constant REPS method, it was found that the stress-based FLCs and the PEPS FLCs of the post-annealed materials were quite similar and both tools are applicable for evaluating the forming limits of Al-Mg-Si alloys for a two-step stamping process with intermediate annealing.

Numerical Analysis of Temperature Distribution and Material Deformation of Thin Foils in Micro Metal Forming Assisted by Resistance Heating

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By using resistance heating assisted micro metal forming process, not only the improvement of the material formability, but also the less consumption of energy can be expected. In this study, finite element (FE) models for the numerical analysis of micro deep drawing process assisted by resistance heating were developed. Coupled thermal-electrical procedure and dynamic explicit procedure were conducted for the analysis of temperature distribution and material deformation, respectively. From the analysis, it is found that the temperature distribution of the blank is caused by the difference in electrical current density, and the fracture is easier to happen at the

area with higher stress of the part. The results obtained from the simulation showed the same tendency with the experiments, which confirmed the feasibility of the developed FE models.

Numerical Simulation of Temperature Field, Microstructure Evolution and Mechanical Properties of HSS during Hot Stamping

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The hot stamping of boron steels is widely used to produce ultra high strength automobile components without any spring back. The ultra high strength of final products is attributed to the fully martensitic microstructure that is obtained through the simultaneous forming and quenching of the hot blanks after austenization. In the present study, a mathematical model incorporating both heat transfer and the transformation of austenite is presented. A FORTRAN program based on finite element technique has been developed which permits the temperature distribution and microstructure evolution of high strength steel during hot stamping process. Two empirical diffusion-dependent transformation models under isothermal conditions were employed respectively, and the prediction capability on mechanical properties of the models were compared with the hot stamping experiment of an automobile B-pillar part.

The Tensile Electroplasticity of Magnesium AZ31 Alloy with a Single Pulse of Electric Current

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The tensile electroplasticity of magnesium AZ31 alloy with a single pulse of electric current is experimentally investigated. A single pulse of electric current with a relatively short duration is applied to the specimen while the specimen is being deformed in plastic region under quasi-static tensile loads. Experimental parameters are selected so that the maximum temperature at the application of the electric current is significantly lower than the general warm forming temperature of the magnesium alloy. A nearly instant decrease of the flow stress (stress-drop) occurs at the application of the electric current. Once the electric current is removed, the flow stress shows a strain hardening until the failure of the specimen. The result of the parameter study shows that the stress-drop and the following hardening behavior strongly depend on the magnitude of the electric energy density (electric energy per unit area).

Formability Improvement in Multi-Stage Deep Drawing of AA5182 with the Aid of High Frequency Induction Heating

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In the present study, a warm forming of an aluminum alloy sheet is numerically investigated for multi-stage deep drawing. For the warm forming process, high frequency induction heating is applied in order to rapidly heat the surface of the drawing punch so as to improve formability of the aluminum alloy. Owing to localized heating capability in a non-contact manner of the induction heating, a drawing punch out of a series of a progressive die can be easily and efficiently heated without a significant increase in cycle time. Coupled numerical analyses for the induction heating and the sheet metal forming processes are then performed to investigate the effect of the induction heating on the formability improvement in the multi-stage deep drawing process of aluminum alloys.

Investigation of electric current-induced annealing on 5052-H32 aluminum alloys during uniaxial tension

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Electrically-Assisted Forming (EAF) is an emerging technique to improve formability of metals by applying electric current during deformation. In recent, some researchers have studied the effect of electric current on mechanical behavior. General observations of electrically assisted deformation include reduced plastic flow stress and increased ductility. However, the governing mechanism of electrically assisted deformation is still controversial.

In this research, electric current-induced annealing on 5052-H32 aluminum alloys during uniaxial tension was investigated. Pulsed electric current was applied to a specimen during uniaxial tensile test. The temperature of specimen was measured by both ther-

mal imaging camera and thermocouple. In the tensile test under the pulsed electric current, the flow stress decreased but the elongation increased drastically compared with the normal tensile test (without pulsed electric current). From electron backscattered diffraction (EBSD) measurement, recrystallization was observed after severe necking. Based on full width at half maximum (FWHM) analysis using X-ray diffraction (XRD) and transmission electron microscopy (TEM), it was observed that dislocation was removed by applying pulsed electric current. The effect of joule heating was insignificant to occur thermal recovery of this material from the result of measured temperature. Finally, this suggests that electric current-induced annealing was generated by passing pulsed electric current under the external stress field.

Electroplastic behaviors of advanced high strength steels under a single pulse of an electric energy density

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The effect of a single pulse of an electric energy density at different plastic strains on the strain hardening behavior of advanced high strength steels (AHSS) is experimentally investigated. During a typical quasi-static tensile test, a single pulse of an electric energy density is applied to a specimen for a short duration (less than 1 second) at different plastic strains. The experimental result shows that the magnitude of the nearly instant stress-drop at the pulse of an electric energy density and the following strain hardening behavior depend on both of the imposed plastic strain prior to the pulse of an electric energy density and the magnitude of the applied electric energy density. The result of the present study suggests that the electroplastic behavior of the selected AHSS is a result of competition between the existing strain hardening and the electrically induced annealing.

Analysis of Varying Properties of Semi-finished Products in Sheet-bulk Metal Forming of Functional Components

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In the automotive industry is an increasing demand on closely-tolerated complex functional components with variants due to ecological and economic challenges. As current forming processes are often limited, a promising approach to fulfill these requirements is the combination of traditional sheet and bulk metal forming processes. In investigations on a combination of deep drawing and upsetting, this topic is researched fundamentally. In this forming sequence a base body is formed by deep drawing, whereas gear teeth are upset at the pre-formed cup. The paper discusses the influence of the blank thickness on forming forces and component properties. Furthermore, the approach of local adapted tribological conditions to reduce the press forces is investigated.

Friction Stir Welding of Stainless Steel Thin Sheets in Lap Configuration

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New research trends for Friction Stir Welding include the use of highly resistant materials as steels and titanium alloys. In the paper a continuum based FEM model for Friction Stir Welding of lap joint made out of thin stainless steel sheets is proposed, that is 3D Lagrangian implicit, coupled, rigid-viscoplastic. The model, whose potential has been analyzed though temperature distribution comparisons, is able to predict temperature, strain and strain rate distributions, with varying process variables. In this way the FEM model can be applied for effective process and tool design.

Theoretical and Experimental Study of The Rule for Heat Transfer Coefficient in Hot Stamping of High Strength Steels

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Heat transfer is a crucial aspect for hot stamping process, the fully austenitized boron steel blank with temperature about 900°C is transferred to the tool, then formed rapidly and quenched in the cooled tool. The desired fully martensitic transformation will happen only if the cooling rate exceeds a critical value approximately 27 K/s. During such process, the heat transfer coefficient (abbreviated as HTC) between the tool and blank plays a decisive role for the variation of the blank temperature. In this work, a theoretical formula based on the joint-roughness model is presented

to describe the law of HTC, which relies on the roughness, hardness, and other material parameters of the tool and blank. Moreover, a non-contact temperature measuring system based on the infrared thermal camera is built to catch the temperature change course, and then the HTC value is derived through the inverse analysis. Based on the theoretical and experimental results, the change rule of HTC especially its dependence on the process pressure will be discussed in detail.

An Investigation of Electroplastic Effect on Formability of AZ31B Sheet Metal

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The electroplastic deformation behavior of AZ31B magnesium alloy sheet was investigated by isothermal uni-axial tensile tests at different temperatures with or without electric pulse passing through the testing samples. The electroplastic effect on flow stress was confirmed. A flow stress model of AZ31B sheet taking into account the influence of electroplastic effect was proposed, and was verified by comparison with the testing results. The mechanism of flow stress decrease with elevated temperature and electric pulse was analyzed by comparing the samples microstructure, it was concluded that electric pulse induced dynamic recrystallization plays an important role in flow stress decrease and formability improvement.

Determination of Warm Forming Limit Diagram for ZEK100

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The formability of a rare-earth alloyed magnesium sheet, ZEK100, is studied through determination of its Forming Limit Diagram (FLD). Limiting dome height experiments were performed at elevated temperatures with in situ digital image correlation (DIC) measurement of strain. FLDs were determined at three different temperatures (50°C, 150°C and 250°C) along the sheet rolling direction (RD) and transverse direction (TD). The experiments showed that temperature has a significant effect on formability; an increase in temperature from 50°C to 250°C resulted in a formability gain of more than 200% .

