ABSTRACTS

MS1 Kwansoo Chung Memorial Symposium : Mechanics in Materials Forming

MS1-1

An integrated computational materials engineering approach for constitutive modelling of 3rd generation advanced high strength steels

Farhang Pourboghrat, Taejoon Park, Hyunki Kim, Bassam Mohammed, Rasoul Esmaeilpour, Louis G. Hector

Constitutive models for the 3rd generation advanced high strength steels (3GAHSS) were developed based on integrated computational materials engineering (ICME) approach. Multiple scale models from the atomic level to the continuum level were integrated to generate material models that can be used to accurately model the material response of the 3GAHSS depending on their microstructures. In addition to the shear deformation in the slip systems, martensitic phase transformation induced by the plastic deformation of the retained austenite was accounted for in the crystal plasticity model. Atomistic simulation results based on the density functional theory (DFT) calculations were utilized to obtain the lattice parameters and elastic coefficients, while micropillar compression data and in-situ HEXRD test data were utilized for the characterization of the developed crystal plasticity model. 3D representative volume elements (RVE) were generated to represent the mechanical behaviour of the 3GAHSS by considering the distributions of grain size, grain shape, and grain orientation measured from the EBSD data. To predict macroscopic mechanical behaviour of 3GAHSS in complex deformations, finite element simulations were performed based on the developed crystal plasticity model and generated 3D RVEs. The CPFE simulation results were implemented in the advanced phenomenological models and utilized to accurately predict the formability and springback of 3GAHSS.

MS1-2

Stress update algorithm based on finite difference method and its application to homogenous anisotropic hardening (HAH) model

Hyun Sung Choi, Jeong Whan Yoon, Frederic Barlat

This paper deals with stress update algorithm based on finite difference method. The proposed algorithm is based on Euler backward method with multi-step return mapping approach. Central difference method was utilized for the approximation of the first and second derivatives of yield function. With the proposed algorithm, it is possible to perform elastic-plastic finite element simulation without any analytical derivatives of yield function. General yield functions including Hill's (1948) and Yld2000-2d, and also the HAH distortion hardening model were implemented to an implicit finite element code ABAQUS/STANDARD). For the verification purpose, various finite element simulations were performed. With the anisotropic functions, single element loading-unloading and cup-drawing simulation were carried out. The results obtained from the proposed algorithm were compared with the results from analytical derivatives and reference data. The availability of the proposed algorithm for distortional plasticity such as HAH model was evaluated by single element loading-reloading simulations: tension-compression and tension-orthogonal tension. The effectiveness of the proposed algorithm compared to the classical Euler backward method was identified from the simulation results.

MS1-3

Effect of ideal flow conditions on springback

Sergei Alexandrov, E Lyamina, D Date

All sheet forming processes incorporate some bending. Various aspects of this process affect its design. One of the important aspects is springback. The present paper concerns with the effect of ideal flow conditions on springback after bending under tension. In general, this process is not an ideal flow process. An ideal flow path is produced if two inequalities are satisfied. A measure of springback is calculated for this case.

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MS1-4

Mechanical performance of resistance spot welded steel sheets

Noh Wooram, Xin Yang, Jung-Han SONG , Myoung-Gyu Lee

Mechanical performance of resistance spot welded steel sheets was evaluated under quasi-static and dynamic loading conditions. Numerical inverse calibration method was mainly utilized to characterize mechanical properties especially for flow curves and ductile fracture criteria of constituent zones of the welded joints. For the base sheets, standard tensile test and high-speed tensile test was conducted under quasi-static and dynamic loading conditions, respectively. Mechanical properties of the weld zones were characterized using the developed miniature tensile specimen. Implementing the mechanical properties and structure to the finite element model, finite element simulation was used to evaluate the mechanical performance of two distinct weld coupons.

MS1-5

Thermomechanical simulations of blanking process operated over a wide range of punch velocities

Jean-Philippe Ponthot, Romain Boman, Cristian Canales

A numerical model based on the finite element method has been developed to simulate the blanking process. Thanks to this model we analyze the influence of punch velocities during blanking on the quality of the sheared edge and the characteristic parameters governing the process (maximum punch force and displacement, temperature increase). In this model, inertia, viscous and thermal effects are properly considered by means of a unified thermomechanical framework. A full remeshing approach is adopted to overcome the high distortion of elements due to large deformations, prior to fracture. The material strain-rate sensitivity is introduced by means of an extension of elasto-viscoplastic constitutive equations for the large strain regime. The inertial effects are considered thanks to an implicit time integration scheme. Crack propagation during the process is tracked using the element deletion method driven by an uncoupled damage criterion. Finally, the coupled thermomechanical problem is solved by an isothermal staggered scheme. Experimental and numerical results are compared for the entire range of punch velocities under consideration. Good agreement between both results has been found.

MS1-6

Determination of forming limits of high strength sound-deadening laminated sheet

Daeyong Kim, Hyeonil Park , Se-Jong Kim, Jinwoo Lee

High strength sound-deadening laminated sheet consists of high strength steel sheets and a viscoelastic polymeric adhesive with high vibrational damping characteristics. In this study, to evaluate formability of sound-deadening laminated sheet, forming limit curves (FLC) were determined. The high strength sound-deadening laminate sheet was fabricated with dual phase (DP) 590 steel sheets as outer skins and polymeric adhesive as a core by roll bonding process. The punched dome tests (Nakajima tests) were performed with varying specimen width. On the specimen prior to deformation, a stochastic pattern was applied to the surface using a white and black spray. Until the fracture occurs, the strain distribution was measured in the stereo image using digital image correlation (DIC) system. FLC of the laminated was successfully determined by capturing limit strains near fracture as well as calculating them according to the ISO standards. FLC of the laminated sheet is slightly higher than that of DP590 sheet but is not significantly different.

MS1-7

Modelling transient behavior during stress relaxation

Krishnaswamy Hariharan, Jayant Jain, Myoung Gyu Lee

Stress relaxation test is widely used to estimate activation parameters during plastic deformation. The one-dimensional theoretical models used to predict the stress relaxation behavior uses the Orowan rate equation to derive the stress drop as a function of time. Classical models assume that the average mobile dislocation density and internal stress remain invariant during the test. Although subsequent works have extended the original models, the treatment is still incomplete. In the present work, two of the existing

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stress relaxation models, power law model and logarithmic model are analyzed using the experimental data obtained from SS 316. The models are modified based on the understanding of mechanics of deformation mechanism during stress relaxation. The modified power law model was found to be inconsistent mathematically whereas the modified logarithmic model was found to improve the accuracy of prediction.

MS1-8

Numerical study of incremental sheet forming processes

Hyunki Kim, Taejoon Park, Rasoul Esmaeilpour, Farhang Pourboghrat

In incremental sheet forming processes, materials are deformed by continuous local contact with a moving tool along predefined tool paths so that their stress or strain histories are significantly different from conventional forming processes such as stamping, drawing, and hydroforming. In this work, numerical conditions, e.g., a rigid surface type, an initial blank size, an element type, and a contact algorithm commonly assumed for the conventional forming, were re-investigated to confirm whether those assumptions are still valid for the incremental sheet forming. An aluminium alloy sheet, AA7075-O, with a thickness of 1.64 mm was considered for this work. The simulation results were compared regarding stress or strain paths at the critical elements, an effective strain distribution, a thickness profile, and reaction forces and moments of the tool. The computational time was also compared, in order to identify optimum simulation conditions.

MS1-9

Prediction of fracture behavior in hole expansion test using microstructure based dual-scale model

Heung Nam Han, Siwook Park , Jinwook Jung , Sung Il Kim , Seok-Jong Seo , Myoung-Gyu Lee

A reliable prediction of sheet formability is required for designing automobile parts, especially for the parts made of Advanced High Strength Steels (AHSS) with complex microstructure. Because of the microstructural complexity of AHSS, finite element (FE) simulations based on the representative volume element (RVE) in which microstructural information is incorporated as a submodel have been used to predict macroscopic mechanical properties of materials. In this work, a dual-scale FE approach was proposed to predict the hole expansion ratio (HER) of a multiphase steel sheet. As a large scale simulation, punching analysis followed by the hole expansion simulation was first performed. The strain history of each element was used as a boundary condition for the subsequent small-scale RVE model. Deformation behavior depends on several factors related to microstructural effects such as grain size, and dislocation density. The equilibrium dislocation density in the pile-up configuration was calculated by applying the Peach-Kohler equation and the mean free path was calculated from the derived dislocation density. The dislocation density based flow stress was implemented in the model. For the failure modeling, realistic microstructure-based finite element approach was presented in combination with continuum damage mechanics to consider the microstructure of investigated steel. In the simulation of punching process, a ductile fracture criterion was suggested to predict shear and fracture zones. The experimentally observed hole-expansion formability was reasonably explained by using the presented dualscale finite element model.

MS1-10

A multi-scale modelling of 3rd generation advanced high strength steels to account for anisotropic evolution of yield surface and plastic potential

Taejoon Park, Hyunki Kim, Ill Ryu, Farhang Pourboghrat, Rasoul Esmaeilpour

Multi-scale models were integrated to account for anisotropic mechanical behavior of the 3rd generation advanced high strength steels (3GAHSS). The micromechanical response of individual phases of the 3GAHSS in non-proportional loading was characterized based on the atomistically informed dislocation dynamics (DD) simulations. The characterized mechanical properties were utilized for the development of the crystal plasticity model to properly account for the cross-loading effect on the interactions of the dislocations. To predict anisotropic evolution of yield surface and plastic potential in non-proportional loading of the 3GAHSS, 3D representative volume elements (3D RVEs) were developed based on the microstructural information from the EBSD data. As for the practical applications such as predictions of formability and

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spring-back, an advanced phenomenological model was also developed based on a combined type nonlinear isotropic-kinematic hardening law and two-yield surface plasticity.

MS1-11

Formability predictions and measurement of 316L stainless steel using self-consistent crystal plasticity

Youngung Jeong, Timo Manninen

A viscoplastic self-consistent (VPSC) crystal plasticity model was used to describe the mechanical behavior of a 316L stainless steel sample. Mechanical anisotropy of the 316L stainless steel was evidenced in the experimental results collected from the uniaxial tension tests along various directions. EBSD images were obtained from the as-received sample, and a representative population of discrete orientations was created to account for the initial crystallographic texture in the model. The hardening parameters were identified by using the flow stress-strain curve obtained from a bulge test. The model-predicted and experimental flow-stress curves and R-values were compared in order to estimate the adequacy of the VPSC model to describe the anisotropic behaviour of the 316L stainless steel sample. Furthermore, the crystal plasticity model, in conjunction with the Marciniak-Kuczyński approach, was used to predict forming limit diagram. The model was validated by comparing with the experimental flow stress curves from uniaxial tension and bulge tests. The predictive accuracy on forming limit diagram was also estimated by comparing with the experimental forming limit strains obtained through Nakajima tests.