Product & Process Design and Optimization

Robust Die Layout Design for Side Outer Panel Using Stochastic Analysis Method

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It is an ordinary process to simulate sheet metal forming in automotive industry. According to a long term experience, reduction of cost and lead time is obvious due to highly accurate results from simulations.
Nevertheless, die engineers are facing unexpected troubles in the field. Usually, this critical troubles are caused by large variation of production condition, such as deviation of material property, fluctuation of facility condition, uncontrollable noises, etc. that are hardly considered in common simulation software.
In this paper, robust die layout for side outer will be designed with Autoform sigma adopting stochastic analysis method. The optimal die condition will be established for unique design.
Through well-organized simulation plot by the software, production parameters could be adjusted to be robust against variation and noise. Every design parameters will be applied to actual die manufacturing process.

Cooling System Optimization Analysis for Hot forming Processes

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Hot forming technology was developed to produce automotive panels having ultra-high tensile stress over 1500MPa. The elevated temperature corresponds with decreased flow stress and increased ductility. Furthermore, hot forming products have almost zero springback amounts. This advanced forming technology accelerates the needs for numerical simulations coupling with thermal-mechanical formulations. In the present study, 3-dimensional finite element analyses for hot forming processes are conducted using JSTAMP/NV and LS-DYNA considering cooling system. Special attention is paid to the optimization of cooling system using thermo-mechanical finite element analysis through the influence of various cooling

parameters. The presented work shows an adequate cooling system functions and microstructural phase transformation material model together with a proper set of numerical parameters can give both efficient and accurate design insight in hot forming manufacturing process. JSTAMP/NV and LS-DYNA can become a robust combination set for complex hot forming analysis which needs thermo-mechanical and microstructural material modeling and various process modeling. The use of the new JSTAMP/NV function for multishot manufacturing process is shown good capabilities in cooling system evaluation. And the use of the advanced LS-DYNA microstructural phase transformation model is shown good evaluation results in martensite amount and Vickers hardness after quenching.

Statistical Investigation of a Blank Holder Force Distribution System for a Multi-Step Deep Drawing Process

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This paper investigates process control possibilities obtained from a new tool concept for adaptive blank holder force (BHF) distribution. The investigation concerns the concept's application to a multi-step deep drawing process exemplified by the NUMISHEET2014 benchmark 2: Springback of draw-redraw pan. An actuator system, where several cavities are embedded into the blank holder plate is used. By independently controlling the pressure of hydraulic fluid in these cavities, a controlled deflection of the blank holder plate surface can be achieved whereby the distribution of the BHF can be controlled. Using design of experiments, a full 3-level factorial experiments is conducted with respect to the cavity pressures, and the effects and interactions are evaluated.

Stretching the Limits of Forming Processes by Robust Optimization: A Demonstrator

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Robust design of forming processes using numerical simulations is gaining attention throughout the industry. In this work, it is demonstrated how robust optimization can assist in further stretching the limits of metal forming processes. A deterministic and a robust optimization study are performed, considering a stretch-drawing process of a hemispherical cup product. For the robust optimization study, both the effect of material and process scatter are taken into account. For quantifying the material scatter, samples of 41 coils of a drawing quality forming steel have been collected. The stochastic material behavior is obtained by a hybrid approach, combining mechanical testing and texture analysis, and efficiently implemented in a metamodel based optimization strategy. The deterministic and robust optimization results are subsequently presented and compared, demonstrating an increased process robustness and decreased number of product rejects by application of the robust optimization approach.

Increase in Mechanical Property of Steel and Duplex Stainless Steel Sheet by Nitrate Nitriding

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Duplex stainless steel (DSS) sheet shows both good corrosion resistance and mechanical properties. But DSS shows low hardness, low wear resistance. If DSS was increased the hardness and wear resistance without decreasing the corrosion resistance, the field of application of DSS will be spread significantly.
Increase of hardness and wear resistance of the stainless steel sheet were achieved by plasma nitriding, gas nitriding and liquid nitriding, etc. Nitrate salt bath treatment, one of the liquid nitriding processes, has the advantages of easy operation, low cost, high energy efficiency, and stability. Nitrate nitriding is one of the good strengthening processes for iron, steel, stainless steel and theirs alloys with the diffusion of interstitial nitrogen atoms.
In this study, Potassium nitrate salts were used to increase the mechanical property of steel and stainless steel sheets after sheet forming.
After nitrate nitriding of steel and stainless steel sheets with potassium and sodium nitrate salt, hardness and tensile test were conducted.
Nitrided steel and stainless steel sheet with nitrate salt showed high tensile strength and high hardness. Especially, Nitrate nitrided steel sheet was shown high tensile strength over 1000 MPa and high hardness.

New software and hardware concepts for an integral in-line quality control in sheet metal forming

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The typical sheet metal forming processes show variations in the forming behavior under scattering process contitions. These can be variations in the material properties such as the hardening behavior, as well as alterations in the process parameters like changes in temperature or the frictional condition. Unfortunately these are also those parameters which are nowadays not directly controlled during the process. The consequence is a decrease of the n-sigma level in many cases to level 4 or even level 3. The presented contribution demonstrates a new concept, which allows the detection and visualization of those parameters and which is directly coupled to an automatic adaptation of the controllable process parameters. A second goal of the new concept is to setup a transparent and unique database of material, process and quality parameters along the production chain.

Application Technologies for Effective Utilization of Advanced High Strength Steel Sheets

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Recently, application of high strength steel sheets for automobiles has increased in order to meet a demand of light weighting of automobiles to reduce a carbon footprint while satisfying collision safety. The formability of steel sheets generally decreases with the increase in strength. Fracture and wrinkles tend to occur easily during forming. The springback phenomenon is also one of the issues which we should cope with, because it makes it difficult to obtain the desired shape after forming. Advanced high strength steel sheets with high formability have been developed in order to overcome these issues, and at the same time application technologies have been developed for their effective utilization. These sheets are normally used for cold forming. As a different type of forming, hot forming technique has been developed in order to produce parts with ultra high strength. In this report, technologies developed at NSSMC in this field will be introduced.

Progress in Press Forming Computer Aided Analysis for High Strength Steel Sheet Applications

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The development of press-forming analysis technologies is important to expand the application of high strength steel sheets to automotive body structures. In general, there are various problems in the forming process of high strength steel sheets. In this study the improvements in the prediction accuracy of stretch-flange-fracture and springback were especially focused. In terms of the prediction accuracy of stretch-flange-fracture, a new stretch-flange-fracture prediction technology was developed based on a maximum principal strain gradient. It enables the accurate prediction of stretch- flange-fracture in press-forming of practical parts. On the other hand, springback prediction technologies were developed to solve springback problems. It is very important to clarify the root cause of springback in order to control. Therefore, a new method of springback factor analysis was developed, which can extract the areas and residual stresses which have major impacts on springback at press-forming.

Direct Drive Digital Servo Press with High Parallel Control

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Direct drive digital servo press has been developed as the university-industry joint research and development since 1998. On the basis of this result, 4-axes direct drive digital servo press has been developed and in the market on April of 2002. This servo press is composed of 1 slide supported by 4 ball screws and each axis has linearscale measuring the position of each axis with high accuracy less than μ m order level. Each axis is controlled independently by servo motor and feedback system. This system can keep high level parallelism and high accuracy even with high eccentric load. Furthermore the 'full stroke full power' is obtained by using ball screws. Using these features, new various types of press forming and stamping have been obtained by development and production. The new stamping and forming methods are introduced and 'manufacturing' need strategy of press forming with high added value and also the future direction of press forming are also introduced.

Enhancing Deep Drawability through Strain Dispersion Using Stress Relaxation

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When the further straining of metal is temporarily stopped during tensile testing, a stress relaxation phenomenon is known to occur whereby the stress diminishes with the passage of time. This phenomenon has been explained as the change of elastic strain into plastic strain. This report proposes new stamping process using the stress relaxation phenomenon for the purpose of strain dispersion. A new step motion which pauses the die during forming was devised, and succeeded in improving the deep-draw forming limit. Verification was conducted by tensile testing in addition to actual stamping tests. As a result, it was concluded that the mechanism that improves the deep-draw forming limit arises from the dispersion of strain by the use of step motion.

Computer Aided Process Planning and Die Design in Simulation Environment in Sheet Metal Forming

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During the recent 10-15 years, Computer Aided Process Planning and Die Design evolved as one of the most important engineering tools in sheet metal forming, particularly in the automotive industry. This emerging role is strongly emphasized by the rapid development of Finite Element Modeling, as well. The purpose of this paper is to give a general overview about the recent achievements in this very important field of sheet metal forming and to introduce some special results in this development activity. Therefore, in this paper, an integrated process simulation and die design system developed at the University of Miskolc, Department of Mechanical Engineering will be analyzed. The proposed integrated solutions have great practical importance to improve the global competitiveness of sheet metal forming in the very important segment of industry. The concept described in this paper may have specific value both for process planning and die design engineers.

Optimal Design at Inner Core of the Shaped Pyramidal Truss Structure

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Sandwich material is a type of composite material with lightweight, high strength, good dynamic properties and high bending stiffness-to-weight ratio. This can be found well such structures in the nature (for example, internal structure of bones, plants, etc.). New trend which prefers eco-friendly products and energy efficiency is emerging in industries recently. Demand for materials with high strength and light weight is also increasing. In line with these trends, researches about manufacturing methods of sandwich material have been actively conducted. In this study, a sandwich structure named as Shaped Pyramidal Truss Structure is proposed to improve mechanical strength and to apply a manufacturing process suitable for massive production. The new sandwich structure was designed to enhance compressive strength by changing the cross-sectional shape at the central portion of the core. As the next step, optimization of the shape was required. Optimization technique used here was the SZGA(Successive Zooming Genetic Algorithm), which is one of GA(Genetic Algorithm) methods gradually reducing the area of design variable. The objective function was defined as moment of inertia of the cross-sectional shape of the strut. The control points of cubic Bezier curve, which was assumed to be the shape of the cross section, were used as design variables. By using FEM simulation, it was found that the structure exhibited superior mechanical properties compared to the simple design of the prior art.

Design Optimization of the Tool Structure for Stamping an Automotive Part with the High Strength Steel

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Optimum shape design of the tool structure is carried out in order to decrease the deformation and the stress from the large amount of stamping load with a simultaneous effect of weight reduction. Topology optimization is carried out to design the shape of the rib structure and Taguchi method is utilized to optimize the core shape. As a result of optimization, the weight of the rib and the core structures is reduced to 3.1% and the deformation and the stress of the rib and the core structures are decreased to 10.6% and 3.7% comparing to the initial design, respectively.

Design Study of the Geometry of the Blanking Tool to Predict the Burr Formation of Zircaloy-4 Sheet

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In this work, we investigated factors that influence burr formation for zircaloy-4 sheet used for spacer grids of nuclear fuel roads. Factors we considered are geometric factors of punch. We changed clearance and velocity in order to consider the failure parameters, and we changed shearing angle and corner radius of L-shaped punch in order to consider geometric factors of punch. First, we carried out blanking test with failure parameter of GTN model using L-shaped punch. The tendency of failure parameters and geometric factors that affect burr formation by analyzing sheared edges is investigated. Consequently, geometric factors influencing on the burr formation is also high as failure parameters. Then, the sheared edges and burr formation with failure parameters and geometric factors is investigated using FE analysis model. As a result of analyzing sheared edges with the variables, we checked geometric factors more affect burr formation than failure parameters. To check the reliability of the FE model, the blanking force and the sheared edges obtained from experiments are compared with the computations considering heat transfer.

Geometric Parameter Inverse Model for Drawbeads Based on Grey Relational Analysis and GA-BP

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In sheet metal forming, the wrinkling and fracture can be eliminated via an appropriate drawbead design. Proper drawbead design method to reduce time and cost is highly required. In the paper, the geometric parameters influencing semi-circular drawbead force are firstly analyzed making use of grey relational analysis, and the main parameters are obtained. The main parameters are sampled making use of Latin hypercube. The box forming is simulated with DYNAFORM, and the sample data are obtained. In the back propagation (BP) neural network, the thinning, thickening and major strains are selected as input parameters, and drawbead geometric parameters are selected as output objective. The inverse model of drawbead geometric parameters is established. The BP neural network weights are optimized with genetic algorithm (GA). Compared with the predictive values by BP, the parameters values by GA-BP are more accurate. Based on the GA-BP, the nonlinear relationship of the forming quality and drawbead geometric parameters is obtained making use of the optimized BP weights. Finally the optimum geometric parameters of drawbeads are obtained based on GA. The numerical simulations of box forming are compared before optimization and after optimization. The results show the optimized drawbeads can greatly improve the formability of sheet metal forming.

The Inverse Problems of Wing Panel Manufacture Processes

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It is shown that inverse problems of steady-state creep bending of plates in both the geometrically linear and nonlinear formulations can be represented in a variational formulation. Steady-state values of the obtained functionals corresponding to the solutions of the problems of inelastic deformation and springback are determined by applying a finite element procedure to the functionals. Optimal laws of creep deformation are formulated using the criterion of minimizing damage in the functionals of the inverse problems. The formulated problems are reduced to the problems solved by the finite element method using MSC.Marc software. Currently, forming of light metals poses tremendous challenges due to their low ductility at room temperature and their unusual deformation characteristics at hot-cold work: strong asymmetry between tensile and compressive behavior, and a very pronounced anisotropy. We used the constitutive models of steady-state creep of initially transverse isotropy structural materials the kind of the stress state has influence. The paper gives basics of the developed computer-aided system of design, modeling, and electronic simulation targeting the processes of manufacture of wing integral panels . The modeling results can be used to calculate the die tooling, determine the panel processibility, and control panel rejection in the course of forming.

Forming Simulation of Woven Composite Fibers and Its Influence on Structural Performance

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In recent years, the interest in composite material as a replacement for metals has been growing. The automotive industry, in its constant quest for weight reduction, is now seriously considering composite materials as a substitute for sheet metal components to meet future fuel consumption standards. How-

ever, composite forming processes are expensive and difficult to control because of its complex composition with fiber and matrix layers or plies and its dependency on many parameters, such as non-linearity of tensile stiffness, effect of shear rate, temperature and friction. Hence, numerical simulation could be a viable approach to predict material behavior during composite forming. The objective of this study is to highlight capabilities of RADIOSS®, a non-linear finite element analysis based structural solver commonly used for stamping and crash analyses, to simulate forming simulation of composite plies made from woven fibers. For validation the well-known double dome model is used with material data published in NUMISHEET'05 proceedings. It is modeled as a woven fabric with an elastic anisotropic fabric material law available in RADIOSS. This material law is able to consider properties along the two directions of anisotropy, warp and weft. The compared result is the shear angle after stamping that is, the variation of angle between warp and weft fibers, at several prescribed points on the ply. The variation of this angle has a strong impact on material characteristics which severely deteriorates when a critical value is reached. Hence, a study on crash simulations is performed, after mapping fibers angles from stamping simulation.

Blank Outline Estimation Approach of Aircraft Part for Rubber Bladder Forming

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Rubber bladder forming is one of sheet metal forming methods for aircraft sheet metal parts. The estimation approach of initial blank outline is a difficult task during the forming die design stage, especially the rubber bladder forming manufacturing. In accordance with the technologic characteristics of rubber bladder forming, a fast and accurate estimation approach is proposed for the initial blank outline of rubber bladder formed part based on the one-step inverse forming finite element method. The friction influential effect between the rubber bladder and sheet metal can be considered by the equivalent external force. Firstly, the designed aircraft sheet metal part is treated as the final configuration of one-step inverse analysis; then a quick reverse simulation is carried out to obtain the initial blank mesh by the one-step inverse finite element method. Finally, the blank outline from the above initial blank mesh is applied to real rubber bladder forming manufacture. The experiment and comparison results demonstrate that the proposed approach can accurate estimate the initial blank outline of aircraft sheet metal part for rubber bladder forming process.