MS1-12

FE implementation of HAH model using FDM-based stress update algorithm for springback prediction of AHSS sheets

Seong Yong Yoon, Hyun Sung Choi, Jeong Whan Yoon, Frederic Barlat

The homogeneous anisotropic hardening (HAH) model was implemented into a finite element (FE) code in order to predict springback for an advanced high strength steel (AHSS) sheet sample after double-stage U-draw bending. The finite difference method (FDM) was utilized as an alternative way to calculate the derivatives of this advanced distortional plasticity model allowing the update of the equivalent plastic strain and stress tensor at each time step in the user-material subroutines (UMAT and VUMAT). The FDM makes it easier to derive the stress gradient of complex yield surfaces. The proposed FDM-based stress update algorithm was verified by comparing the springback profiles after the single- and double-stage U-draw bending tests for a DP980 sheet sample predicted with analytical and numerical approaches. In addition, the springback measurement parameters and computational efficiencies depending on both approaches were also compared. The results indicate that the computational efficiency and accuracy of the FE simulations with the FDM-based stress update algorithm were similar to those of the analytical method.

MS1-13

A crystal plasticity study on the deformation of an AZ31 alloy sheet under elevated temperature

Dayong Li, Zihan Li, Guowei Zhou, Yinghong Peng

In order to investigate the evolution of deformation mechanisms of AZ31B Mg alloy sheet and their correlation with material property development under intermediate temperatures, systematic experimental examination and the crystal plasticity analysis are performed. The mechanical responses of AZ31B Mg alloy sheet are measured under uniaxial tension and compression along rolling direction, transverse direction and normal direction directions and over the temperature range 100-300°C. A series of EBSD experiments is also carried out in order to explore nucleation features in the dynamic recrystallization (DRX) of AZ31 Mg alloy sheets. Furthermore, a phenomenological DRX criterion is introduced into the visco-plastic self-consistent model through a dislocation density based hardening model to analyze the deformation of AZ31 Mg alloy sheets at 200°C.

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MS1-14

Failure prediction of AZ31B Mg sheet at room temperature considering material anisotropy and differential work hardening

Kanghwan Ahn

Failure predictions of AZ31B Mg sheet at room temperature were conducted considering material anisotropy as well as differential work hardening for the range from uniaxial to balanced biaxial loading paths. The maximum shear stress criterion was used as a failure criterion, and both the associated and non-associated flow rules were employed along with the quadratic anisotropic functions to derive the analytic expressions for failure. Different levels of material anisotropy were considered in formulation, and procedures of determining the material coefficients considering the differential work hardening behavior were provided. Failure predictions using the analytical expressions were compared with the experimental results obtained by hemispherical dome tests. The results show that in the failure prediction of AZ31B Mg sheet, both the material anisotropy and the differential work hardening need to be addressed properly to make an accurate failure prediction.

MS1-15

Effect of distortional hardening behaviour on material response of pure titanium sheets during hydraulic bulge test

Quoc Tuan Pham, Myoung Gyu Lee, Young Suk Kim

Plastic characteristics of pure titanium sheets are identified by conducting several tensile tests and hydraulic bulge test. Distortional hardening behaviour of the tested material is examined experimentally by comparing the uniaxial tensile results of three specimens taken from different orientations. This study verifies the effect of the distortional hardening behaviour on the material responses for pure titanium sheet by conducting a finite element analysis for the bulge test. For this purpose, a material model is calibrated based on the experimentally measured data. In this model, both yield surface and potential surface were well described by the Yld2000-2d function under the theory of associated flow rule. To match with experimental observation, all parameters of the yield function are implied as functions of the equivalent plastic work during plastic deformation. Additionally, a modified Voce hardening function was applied to reproduce the hardening behaviour for the examined material over large strains. Based on simulation results, it is concluded that the DH behaviour strongly affects the evaluation of the apex height during the bugle test.

MS1-16

Constitutive modeling and FE implementation for anisotropic hardening under proportional loading conditions

Eun-Ho Lee, Thomas B. Stoughton, Jeong Whan Yoon

Anisotropic hardening response (or evolution of yield surface) is an important issue for numerical modeling of sheet metal forming and springback. Lee et al. (2017) recently introduced an improved constitutive model based on the Stoughton and Yoon (2009)'s equation, called the S-Y2009 model in this paper, in order to capture the anisotropic hardening in proportional loading conditions. The Lee et al. (2017)'s model was built by coupling the S-Y2009 model and a non-quadratic model to control the curvature of the yield fitting for more accurate prediction of the yield surface. The Lee et al. (2017)'s model (called the coupled model in this paper) showed good agreements with the measured data. However, in the aforementioned paper, a simulation study for sheet metal forming process with the coupled model was not reported. This paper presents the coupled model in two points of view. The first is the ability of the coupled model to capture the evolution of the yield surface. The other is the performance of the coupled model to describe the anisotropic hardening in a bulge test simulation. Predicting the anisotropic hardening including the biaxial stress state is important to follow the measured data. For the simulation, the coupled model was implemented into Vectorized User MATerial interface (VUMAT) of ABAQUS. The Yld2000-2d model was also incorporated in the comparison because the Yld2000-2d model has been showing good agreements with the initial anisotropy. The results of this study show that capturing the anisotropic hardening is important

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and the presented approach can be a good model in the sheet metal forming simulation under the proportional loading conditions.

MS1-17

Ductile fracture of AA6111 alloy including the effect of bake-hardening

Yannis P. Korkolis, Jinjin Ha, Madhav Baral

The thermal cycle of paint baking for auto bodies alters the mechanical properties of aluminum alloys including, possibly, their fracture behavior. In this study, the plasticity and fracture of AA6111 sheet after a 30 min heating cycle at 180°C is investigated. Uniaxial tension, plane-strain tension and disk compression experiments are performed to assess the plasticity of the material. The results are used to calibrate Yld20004-18p anisotropic yield function. An evolution of the yield locus with plastic deformation is observed. This is represented by evolving the exponent of the yield function, rather than the coefficients themselves. The post-necking hardening curve is identified by numerically simulating a notched-tensile test. The fracture locus is probed using notched-tension, center-hole, and shear experiments. In every case, digital image correlation (DIC) is used to acquire the surface strain fields. In parallel, finite element simulations of the fracture specimens are used to approximate the fracture strains, triaxiality, and Lode angle parameter. Yld2004-18p model shows good overall agreement with the experiments; thus, the fracture locus is probed with this model.

MS1-18

Influence of paint baking process on fracture initiation of an Al-Mg-Si alloy sheet

Suhyun Gwak, Inje Jang, Jongsup Lee, Wooram Noh, Myounggyu Lee , Junghan Song, Cheolyoung Jeong

Some of the aluminium alloy sheets widely employed in the light weight automotive body are well known to have hardening mechanism originating from precipitation. Sensitive to heat treatment process, variation of precipitation status induces change of mechanical properties f the aluminium sheets. In this study, fracture phenomenon of a paint bake-hardenable Al-Mg- Si alloy sheet was investigated. As a paint baking process of the aluminium sheet, the heat treatment was isothermally performed on the sheet at 180 °C for 20 minutes, i.e., artificial ageing. The mechanical properties especially for the flow curve and the ductile fracture criterion were characterized by conducting different types of tensile tests for variation of loading path and by analytical analysis of hybrid method. Furthermore, the effect of the baking process on fracture initiation was also quantitatively evaluated by comparison between fracture strain of the aluminium sheet before and after ageing.

MS1-19

Constitutive modelling of carbon fiber-reinforced shape memory polymer composites

Woong-Ryeol Yu, Seok Bin Hong, Jingyun Kim, Nam Seo Gu

Shape memory polymer (SMP) is one of smart polymers which exhibit shape memory effect upon external stimuli such as heat, moisture, electricity etc. To overcome low mechanical properties of SMP, a woven carbon fiber-reinforced shape memory polymer composite (SMPC) has been proposed. However, the prediction of the mechanical behavior of woven carbon fiber-reinforced SMPC is not routine due to anisotropy and multidimensional deformation during bending or unfolding. In this study, a 3D constitutive model of woven carbon fiber reinforced SMPC was developed based on phenomenological three elements in parallel; rubbery and glassy phases and anisotropic fiber part. To treat the anisotropic behavior of woven fabric reinforcement such as high stiffness with slight nonlinearity in the warp and weft directions and nonlinear shear behavior, an anisotropic hyperplastic constitutive model was used that decompose total strain energy into warp and weft stretching and fabric shearing energies. Finally, 3D constitutive equation was obtained by summing the stresses resulting from rubbery and glassy phases and fiber part considering interface effect between matrix and fiber. The developed equation was implemented into COMSOL software. Finally, shape memory bending and anisotropic behavior of woven carbon fiber-reinforced SMPCs was simulated.

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MS1-20

Effect of deformation induced nonlinear and anisotropic elasto-plasticity on sheet forming simulations

Myoung-Gyu Lee, Jeong-Yeon Leeb, Hongjin Choi, Yumi Choia, Kijung Lee, Jinwoo Lee

Anisotropy in initial yield and subsequent hardening in flow stress has been modeled in the finite element simulations to enhance the accuracy of formability and springback in sheet metal products. As continued efforts in the field of constitutive modeling, the evolution of anisotropy during the plastic deformation and its dependency on deformation path were also studied by many researchers. In addition to the plastic behavior, the elastic nonlinearity in pre-deformed sheet metals has been also regarded as a key factor which influences the accuracy of the sheet metal forming simulation, particularly in the springback simulation. In this study, recent reviews on the constitutive modeling for the deformation induced nonlinear and evolution of anisotropy are provided mainly using the published data [1,2]. To model the initial anisotropy the Hill 1948 yield function with non-associated flow rule and Yld2000-2d non-quadratic yield function were considered. Also, these yield surfaces evolve as a function of equivalent plastic strain. For better modeling the nonlinearity of elastic behavior during the deformation, recently developed multi-surface elasticity model was implemented in the simulation. To investigate the effect of the considered anisotropic plasticity and nonlinear elasticity on forming simulation, cylindrical circular cup drawing was experimentally conducted and its earing profile and springback after splitting of the formed cup in the circumferential direction were compared with the simulated results. The results showed that the finite element simulations could predict the deformed shapes after forming and springback with enhanced accuracy when the constitutive model could represent the complexity in the anisotropy and nonlinearity during plastic deformation.

MS1-21

An elasto-plastic constitutive model of magnesium alloy sheet at warm forming temperature under strain path changes

Jinwoo Lee, Dong-Hoon Yoo, Young-Seon Lee, Daeyong Kim, Myoung-Gyu Lee

In the current work, a continuum-based approach is discussed in order to describe the plastic hardening behavior of magnesium alloy sheets under strain path changes at warm forming temperature. The constitutive model is represented to use an anisotropic distortional yield function combining a stable component and a fluctuating component. The stable component includes the yield function that represents the material’s anisotropy or the strength effect between tension and compression. The evolution of the fluctuating component is reformulated based on recently developed HCP metal’s distortional hardening model at room temperature. The modified models were implemented into finite element (FE) software via user-material subroutine. Predicted stress-strain curves of tension-compression-tension (TCT) and compression-tension-compression (CTC) loadings for two pre-strains were compared with experimental results. Overall, the proposed model could give reliable agreement with experimental data.