Effect of Process Parameters on Deep Drawing of Ti-6Al-4V Alloy Using Finite Element analysis

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Deep drawing process depends on the large number of process parameters and their interdependence. Optimization of process parameters in deep drawing is a vital task to reduce manufacturing cost and understand their influence on the deformation behaviour of the sheet metal. In this paper, significance of important process parameters namely, punch speed, blank holder pressure (BHP) and temperature on the deep-drawing characteristics of a Ti-6Al-4V alloy are investigated. Taguchi technique was employed to identify the influence of these parameters on thickness distribution. The finite element model of deep drawing process has been built up and analyzed using Dynaform version 5.6.1 with LS-Dyna version 971 as solver. Based on the predicted thickness distribution of the deep drawn circular cup and analysis of variance (ANOVA) results, it is concluded that punch speed has the greatest influence on the deep drawing of Ti-6Al-4V alloy blank sheet. Temperature and BHP effect are negligible in deep drawing of Ti-6Al-4V alloy at low warm temperatures (less than 450° C) but it may contribute to a significant extent at higher temperature. Also thickness distribution is predicted using artificial neural network (ANN). It is observed that the predicted thickness distribution is in good agreement with the experimental data.

Advancements in Tailored Hot Stamping Simulations: Cooling Channel and Distortion Analyses

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Hot stamped components have been widely used in the automotive industry in the last decade where ultra high strength is required. These parts, however, may not provide sufficient toughness to absorb crash energy. Therefore, these components are tailored by controlling the microstructure at various lo-

cations. Simulation of tailored hot stamped components requires more detailed analysis of microstructural changes. Furthermore, since the part is not uniformly quenched, severe distortion can be observed. CPF, together with ESI have developed a number of techniques to predict the final properties of a tailored part. This paper discusses the recent improvements in modeling distortion and die design with cooling channels.

Instabilities and Surface defects

Prediction of Biaxial Forming Limits of Textured BCC Polycrystals

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Phenomenological material models have been mainly used for predicting forming limit curves for the failure analysis of sheet metal forming. In the phenomenological approaches, however, the effect of texture evolution is ignored. In this work, a rate-dependent crystal plasticity constitutive model is implemented in the Marciniak-Kuczynski framework to predict the local instabilities considering texture evolution. Implicit numerical algorithm utilizing the Simplex algorithm is developed to integrate the equilibrium equations without the derivatives of the constitutive equations. The effects of the single crystal behavior on the biaxial forming limits of BCC polycrystals are analyzed.

Numerical Investigation on the Effect of Skin Passing and Roller Leveling on the Bending Behaviour of Mild Steel

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The common grades of steel used in roll forming are: hot rolled, high strength low alloy and recovery annealed cold rolled sheet. These steels are prone to ageing and are often skin passed and/or roller leveled to eliminate ageing as this can lead to problems in forming. Shape defects such as bow, twist and camber can be increased due to a change of the elastic-plastic transition point of the material. In consideration of this effect the knowledge of the material properties in the elastic plastic transition range is necessary if the processes are to be modelled accurately. Previous studies have indicated that residual stresses are not well identified in the standard tensile test, but were shown clearly in a bending test. The elastic plastic transition in bending and the moment curvature characteristic were changed significantly by a light cold rolling reduction.

In this work the FEA package Abaqus is used to investigate the effect of residual stresses introduced through skin passing and/or roller leveling on the bending/yielding behaviour of mild steel. Therefore, a skin passing/ roller leveling process is simulated, followed by a subsequent bending test. Residual stress free sheet is compared in bending to just skin passed, roller leveled and a combined skin passed and roller leveled strip. Skin passing significantly reduces the bending yield stress due to residual stresses. This has a softening effect on subsequent bending operations. A roller level process prior to roll forming can restore the bending yield stress by reducing the residual stress across the thickness. This has implications for forming aged material.

An Integrated Approach for Prediction of Surface Deflection by using Stoning Simulation and Curvature Analysis

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Recently, numerical predictions for surface deflection by finite element analysis have been carried out actively by various methods such as curvature analysis, stoning simulation and highlighting. Measures of surface deflection based on curvature analysis had been proposed by several researchers and showed good correspondences with experimental results. The maximum variation of curvature difference between the panel and the tool was also proposed as a measure for surface deflection and successfully predict the surface deflection. However, the curvature is strongly dependent on the calculation method and the quality of data points. On the other hand, a measure based on stoning simulation has not been extensively studied yet due to the insufficient information from stoning simulation. Regardless of the lack of the reliable measure, stoning simulation has been widely accepted in the field owing to robustness, the easiness of use and understanding. In this study, we proposed a new integrated approach by using stoning simulation and curvature analysis. Firstly, for the detection of surface deflection, stoning simulation was utilized. Then, for the quantification of surface deflection, curvature analysis was applied. As a verification example, a

shallow rectangular drawing with inner rectangular embossing was considered. The measure was compared between experiment and simulation. It was shown that the proposed approach can be utilized for the reliable detection of the surface deflection and the accurate quantification of surface deflection.

Influence of Prestrain on the Occurrence of PLC Effect in an Al-Mg Alloy

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In the present work, the jerky flow in an Al-Mg alloy during simple shear tests for various strain paths and temperatures is studied. Direct observations of the sample surface using digital image correlation is used to investigate the type and the dynamics of Portevin-Le Chtelier (PLC) bands as a function of shear strain and temperature. The influence of strain path changes on the occurrence of PLC effect is evidenced through cyclic shear tests, composed of a loading up to several values of the shear strain followed by a reloading in the opposite direction. It is shown that the occurrence of PLC effect modifies the transient behavior after strain path changes.

Size Effects on Free Surface Roughening and Necking Behavior of Metal Thin Sheets Using Inhomogeneous Finite

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The effect of thickness on surface roughening and onset of necking behavior was investigated experimentally. In addition, the effect of surface roughening and material properties on onset of necking behavior was discussed by using inhomogeneous FE simulation. Tensile test is conducted for pure aluminum, pure aluminum and pure titanium thin sheet with thickness of 0.05 and 0.5mm to observe the free surface roughening and necking behavior. Proposed inhomogeneous FE model can simulate the free surface roughening and necking behavior. The slope of ratio of surface roughness to thickness Rz/t is completely different between thickness of 0.5mm and 0.05. Therefore, the size effect on the ratio of surface roughness to thickness Rz/t can be observed. The magnitude relation between the increase in ratio of surface roughness to thickness and strain hardening exponent n value would affect the onset of localized necking behavior.

Surface Evaluation Method and Stamping Simulation for Surface Deflection of Automotive Outer Panels

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In designing dies of automotive outer panels, the most difficult process is to modify surface deflection. To fabricate high-quality outer panels without modifying dies, it is important to develop an evaluation method and a numerical analysis method for surface deflection of outer panels. In this study, we have developed a new evaluation method that uses the maximum value of curvature calculated using reflecting curves in the surface. This new evaluation method made the examiner's evaluation to conform with the digital evaluation. The evaluation results with the new method shows better agreement with the sensory value than those with the conventional methods. We have proposed the new analysis method to predict surface deflection correctly. By the proposed simulation method, plastic deformation is calculated in consideration of stress in thickness direction, and restriking conditions have been examined. We have applied our methods to the fabrication of automotive outer panels, and verified that these are useful and practical.

Twisting Of Sheet Metals

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Twisting of metallic sheets is one particular mode of springback that occurs after drawing of elongated parts, i.e. with one dimension much larger than the two others. In this study, a dedicated device for drawing of elongated part with a U-shaped section has been designed on purpose, in order to obtain reproducible data. Very thin metallic sheet, of thickness 0.15 mm, has been used, so that the maximum length of the part is 100 mm. Two different orientations of the part with respect to the tools have been chosen: either aligned with the tools, or purposefully misaligned by 2°. Several samples were drawn for each configuration, leading to the conclusion that almost no twisting occurs in the first case whereas a significant one can be measured for the second one.

In a second step, 2D and 3D numerical simulations within the implicit framework for drawing and springback were carried out. A mixed hardening law associated to von Mises yield criterion represents accurately the mechanical behavior of the material. This paper highlights a comparison of numerical predictions with

experiments, e.g. the final shape of the part and the twisting parameter.

Plastic Instability in Complex Strain Paths predicted by the Homogeneous Yield Function-based Anisotropic Hardening Model

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The present paper aims at predicting plastic instabilities under complex loading histories using an advanced sheet metal forming limit model. The onset of localized necking is computed using the Marciniak–Kuczinsky (MK) analysis. The homogeneous yield function based anisotropic hardening model (HAH) of Barlat et al. (2011) coupled with Yld2000-2D (Barlat et al., 2003) anisotropic yield function describe the asymmetric yielding. The Swift strain-hardening power law is considered to approximate the material hardening behavior. Simulations are carried out for linear and several strain path changes. The validity of the model is assessed by comparing the predicted and experimental forming limits by using as reference material a low carbon steel sheet. A remarkable accuracy of the developed software to predict the forming limits under linear and non-linear strain path is achieved. The effect of the microstructure history deviator, defining the past behavior experienced by material, on the formability evolution under strain path changes is analyzed. A comparative study between the HAH model and an isotropic hardening on the prediction of the forming limits is also performed.

Effect of Shear Cutting Induced Strain on Edge Crack Sensitivity of Workpiece

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Failure prediction in sheet metal forming simulation still shows some severe gaps especially in context to high strength steels and other light weight material manufacturing. Prediction of edge cracks of sheet metals due to forming operations resulting from shear cutting of the sheets is one example for such limitations in failure detection. Literature shows a direct link between shear cutting process and reduced formability due to edge cracking. The aim of this study was to find a correlation between strain induced along workpiece outline due to cutting process and corresponding development of edge crack sensitivity of component edge. A strain measurement system was used to acquire the strain in sheet thickness direction on the one hand and the maximum strain value emerging before necking by conducting newly devel-oped Diabolo Test on the other hand. The Diabolo Test is a novel test setup for gauging the edge crack sensitivity along trimmed parts edges and was developed as an alternative to the Hole Expanding test according to ISO 16630. To quantify effects of changings in strain distribution in sheet thickness direction on edge crack sensitivity strain measurements with different sheet thicknesses and cutting clearances were conducted. By generating a deeper comprehension of mechanisms of edge cracking, the obtained data could be used to get one step further in modeling edge crack sensitivity in sheet metal simulation.

Mechanical Stability Analysis on Spherical Sandwich Sheet at Low Temperature Loading Conditions

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The spherical sandwich sheet (S-S-S) is generally used in the aerospace industry, for example, the airplane, the rocket's fairing, the spacecraft and the satellite for the purpose of heat-insulation, weight-saving and dimension-reducing. The stability of the S-S-S is of general concern because of its particularly thin but large size. For some S-S-S used in fuel tank storing liquid oxygen of the rocket, it must be facing low temperature down to about -183° C. Low temperature condition affects the stability of the S-S-S and then causes buckling of the structure. In this paper, a finite element (FE) model is established for evaluating the stability of the S-S-S via the sequential coupling mode. The material mechanical properties related to temperature are concerned in the FE model. The buckling modes and critical buckling loading are predicted accurately, since the FE model includes heat transfer simulating, thermal stress computing, buckling and post buckling process. It is found that the thermal stress generated from the low temperature loading reduces the critical buckling loading and changes the buckling modes of the S-S-S.

Roll forming and bending

the product with identical geometry.

Roll Forming of Eco-friendly Stud

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In order to manufacture an eco-friendly stud, the sheared pattern is designed by the Taguchi method and expanded by the side rolls. The seven geometrical shape of sheared pattern are considered in the structural and thermal analyses to select the best functional one in terms of the durability and fire resistance of dry wall. For optimizing the size of the sheared pattern chosen, the L_9 orthogonal array and smaller-the-better characteristics of the Taguchi method are used. As the roll gap causes forming defects when the upper-and-lower roll type is adopted for expanding the sheared pattern, the side roll type is introduced. The stress and strain distributions obtained by the FEM simulation of roll-forming processes are utilized for the design of expanding process. The expanding process by side rolls shortens the length of expanding process and minimizes the cost of dies. Furthermore, the stud manufactured by expanding the sheared pattern of the web is an eco-friend because of the scrapless roll-forming process. In addition, compared to the conventionally roll-formed stud, the material cost is lessened about 13.6% and the weight is lightened about 15.5% .

The Effect of Tooling Design Parameters on Web-warping in the Flexible Roll Forming of UHSS

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To reduce weight and improve passenger safety there is an increased need in the automotive industry to use Ultra High Strength Steels (UHSS) for structural and crash components. However, the application of UHSS is restricted by their limited formability and the difficulty of forming them in conventional processes. An alternative method of manufacturing structural auto body parts from UHSS is the flexible roll forming process which can accommodate materials with high strength and limited ductility in the production of complex and weight-optimised components. However, one major concern in the flexible roll forming is web-warping, which is the height deviation of the profile web area. This paper investigates, using a numerical model, the effect on web-warping with respect to various forming methods. The results demonstrate that different forming methods lead to different amount of web-warping in terms of forming the product with identical geometry.

The Effect of Forming Strategy on the Longitudinal Bow in Roll Forming of Advanced High Strength Steel

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In roll forming, the sheet is deformed gradually in successive roll stands. The tooling design plays a major role in the quality of the roll formed parts. Two design strategies are possible, constant arc length and constant bend radius. The former offers an overall bending curvature greater than that from the latter. This implies a larger compression and stretching in the profile along the forming process is possible. This has a significant effect on the final quality of the roll formed parts. Although a wide range of research has been carried out on roll forming process, up till now no case has been found in the literature considering this effect. Therefore, the key significance of this paper is to investigate the optimal roll forming process design, and hence improve the quality of the rolled products in terms of longitudinal bow. For this purpose, Finite Element Analysis (FEA) was used to model the roll forming process with two design approaches, constant arc length and constant bend radius, by using Abaqus standard. A material hardening model was imported from a developed inverse routine of cyclic pure bending test, and then integrated into FEA- model of roll forming. A forming radius R15 mm of V- shaped profile made of DP78 has been formed using five forming stations. Longitudinal bow was determined and analyzed. It was observed the longitudinal bow has been decreased by 50% for the constant bend radius compared to the rival one. This study assists the roll forming process designer to improve the final quality of the products.

Numerical and Experimental Investigations on Cold U-Bending of Alloy 690 Heat Transfer Tube

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Steam generators are enormous heat exchangers that use heat energy derived from a reactor of nuclear power plant for generating steam. The steam obtained is drained into a turbine, and plays an im-

portant role for power generation. The heat transfer tubes of each steam generator used in a pressurized water reactor (PWR) are composed of about 8,000 \ 13,000 U-shaped tubes. These tubes act as the structural material and the thermal boundary, and account for about 70% of the cooling surface area, transmitting thermal energy between the high-temperature, high-pressure primary coolant derived from the reactor and the secondary coolant system. The heat transfer tubes were fabricated from of Alloy 690 seamless tubes. In this study, numerical and experimental investigations are carried out on the U-bending process for manufacturing U-shaped heat transfer tubes from long straight Alloy 690 tubes. In the numerical simulation, 3-dimensional finite element analysis is performed using ABAQUS Explicit/Implicit. In detail, process parameters such as the angular speed, U-bending period, and bending angle taking into account elastic recovery after cold U-bending are considered. Additionally, experimental investigations are conducted to verify the suitability of the predicted U-shaped geometries in terms of the ovality and wall thickness of the U-shaped heat transfer tubes.

Friction and contact

Boundary and Mixed Lubrication Friction Modeling under Forming Process Conditions

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A multi-scale friction model for large-scale forming simulations is presented. A framework has been developed for the boundary and mixed lubrication regime, including the effect of surface changes due to normal loading, sliding and straining the underlying bulk material. Adhesion and ploughing effects have been accounted for to characterize friction conditions on the micro scale. To account for the lubricant effects special hydrodynamic contact elements have been developed. Pressure degrees of freedom are introduced to capture the pressure values which are computed by a finite element discretization of the 2D averaged Reynolds equations. The boundary friction model and the hydrodynamic friction model have been coupled to cover the boundary and mixed lubrication regime. To prove the numerical efficiency of the multi-scale friction model, finite element simulations have been carried out on a top hat section. The computed local friction coefficients show to be dependent on the punch stroke, punch speed and location in the product, and are far from constant. The location and range of friction coefficient values are in the order of what to expect from practice. The agreement between the numerical results and the experiments for different lubrication types and amount of lubrication is good. The multi-scale friction model proves to be stable, and compared to a Coulomb-based FE simulation, with only a modest increase in computation time.