MS1-22

Crystal plasticity based constitutive modeling of ZEK100 magnesium alloy combined with *in-situ* HEXRD experiments

Hyuk Jong Bong, Xiaohua Hu, Xin Sun, Yang Ren, Raj K Mishra

In the current works, both micro- and macro-mechanical properties of a hexagonal close-packed (HCP) polycrystalline ZEK100 magnesium alloy were investigated. In the experimental perspective, in-situ high energy X-ray diffraction (HEXRD) from a synchrotron source was conducted during the uniaxial tension along the rolling direction (RD) and the transverse direction (TD) to measure the lattice strain evolutions and stress-strain behaviors. In the modeling perspective, crystal plasticity finite element (CPFE) model was developed incorporating the deformation twinning for the HCP-structured metals. The HEXRD experiments and crystal plasticity models were then coupled to characterize the constitutive behaviors of the ZEK100 alloy. The lattice strain data representing the microscopic behavior of the material and the macroscopic stress-strain behavior were then tied together as objective values to estimate the critical resolved shear stress (CRSS) and hardening parameters of available slip and twin systems of the ZEK100 alloy using the

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developed CPFE model. The stress-strain behavior as well as the lattice strain variation during the uniaxial tension tests are presented using the CPFE model and compared with the actual HEXRD data.

MS2 Materials and Process Modeling for Hot-Stamping

MS2-1

Biaxial deformation on AA5182-O aluminum alloy sheet at warm temperature

Hiroshi Hamasaki, Fumiaki Tamashiro

Warm temperature biaxial tension test apparatus was developed in this study. This device can achieve stress ratio and strain rate controls simultaneously because it is necessary to keep those parameters for an accurate measurement of equi-plastic work locus. The warm temperature biaxial tension tests were conducted on AA5182-O aluminium alloy sheet with the thickness of 1 mm. The obtained results showed that the shapes of equi-plastic work loci did not have strong temperature dependency.

MS2-2

Development of a material model for AA7075 aluminium hot stamping

Guillaume D'Amours, Andrey Ilinich

This paper presents the development and validation of a material model for finite element analysis of aluminium hot stamping. It is based on Hill ’48 yield function with a non-associated flow rule and isotropic, temperature and rate sensitive hardening. The model also includes phenomenological damage treatment which was developed for plastic instability and fracture prediction in non-isothermal conditions. A special attention was given to the calibration of thermal conductance. Validation was performed with a series of cross die hot stamping tests with in-situ temperature measurements.

MS2-3

Unified constitutive model of aluminum alloy 2219 at elevated temperature

Tian Gan, Zhong-qi Yu, Yi-xi Zhao, Xin-min Lai

Exploring the hot deformation behaviors of materials is essential for the precise numerical simulation of hot forming processes. In this study, the hot tensile deformation behaviors of aluminum alloy 2219-O are studied by uniaxial tensile tests at the temperature range of 473-673 K and stain rate range of 0.001-0.1 s^{-1}. Mechanism-based unified constitutive equations are developed to model the grain size, recovery and dislocation density. The results show that under the tested deformation conditions, the flow stress decreases with the increase of deformation temperature or the decrease of strain rate. Additionally, the increasing of elongations to fracture in this study indicates that the elevated temperature can improve the plasticity of AA2219-O. Moreover, the flow stresses predicted by the developed unified constitutive model well agree with the experimental data, which indicate that the developed constitutive model is valid.

MS2-4

Suitability of material models in finite element simulation of stress relaxation for titanium sheets

Xiaoqiang Li, Hongrui Dong, Guiqiang Guo, Dongsheng Li

Titanium alloys are important aerospace materials due to their low density, high strength to weight ratio and excellent corrosion resistance, but it is difficult to form them under room temperature due to poor formability and large springback, which is often formed by hot forming. And stress relaxation behaviour of material plays an important role in hot forming. In this paper, different material models are compared in simulating stress relaxation of Ti-6.5Al-2Zr-1Mo-1V sheet, and validated by experiments. A series of uniaxial tensile stress relaxation tests are performed on the Ti-6.5Al-2Zr-1Mo-1V alloy sheet over the temperature ranging from 773 K to 973 K, and the strain 10%. According to the result of stress relaxation tests, Time-Hardening model and Hyperbolic-Sine model are calibrated and validated. It is shown that for stress relaxation process, from 0 to 900 seconds, the maximum stress simulation error (6 MPa) of Time-Hardening model is lower than Hyperbolic-Sine model (25 MPa), but from 1800 to 3600 seconds, the maximum stress simulation error (15 MPa) of Time-Hardening model is larger than Hyperbolic-Sine model (5 MPa). In

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addition, it can be concluded that the stress simulation error will have little effect on shape accuracy of formed parts during the simulation.

MS2-5

Properties prediction modelling for hot stamping products and its validation in a U-cap part

Xianhong Han, Chenglong Wang, Yanan Ding, Zhenshan Cui

Microstructure evolution models were introduced to describe the ultra-high strength hot stamping process, where both diffusional and non-diffusional phase transformations were contained. In addition, the mechanical properties of the final hot stamping products including hardness, strength and elongation etc. were predicted through a series of analytical and empiric models. Based on the platform of LS-DYNA, the presented models were used to simulate the hot stamping process of a U-cup part, the predicted phase fractions and mechanical properties were close to the measured results.

MS2-6

Analysis of flow stress behaviour of inconel alloys at elevated temperatures using constitutive model

Nitin Kotkunde, Gauri Mahallea, Rushabha Shah , Amit Kumar Gupta, Swadesh Kumar Singh

A reliable and accurate prediction of flow behaviour of metals considering the coupled effects of strain, strain rate and temperature is vital in analyzing the workability of the metal. In this study, Khan-Huang-Liang (*KHL*) phenomenological based constitutive models has been developed for flow stress prediction of Inconel 625 and 718 alloys. Firstly, uniaxial tensile tests have been performed from room temperature to 400 °C at an interval of 100 °C and slow strain rate ranges of 0.0001–0.01 s^{-1}. *KHL* constitutive model has been developed using uniaxial tensile test data. The predicted flow behaviour has been compared with experimental stress-strain data. The prediction capability of these models has been verified using various statistical measures such as correlation coefficient *(R*), average absolute error *(Δ*) and its standard deviation *(S*). Based on the analysis of statistical measures revealed that *KHL* model has good in agreement with experimental flow stress behaviour.