Nonlinear Friction Model for Servo Press Simulation

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The friction coefficient was measured under an idealized condition for a pulse servo motion. The measured friction coefficient and its changing with both sliding distance and a pulse motion showed that the friction resistance can be reduced due to the re-lubrication during unloading process of the pulse servo motion. Based on the measured friction coefficient and its changes with sliding distance and re-lubrication of oil, a nonlinear friction model was developed. Using the newly developed the nonlinear friction model, a deep draw simulation was performed and the formability was evaluated. The results were compared with experimental ones and the effectiveness was verified.

Modelling, simulation, and processing technology on product manufacture

Prediction of Particle Orientation in Simple Upsetting Process of NdFeB Magnets

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In the common industrial sheet metal forming process, in which in-homogenous deformation under the plane stress condition is typically the case, sheets are so ductile that their forming fails more often than not after catastrophic strain localization, especially in the thinning mode, as a result of the boundary value problem of the constitutive law. In such a case, the measurement of the fracture criteria might be impractical and criteria to account for catastrophic strain localization replace the fracture criteria as a tool to evaluate sheet formability. The catastrophic strain localization, as a mathematical consequence under typical forming conditions rather than as a material property, is approximately deformation path-independent (or boundary condition independent) at room temperature as will be reviewed in this work for typical forming limit stretching and deep draw forming tests as well as their simplified models such as the M-K, Hill and Dorn.

Development of Element Subdivision Method for Modeling Grain Refinement Mechanism in Extrusion Process

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This study aims to develop an element subdivision method for modeling the grain refinement mechanism in extrusion process. The proposed method, a criterion based on von Mises strain, was applied in finite element model to analyze the deformation process in an extrusion die which has a straight channel part combined a conical part with three inclination angles of 5°, 10°and 15°. A two dimensional quadratic element was used to mesh the billet with an edge length of 45μm according to the average diameter of initial grain from experimental result. Firstly, the extrusion process in the case of die angle of 5°with guess values was modeled and grain size on the cross-sectional surface of extruded aluminum alloy part (A6061) was observed. Secondly, the optimized value of criterion can be obtained by comparing the grain gradient of the die exit with that of experimental result. Applying the optima value of criterion into the case of die angle of 10°and 15°the numerical punch load history also agreed well with that of experiment. Consequently, the developed method can accurately model the grain refinement and predict the effective load in extrusion process.

Study on Bulging Behavior of Rotating Cylinder Compression Forming Based on Upper Bound Method and Experiment

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Rotating cylinder compression forming results in a lower compression force than traditional cylinder compression forming. However, friction-induced power losses and bulging deformation are nevertheless unavoidable. Accordingly, the present study proposes a hybrid method comprising the Upper Bound Method (UBM) and an elliptical curve-fitting technique to predict both the rotating compression force and the bulge profile. It is shown that the predicted results for the rotating compression force are in good agreement with the experimental results and those obtained from Finite Element Method (FEM) simulations and Slab Method (SM) analysis. In addition, the predicted bulge profiles of the compressed cylinders are in good qualitative agreement with the experimental profiles. Overall, the results show that the proposed method provides a low-cost and computationally straightforward means of estimating the compression force and bulge profile in rotating cylinder compression forming.

Electrohydraulic Forming of Dual Phase Steels; Numerical and Experimental Work

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Electrohydraulic Forming (EHF) is a high velocity forming process, in which the strain-rate in the sheet metal can reach very high values depending on the prescribed input energy, the chamber geometry, the die geometry, instrumentation efficiency and the mechanical properties of the sheet material. In EHF, a high voltage discharge between electrodes that are submerged in a water-filled chamber generates a plasma channel that leads to propagation of a shockwave through the water that forms the sheet, with or without a die, in less than a millisecond. EHF generates a complex pressure pulse history that is extremely challenging to simulate. In this work, three-dimensional finite element simulations of DP590 sheet were completed in free-forming (EHFF) and die-forming (EHDF) conditions using ABAQUS/Explicit and a combination of Eulerian and Lagrangian elements. The Johnson-Cook constitutive plasticity model was selected and the parameters were calibrated based on uniaxial tensile test data

at different strain-rates. A comprehensive numerical study was carried out with a view to understanding the differences between EHFF and EHDF in terms of the history of the deformation profile of the specimen, the strain-rate history, the loading path and through-thickness stresses. Higher strain-rates and more complex strain-paths were predicted in EHDF compared to EHFF due to dynamic sheet/die interaction. Good correlation between the experimental and numerical results demonstrated the ability of numerical models to accurately predict the history of the deformation profile in both EHDF and EHFF conditions.

Optimization of an Asymmetric Thin-walled Tube in Rotary Draw Bending Process

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The rotary draw bending is one of the advanced thin-walled tube forming processes with high efficiency, low consumption and good flexibility in several industries such as automotive, aerospace and shipping. However it may cause undesirable deformations such as over-thinning and ovalization, which bring the weakening of the strength and difficulties in the assembly process respectively. Accurate modeling and effective optimization design to eliminate or reduce undesirable deformations in tube bending process have been a challenging topic. In this paper, in order to study the deformation behaviors of an asymmetric thin-walled tube in rotary draw bending process, a 3D elastic-plastic finite element model has been built under the ABAQUS environment, and the reliability of the model is validated by comparison with experiment. Then, the deformation mechanism of thin-walled tube in bending process was briefly analysis and the effects of wall thickness ratio, section height width ratio and mandrel extension on wall thinning and ovalization in bending process were investigated by using Response Surface Methodology. Finally, multi-objective optimization method was used to obtain an optimum solution of design variables based on simulation results.

Study on Cold Forming of Special Fasteners Using Finite Element Method

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The cold forming plays an important role in the field of fasteners. It can be extended to the automotive industry, construction, aerospace and 3C products. This study used Deform-3D analysis software to investigate the effect of the preforms for standard hex nuts. The effective stress, effective strain, velocity field and other information could be obtained from the numerical simulation. The outcome was verified with the physical phenomena and experiments. Furthermore, the analytical process can also be used to explore the forming technology of the special shaped nuts. When comparing to the standard hex nuts during the different stages, the optimized cold forming parameters could be extracted from the simulation and adopted to improve the performance of manufacturing for the special shaped nuts. The results can help the multi-pass processing factory to establish a cold forming capacity in the development of new products. Consequence, the ability of self-design and self-manufacture for special shaped fasteners in Taiwan would be increased widely to enhance the international competition of domestic industries.

Manufacture of Gradient Micro-Structures of Magnesium Alloys Using Two Stage Extrusion Dies

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This paper aims to manufacture magnesium alloy metals with gradient micro-structures using hot extrusion process. The extrusion die was designed to have a straight channel part combined with a conical part. Materials pushed through this specially-designed die generate a non-uniform velocity distribution at cross sections inside the die and result in different strain and strain rate distributions. Accordingly, a gradient microstructure product can be obtained. Using the finite element analysis, the forming temperature, effective strain, and effective strain rate distributions at the die exit were firstly discussed for various inclination angles in the conical die. Then, hot extrusion experiments with a two stage die were conducted to obtain magnesium alloy products with gradient micro-structures. The effects of the inclination angle on the grain size distribution at cross sections of the products were also discussed. Using a die of an inclination angle of 15°, gradient micro-structures of the grain size decreasing gradually from 17 μm at the center to 4 μm at the edge of product were achieved.

Analysis Of The Flow Imbalance On The Profile Shape During The Extrusion Of Thin Magnesium Sheets

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The extrusion process facilitates the production of magnesium sheets featuring a very thin thickness as well as excellent surface properties by using a single process step only. However, the extrusion of the magnesium sheets applying not optimized process parameters, e.g. low billet temperature or/ and poorly deformable magnesium alloy, produce pronounced buckling and waving of the extruded sheets as well as a variation of accuracy in profile shape along the cross section. The present investigation focuses on the FEM-simulation of the extrusion of magnesium sheets in order to clarify the origin of the mentioned effects. The simulations identify the flow imbalance during extrusion as the main critical factor. Due to the flow imbalance after passing the die a large compression stress zone is formed causing the buckling and waving of the thin sheets. Furthermore, the simulations of the magnesium sheet extrusion reveal that the interaction of the material flow gradients along the width and along the thickness direction near the die orifice lead to the variation of the accuracy in profile shape.