MS2-7

Deep drawing of press hardening steels

Melanie Tomasch, Werner Ecker, Robert Kaiser, Thomas Antretter

Press hardening of low alloy steel sheets is an efficient way of manufacturing high strength automotive components relevant for passenger safety in case of a crash. The press hardening process combines the advantages of good formability at elevated temperatures as well as high strength and good form accuracy after quenching in the closed die. Since cooling during forming and subsequent quenching has a significant influence on the mechanical behaviour of a steel sheet, a strongly coupled thermo-mechanical model has been developed for the simulation software ABAQUS. Accurate simulation results require the knowledge of temperature dependent thermal and mechanical material properties as well as occurring interactions between the sheet and the die. They were determined in a series of experiments and provide the input for the numerical model. During the quenching step in the closed die, the high strength of the component is achieved by a martensite phase transformation. This transformation is strongly influenced by the deformation in the heavily bent areas as well as the temperature evolution of the sheet. Accurate results for the shape of the final components and for the properties within the operating service time can only be obtained if the numerical model accounts for the microstructure formation including the TRIP (Transformation Induced Plasticity) effect. This is accomplished by means of a user subroutine. Consequently, the model allows to analyse the forming and cooling process in the closed die in detail throughout the entire process cycle. Concluding, the final geometry, the wall thickness distribution of the component and the press forces during forming are used as parameters to compare the simulation results with forming experiments and to validate the chosen material model.

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MS3 Advanced Material Characterization Using DIC and Inverse Methods

MS3-1

Inverse yield locus identification using a biaxial tension apparatus with link mechanism and displacement fields

Sam Coppieters, Hakoyama Tomoyuki, Dimitri Debruyne, Susumu Takahashi, Toshihiko Kuwabara

The main impetus for this work is the reduction of experimental work associated with yield locus identification of sheet metal through homogeneous tests. Inverse identification strategies have been devised to simultaneously extract a number of model parameters from an experiment leading to non-uniform stress and strain fields. Amongst them, the Finite Element Model Updating (FEMU) technique is probably the most intuitive approach for which conclusive proof of concept can be found in literature. A thorough understanding, however, of the key FEMU-ingredients and their impact on the identification of plastic anisotropy of sheet metal is currently missing. This paper scrutinizes via a virtual heterogeneous experiment the impact of the number and spreading of load steps, the boundary conditions and DIC settings on the identification of the yield locus.

MS3-2

Development of new experimental test for sheet metals through-thickness behaviour characterization

Attilio Lattanzi, M Rossi, A Baldi, D Amodio

The present work proposes a new testing system to evaluate the through-thickness shear behaviour of anisotropic sheet metals, that can be employed in identification methods such as the Virtual Fields Method (VFM) and the Finite Element Model Updating (FEMU). In fact, only the planar components of anisotropy are usually considered due to assumption of plane stress condition, and the through-thickness shear behaviour can be relevant in the prediction of failure models and plastic instabilities in such industrial applications where localized shear occurs during metal forming processes. The new experimental protocol is based on the application of Unnotched Iosipescu test to large strain plasticity, using DIC for the thickness surface displacement measurement. Here, a first configuration of the experimental set-up is tested employing specimens obtained from S355 steel blank. Then, the test performed is used to identify the anisotropy shear parameter in the thickness plane of constitutive model Hill48 via FEMU method.

MS3-3

Application of the Virtual Fields Method to determine dynamic properties at intermediate strain rates

Jin-Hwan Kim, Jin-Seong Park, Frederic Barlat, Fabrice Pierron

Crash analysis simulation is now very important in automotive industry to assess automotive crashworthiness and safety. In order to acquire reliable crash simulation results, precise material behaviors at intermediate strain rates should be used as input data. To determine the stress-strain curves at various strain rates, the number of expensive and complicated experiments is large. The present study aims at determining the stress-strain curves of sheet metals at various strain rates from a single dynamic experiment. A new type of high speed tensile tester for sheet metal specimens was built and high speed tensile tests were carried out. Full-field heterogeneous strain fields were measured by a digital image correlation technique using a high-speed camera. The load data was acquired from strain gauges attached to the elastic deformation region on the specimen. Then, an inverse identification scheme with a rate dependent hardening law was applied to retrieve dynamic parameters. The stress-strain curves of advanced high strength steel at intermediate strain rates (100 /s - 300 /s) were successfully obtained from a single experiment.

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MS3-4

Enhancing the hydraulic bulge-test using full-field DIC data

Marco Rossi, Attilio Lattanzi, Dario Amodio

The bulge test is an important experimental technique to identify the properties of materials and, in particular, metals. One of the main advantages of such technique, in testing metals, is the possibility of reaching high levels of deformation before fracture. For instance, a tensile test allows to evaluate the hardening curve only up the occurrence of necking, i.e. at the maximum force in the load vs. displacement curve. A bulge test can be performed using mechanical punches or the hydraulic pressure of a fluid. When hydraulic pressure is used, the test is not affected by friction. The hydraulic bulge test (HBT) is therefore a very efficient method to evaluate the properties of metals at large strains. Usually, the outcome of the HBT is the hardening curve in the equi-biaxial stress state that occurs at the top of the dome, during the expansion. In order to obtain the stress value is important to measure the curvature of the dome, this involve a second derivative of the vertical displacement field that can lead to measurement errors, especially if an optical technique is used to obtain the shape of the bulge. If DIC is employed as full-field measurement technique to evaluate the displacement and the strain field of the sheet metal during the HBT, only few measurement points in the center of the dome are actually used in the evaluation of the stress-strain curve. Accordingly, there is a large part of information that is not used in the identification procedure In this paper, the whole full-field measurement is exploited to derive the hardening behavior using an adaptation of the Virtual Fields Method (VFM). Suitable virtual fields are used to write the equilibrium equation in a large zone of the sheet metal during the test. All the strain data measured with DIC in such zone are then used in the identification procedure. The method is illustrated through simulated experiments on stainless steel sheet metals.