Shell and Solid Modeling for Structural Body-In-White Part

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Finite-Element Analysis (FEA) is a numerical method that facilitates designers to produce a part with the high degree of reliability. These advantages allow manufacturing engineer to produce a virtual tool prototype. This approach has eliminated the requirement to manufacture the prototype model from soft tool parts and soft tool press die. This research focuses on the numerical experiments for an advanced high-strength steel part in Body-in-White. The patchwork blank sheet of a structural body in white is modeled with three conditions shell elements without spot welding nuggets, Shell elements with spot welding nuggets and Solid elements. Shell elements are usually the obvious choice in the blank in sheet metal forming simulation primarily due to the rapid and fairly accurate results generated. Solid elements of the other hand require extremely high computation time. The main objective of this study is to critically compare plastic deformation results obtained from three approaches on a B-Pillar part with 1.75mm thickness. The finite-element models are developed from the CAD data of production tool and blank material. The blank material is meshed with quad elements for optimized computing time and results. The input parameters for the simulation models are obtained from the current setup at Press Machine and Production Tool. The analyses of plastic deformation for all three blank material models are compared to the actual part thickness. Percentage of deviation from the actual part geometry will indicate the best approach in producing finite-element models for Hot forming process.

Research on the Innovative Hybrid Impact Hydroforming

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The innovative hybrid impact hydro-forming (IHF) technology is a kind of high strain rate forming technique which can be used for forming complex parts with small features, such as convex tables, bars etc. The present work investigates IHF using a numerical /experimental approach. In this paper, the theory of IHF is presented and finite element simulation was carried out by using MSC. The pressure distribution changes in the depth direction, but not in the width direction. However, the pressure is uniform everywhere in traditional hydro-forming. Using this shock wave loading conditions, forming experiments were carried out. Punching occurred as a result of combined tensile and shear stress effects. Furthermore, results show that using IHF technology, the design constraint to make precise die may be considerably reduced. The need to accurately control punch-die clearance may also be eliminated. Therefore, the research is very useful for forming complicated products.

Study of Electrode Slice Forming of Bicycle Dynamo Hub Power Connector

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Taiwan's bicycle industry has been an international reputation as bicycle kingdom, but the problem in the world makes global warming green energy rise, the development of electrode slice of hub dynamo and power output connector to bring new hope to bike industry. In this study connector power output to gather public opinion related to patent, basis of collected documents as basis for design, structural components in least drawn to power output with simple connector. Power output of this study objectives connector hope at least cost, structure strongest, highest efficiency in output performance characteristics such as use of computer-aided drawing software Solid works to establish power output connector parts of 3D model, the overall portfolio should be considered part types including assembly ideas, weather resistance, water resistance, corrosion resistance to vibration and power flow stability. Moreover the 3D model import computer-aided finite element analysis software simulation of expected the power output of the connector parts manufacturing process. A series of simulation analyses, in which the variables relied on first stage and second stage forming, were run to examine the effective stress, effective strain, press speed, and die radial load distribution when forming electrode slice of bicycle dynamo hub.

Poster Session

A Novel Inspection System for Cosmetic Defects

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The appearance of automotive skin panels creates desirability for a product and differentiates it from the competition. Because of the importance of skin panels, considerable care is taken in minimizing defects such as the hollow defect that occur around door-handle depressions. However, the inspection process is manual, subjective and time-consuming. This paper describes the development of an objective and inspection scheme for the hollow defect. In this inspection process, the geometry of a panel is captured using a structured lighting system. The geometry data is subsequently analyzed by a purpose-built wavelet-based algorithm to identify the location of any defects that may be present and to estimate the perceived severity of the defects without user intervention. This paper describes and critically evaluates the behavior of this physically-based algorithm on an ideal and real geometry and compares its result to an actual audit. The results show that the algorithm is capable of objectively locating and classifying hollow defects in actual panels.

On Stress Measurement Errors in Biaxial Tensile Testing and the Impact on Yield Surface Identification

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The introduction of slits in the arms of a cruciform specimen, as originally proposed by Kuwabara et al. [1] (Fig.1(a)), has been instrumental in avoiding geometrical constraints on the biaxial gauge area. Recently, Hanabusa et al. [2] proposed a method to further improve the accuracy of the testing method. Hanabusa et al. [2] numerically determined the optimal strain measurement position within the biaxial gauge area assuming that the strain can be measured without error. In this paper the purpose is to investigate the influence of the strain measurement error on the evolution of the stress error in biaxial tensile testing. It is clear that the accuracy and the precision of the strain measurement determines the accuracy of the stress points forming the contour of plastic work. Consequently, the accuracy of the identified yield function will also be affected. In this work, digital image correlation (DIC) is used to measure surface strains. First, the theoretical stress error as a function of the plastic work per unit volume is derived for different stress ratios. Then the focus is on the inclusion of the strain measurement error in the stress error assessment and the consequences for the identification of the yield function.

Incremental Analysis of Springback and Kinematic Hardening by the Variation of Tension During Deep Drawing

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Springback is considered as one of the major problems in sheet metal forming. It leads to assembly defects and cause a huge amount of cost for tool modifications. In this work a tool for incremental analysis of springback analysis has been presented. Development of springback with punch travel has been analyzed for the simple U draw-bend geometry, tunnel geometry with open base and modified tunnel geometry with closed base and variable flange height. The effect of tension variation in the sheet with punch travel has been considered as the steering parameter for the springback and various profiles of varying tension are studied, which would generate different tensile forces in sheet. It is found

that the tension in the part in the last quarter of punch travel has a profound effect on the spring-back reduction as compared to the traditionally applied constant BHF. Two selected kinematic hardening models, namely Yoshida-Uemori(YU) model and Armstrong-Frederick(AF) model are used to study the coupled effects of tension and material hardening.

Efficient Simulation of Press Hardening Process Through Integrated Structural and CFD Analyses

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Altair

Press hardened steel parts are being increasingly used in automotive structures for their higher strength to meet safety standards while reducing vehicle weight to improve fuel consumption. However, manufacturing of sheet metal parts by press hardening process to achieve desired properties is extremely challenging as it involves complex interaction of plastic deformation, metallurgical change, thermal distribution, and fluid flow. Numerical simulation is critical for successful design of the process and to understand the interaction among the numerous process parameters to control the press hardening process in order to consistently achieve desired part properties. Until now there has been no integrated commercial software solution that can efficiently model the complete process from forming of the blank, heat transfer between the blank and tool, microstructure evolution in the blank, heat loss from tool to the fluid that flows through water channels in the tools. In this study, a numerical solution based on Altair HyperWorks product suite involving RADIOSS, a non-linear finite element based structural analysis solver and AcuSolve, an incompressible fluid flow solver based on Galerkin Least Square Finite Element Method have been utilized to develop an efficient solution for complete press hardening process design and analysis. RADIOSS is used to handle the plastic deformation, heat transfer between the blank and tool, and microstructure evolution in the blank during cooling. While AcuSolve is used to efficiently model heat loss from tool to the fluid that flows through water channels in the tools. The approach is demonstrated through some case studies.

Investigation on Process Parameters of Flexible Stretch Forming Process Using Orthogonal Experiment Design

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The flexible stretch forming process (FSFP), is useful sheet metal forming method to produce the small batch three dimensional surfaces. Elastic recovery is one of the very important factors to influence the shape accuracy. The main purpose of this paper is to investigate the influence of design parameters on the elastic recovery. The prestrain, the punch size, the objective radius of surface and thickness of the elastic pad are selected as the design parameters. The value of elastic recovery is selected to evaluate the shape accuracy. The orthogonal experiment design is adopted to investigate the relationship between shape accuracy and design parameters. The analysis of variances (ANOVA) is applied to analyze the value of elastic recovery. The optimal combination is PS3R3PR2T2, which is 0.01 for the prestrain, 500mm for the objective surface radius, 10mm for punch radius and 5mm for elastic pad thickness. The orthogonal experiment design and ANOVA approach may provide a useful guidance to determine design parameters and improve the forming quality in FSFP.