MS3-5

Prediction of mechanical properties on large diameter welded pipes through advanced constitutive modelling

Steven Cooreman, Philippe Thibaux, Martin Liebeherr

Large diameter welded pipes are amongst the most cost effective transportation means for oil and gas. In general, one can differentiate between longitudinally (LSAW) and spirally welded (HSAW) pipes, whereby LSAW pipes are produced from plate and HSAW pipes from coil. Pipe forming involves several cold forming steps, such as (cyclic) bending and (mechanical) expansion. Obviously, the mechanical properties on pipe differ from those of the base material. Detailed understanding of how the mechanical properties evolve during pipe forming would help steel mills to target specific base material properties to ensure the final pipe strength. Therefore, an FE (Finite Element) model, capable of simulating different pipe forming processes, was developed using the commercial FE software Abaqus. Thereby, an advanced constitutive model, accounting for isotropic, kinematic and distortional hardening was implemented via a UMAT user subroutine. A reverse engineering strategy was applied to calibrate the constitutive model. The model was then used to simulate spiral pipe forming of a 28” x 16mm HSAW pipe.

MS3-6

Verification of accuracy of yield functions of sheet steels under shear strains in uniaxial tensile tests in multiple directions

Akinobu Ishiwatari, Kana Yamamoto, Yasuhiro Kishigami, Jiro Hiramoto

Sheet steels have more or less plastic anisotropy. It is therefore important to consider the anisotropy of a sheet steel in FE analysis of press forming. There are many anisotropic yield functions proposed such as Hill ’48, Blart’s and Gotoh’s orthotropic yield function. These yield functions have material parameters to express the anisotropy of a sheet steel, and the parameters need to be calibrated based on r-values and stresses in tension tests in various directions, and/or stresses and strains in bulge tests or in biaxial tension tests. The accuracy of a calibrated yield function should be confirmed by using the results of another material test which is not used in the calibration. However, some functions have many parameters and need many calibration tests. A new method to check parameters of yield functions was developed making use of shear strains in a uniaxial tension test. In this study, shear strains were measured by DIC in uniaxial

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tension tests in various directions. The results, the ratios of a share strain to the tensile strain, were compared with theoretical values from the calibrated yield functions.

MS4 Forming of HCP Metals

MS4-1

Prediction of the torsional response in HCP metals

Benoit Revil Baudard, Nitin Chandola, Oana Cazacu

One of the greatest challenges that a researcher in the field of the theory of plasticity is facing is that it has to establish general mathematical relations between the stresses and strains that should be applicable to any loading, although the experimental information available is generally restricted to uniaxial tension and/or compression tests. In particular, it has been long recognized that classic yield criteria cannot accurately capture the torsional response of hcp metals. In this paper, it is shown that Cazacu et al. [1] orthotropic yield criterion, identified based on uniaxial tests, captures the unusual characteristics of the torsional response of hcp AZ31 Mg. Furthermore, for the first time, on the basis of the same criterion, it is predicted the shape of the yield surface of this material for combined tension-torsion and combined compression-torsion loadings. Most importantly, it is shown that from the analysis of the stress-strain responses in a few very simple mechanical tests, using this criterion one can predict whether axial strains develop in torsion.

MS4-2

A mechanism-driven plasticity model for deformation by glide and twinning and its application to magnesium alloys

Dirk Steglich, Jacques Besson

The plastic deformation of two different rolled magnesium sheets (AZ31 and ZE10) under quasi-static tensile and compressive loading conditions at room temperature is studied. Beside glide by dislocation motion, deformation twinning leads to evolving flow stress asymmetry and evolving plastic anisotropy in these alloys. These mechanisms cause a significant change in the shape of the yield surface. A phenomenological plasticity model in which the primary deformation mechanisms, slip and (extension) twinning, are treated separately is developed here and incorporated in the finite element framework. Deformations caused by these mechanisms are modelled by a symmetric and an asymmetric plastic potential, respectively. The hardening functions are coupled to account for the latent hardening. The necessary input for model parameter calibration is provided by mechanical tests along different orientations of the rolled sheets. Tensile tests of flat notched samples and shear tests of sheets are furthermore incorporated in the parameter optimisation strategy, which is based on minimising the difference between experimental behaviour and FE result. The model accounts for the characteristic tension-compression asymmetry and the evolution of strain anisotropy. Both, the convex-up and the concave-down shaped stress-strain response are predicted. The method is further probed on the simulation of forming operations.

MS4-3

Crystal plasticity analysis of anisotropic deformation behavior of porous magnesium with oriented pores

Tsuyoshi Mayama, Masakazu Tane, Yuichi Tadano

Numerical calculations for porous magnesium with cylindrical oriented pores showed significant influences of active deformation modes in magnesium (Mg) on distinctive “two-stage deformation behavior” during compression. Calculated results also imply that larger grain aspect ratio results in better energy absorption efficiency.

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MS4-4

Slip activity in a CP-Ti oligocrystal : numerical study and comparison with experiments

Pierre Baudoin, Takayuki Hama, Hirohiko Takuda, Sohei Uchida

In recent years, direct comparisons between simulations and experiments dedicated to test samples containing a small number of grains (oligocrystals) instrumented using full field measurements techniques (DIC, grid method) have proved fruitful to investigate and accurately reproduce the behavior of BCC and FCC crystals. The extension of this approach to HCP metals and CP-Ti in particular is the objective of the present work. The deformation behavior of a grade 2 CP-Ti material is investigated numerically, by comparing the predictions of strain field in a 32 grains oligocrystal loaded in tension with experimental results. It is found that the set of constitutive parameters identified by the authors in a previous study [Hama et al., Int. J. Plast., 2017(91), 77] reflects the experimental behavior satisfactorily for strain fields.