Computational Stoning Method for Surface Defect Detection

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Surface defects on outer panels of automotive bodies must be controlled in order to improve the surface quality. The detection and quantitative evaluation of surface defects are quite difficult because the deflection of surface defects is very small. One of detecting methods for surface defects used in factories is a stoning method in which a stone block is moved on the surface of a stamped panel.

The computational stoning method was developed to detect surface low defect by authors based on a geometry contact algorithm between a stone block and a stamped panel. If the surface is convex, the stone block always contacts with the convex surface of a stamped panel and the contact gap between them is zero. If there is a surface low, the stone block does not contact to the surface and the contact gap can be computed based on contact algorithm. The convex surface defect can also be detected by applying computational stoning method to the back surface of a stamped panel. By performing two way stoning

computations from both the normal surface and the back surface, not only the depth of surface low defect but also the height of convex surface defect can be detected. The surface low defect and convex surface defect can also be detected through multi-directions. Surface defects on the handle emboss of outer panels were accurately detected using the computational stoning method and compared with the real shape. A very good accuracy was obtained.

Numerical crash modeling of a hot stamped component with tailored mechanical properties

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By increasing the vehicle occupants safety expectations, the automakers are imposed to develop new technologies and strategies to satisfy these requirements. Hot stamping of boron steels has been one of the most focused technologies to improve vehicles structural performance during past few years. Heating blanks up to austenitization temperature, forming and rapid cooling in a water-cooled die result in high ultimate tensile strengths up to 1500MPa. However, to increase the energy absorption capacity of some vehicle parts, e.g. B-Pillar, hot stamped process resulting parts with tailored mechanical properties have been recently developed. In this study, a numerical crash model of a hot stamped B-Pillar with tailored mechanical properties has been created using Finite Element Software ABAQUS v6.12. A 3-point bend configuration is used by applying a series of appropriate boundary conditions to achieve the most realistic model when compared to a real vehicle side crash. A wide range of strain rate-dependant flow curves have been employed in material modelling for different zones of the hot stamped part. The effects of properties distribution in all zones have been investigated on crashworthiness response of the part.

Benefits of a New Bi-Mesh Technique Applied to Incremental Forming Simulation with FORGE

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We present a fully parallel Bi-Mesh method which permits to dramatically speed-up incremental forging computations by taking advantage of the localization of the deformation area. Working on two meshes at each time step, one to solve the mechanical problem and one to solve the thermal problem and store the results, permits to take advantage of recent adaptive remeshing techniques without suffering from the usual remapping issues. This method has been successfully implemented in the commercial software FORGE and is compatible with a wide range of other FEM facilities. Speed-up larger than 4 are common and speed-up larger than 10 can be reached in favorable cases.

Anisotropic Hardening Model Based on Non-Associated Flow Rule and Combined Nonlinear Kinematic Hardening for Sheet Materials

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A material model for more effective analysis of plastic deformation of sheet materials is presented in this paper. The model is capable of considering the following aspects of plastic deformation behavior of sheet materials: the anisotropy in yielding stresses in different directions by using a quadratic yield function (based on Hills 1948 model and stress ratios), the anisotropy in work hardening by introducing non-constant flow stress hardening in different directions, the anisotropy in plastic strains in different directions by using a quadratic plastic potential function and non-associated flow rule (based on Hills 1948 model and plastic strain ratios, r-values), and finally some of the cyclic hardening phenomena such as Bauschingers effect and transient behavior for reverse loading by using a coupled nonlinear kinematic hardening (so-called Armstrong-Frederick-Chaboche model). Basic fundamentals of the plasticity of the model are presented in a general framework. Then, the model adjustment procedure is derived for the plasticity formulations. Also, a generic numerical stress integration procedure is developed based on backward-Euler method (so-called multi-stage return mapping algorithm). Different aspects of the model are verified for DP600 steel sheet. Results show that the new model is able to predict the sheet material behavior in both anisotropic hardening and cyclic hardening regimes more accurately. By featuring the above-mentioned facts in the presented constitutive model, it is expected that more accurate results can be obtained by implementing this model in computational simulations of sheet material forming processes. For instance, more precise results of springback prediction of the parts formed from highly anisotropic hardened materials or that of determining the forming limit diagrams is highly expected by using the developed material model.

Numerical Simulation of Hybrid Forming Based on Electromagnetic Forming Process

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Electromagnetic forming (EMF) process is one of a high-speed forming process, which uses an electromagnetic body (Lorentz) force to deform workpiece. Advantages of this forming technique can be summarized as the improvement of formability, the reduction in wrinkling occurrence. In this study, hybrid forming process is presented to evaluate the efficiency of EMF process. Hybrid forming process is the combined process to deform the complicated shape which is difficult to form with the conventional deep drawing process because of tearing. In order to evaluate efficiency of EMF, a series of numerical simulations were conducted with ANSYS multi-physics. Two types of traditional cylindrical deep drawing numerical simulations which have different punch radius and the same drawing depth were performed. In the deep drawing process with 15mm punch radius, tearing was not occurred at the bottom corner of the workpiece. However, tearing was occurred at the bottom corner region in punch with small radius (5mm). To resolve the tearing problem, EMF process was applied to the deformed workpiece. In the FEM, an electromagnetic-structural coupling simulation was performed and then the electromagnetic force results were transferred to the explicit FEM code LS-DYNA as an input load to analyze the transient dynamic plastic deformation of the sheet material. The EMF forming coil consists of four turns with 15 mm punch radius. The maximum values of discharge are 15kV (32kJ). In the hybrid simulation results, an apparent decrease of bottom corner radius can be observed, and a much smaller radius without tearing can be achieved. This simulation result shows that hybrid forming can improve the formability of the aluminum cylindrical parts.

Numerical and Experimental Investigations on Cold U-Bending of Alloy 690 Heat Transfer Tube

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Steam generators are enormous heat exchangers that use heat energy derived from a reactor of nuclear power plant for generating steam. The steam obtained is drained into a turbine, and plays an important role for power generation. The heat transfer tubes of each steam generator used in a pressurized water reactor (PWR) are composed of about 8,000 13,000 U-shaped tubes. These tubes act as the structural material and the thermal boundary, and account for about 70% of the cooling surface area, transmitting thermal energy between the high-temperature, high-pressure primary coolant derived from the reactor and the secondary coolant system. The heat transfer tubes were fabricated from of Alloy 690 seamless tubes. In this study, numerical and experimental investigations are carried out on the U-bending process for manufacturing U-shaped heat transfer tubes from long straight Alloy 690 tubes. In the numerical simulation, 3-dimensional finite element analysis is performed using ABAQUS Explicit/Implicit. In detail, process parameters such as the angular speed, U-bending period, and bending angle taking into account elastic recovery after cold U-bending are considered. Additionally, experimental investigations are conducted to verify the suitability of the predicted U-shaped geometries in terms of the ovality and wall thickness of the U-shaped heat transfer tubes.

Tool Design and Experimental Investigation for Cold Forging of Inner Race with Six Skewed Cross Ball Grooves

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As one of asymmetric automotive parts, the inner race of CV (constant velocity) joints has six skew-angled cross ball grooves, and plays an important role in transmitting torque between the transmission and driven wheels. Until present, this metal component has been produced by a machining process including material removal due to the 3-dimensional asymmetric configuration. In this study, a cold forging sequence by using a semi-closed die set is proposed to obtain the inner race. The presented forging process consists of six longitudinally split cross ball grooving dies, a die holder, upper and lower forging punches. And the operation mechanism of the proposed semi-closed die set is also considered to ensure the interference between each tool part. Tool design has been carried out, and the design result has been applied to the structural integrity evaluation of the proposed tool geometry. A 3-dimensional numerical simulation and experimental investigations for this proposed cold forging process are also performed by using the initial billet material of the spheroidized and phosphophyl-

lite (Zn2Fe(PO4)2) coated SCr420H. In addition, the dimensional accuracy of the forged inner race is investigated. It is shown that the proposed semi-closed die cold forging procedure could be successfully applied to the production of the inner race with the six split cross ball grooves, and achieved the dimensional accuracy under about 2.0%.