MS4-5

Effect of deformation twinning on forming limit analysis of polycrystalline magnesium

Yuichi Tadano

A formability assessment using the crystal plasticity model is conducted to investigate the effect of deformation twinning on the formability of polycrystalline magnesium sheet. For presenting the polycrystalline behaviors of magnesium, the homogenization-based finite element method is introduced, and the Marciniak-Kuczyńsk type sheet necking analysis is demonstrated. Two kinds of deformation twinning model, i.e., the asymmetric slip type and van Houtte's models are adopted, and the effect of those models on the forming limit analysis is numerically discussed. It is revealed that the lattice reorientation due to deformation twinning plays an important role in plastic flow localization of magnesium, while shear deformation caused by deformation twinning has an insignificant effect.

MS4-6

Experimental and numerical study of the inelastic behavior of magnesium alloys during cyclic loading-unloading

Huamiao Wang, Ding Tang, Dayong Li, Yinghong Peng, Peidong Wu, Jian Wang

Magnesium alloys exhibit significant inelastic behavior during unloading, especially when twinning and detwinning are involved. It is commonly accepted that noteworthy inelastic behavior will be observed during unloading if twinning occurs during previous loading. However, this phenomenon is not always observed for Mg sheets with strong rolled texture. Therefore, the inelasticity of AZ31B rolled sheets with different rolled textures during cyclic loading-unloading are numerically investigated by elastic viscoplastic self-consistent polycrystal plasticity model. The incorporation of the twinning and detwinning scheme enables the treatment of detwinning, which plays an important role for inelastic behavior during unloading. The effects of texture, deformation history, and especially twinning and detwinning on the inelastic behaviors are carefully investigated and found to be remarkable. The simulated results are in good agreement with the available experimental observations, which reveals that the inelastic behavior for strongly rolled sheets is very different than that for extruded bars.

MS5 Advances in Multiscale-Modeling of the Effect of Anisotropy in Forming

MS5-1

Yield locus prediction using statistical and RVE-based fast Fourier transform crystal plasticity models and validation for drawing

Albert Van Bael, Panagiotis Seventekidis , Marc Seefeldt , Dik Roose , Fengbo Han , Franz Roters , Piet Kok

A methodology is presented to predict yield loci of drawing steels with virtual mechanical tests using (i) the statistical ALAMEL crystal plasticity model (VEF software of KU Leuven) and (ii) an approach based on representative volume elements (RVE's) solved with a spectral numerical Fast Fourier Transform (FFT) technique (DAMASK software of MPIE). In the latter case, the RVE's are defined in the form of a regular mesh of grid points in 3D-space with a crystal orientation assigned to each grid point. The experimental texture is derived from XRD pole figure measurements. Only tensile curves in the rolling direction are used to calibrate the hardening model included in the crystal plasticity models. For an interstitial free steel the

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predictions are compared to experimental yield loci, as obtained from uniaxial tests, plane strain tests, shear tests and through-thickness compression tests. Analytical FACET yield loci are calibrated to the crystal plasticity (CP) models and these are used in FE simulations of a square cup deep drawing process, validated by experiments.

MS5-2

Anisotropic yield criteria

Oana Cazacu

The most widely used isotropic yield criteria are defined in terms of the principal values of the stress deviator. In this paper, it is demonstrated that these yield criteria are expressible as polynomials in terms of the second and third invariants of the stress deviator. Using these new mathematical results, new, simple and explicit expression of Yld91 and Karafillis and Boyce [1] orthotropic yield criteria in terms of stress components are obtained. Moreover, it is shown that for orthotropic BCC materials, Yld 91 and Karafillis and Boyce [1] criteria are particular forms of Cazacu and Barlat [2] orthotropic yield criterion.

MS5-3

Study on the influence of orthotropy and tension–compression asymmetry of metal sheets in springback and formability predictions

Marta C. Oliveira, Pedro D. Barros, Diogo M. Neto, José L. Alves, Luís F. Menezes

Most yield criteria possess a point-symmetry with respect to its center, meaning that a stress state and its reverse state have the same absolute value. However, this can be an unrealistic approximation, even for cubic metals (both face-centered cubic and body center cubic)), which can present a small asymmetry between the yield stress in tension and compression, i.e. a strength differential (SD) effect. This work analyzes the influence of taking or not into account the SD effect in the modeling of the sheet orthotropic behavior in the numerical simulation of a cylindrical cup drawing process. The yield criterion adopted is the CPB06 [1], including its version with two linear transformations [2], allowing a better fitting of the experimental data available. The material analyzed presents a quite small tension-compression ratio of 0.963. However, this small SD effect leads to a slightly higher punch force during the bending dominated stage, resulting in a very small influence on the springback prediction. The influence on the thickness evolution during the process is negligible.

MS5-4

Plastic deformation of metallic materials during dynamic events

Benoit Revil Baudard, Oana Cazacu, Geremy Kleiser, Nitin Chandola

Recently, fully implicit computational capabilities have been developed to predict the plastic behavior of metallic materials (i.e. Ti, Mo) during dynamic events. It is to be noted that within this formulation framework, the equilibrium equations are solved for each time increment. The couplings of the numerical framework to the Cazacu et al. [1] plasticity model that accounts for all the key features of the plastic behavior of airframe materials, i.e. the tension-compression asymmetry and the orthotropic behavior, results in high fidelity prediction of the mechanical behavior during dynamic events. The improved predictive capabilities have been assessed for different strain rate conditions and different metallic materials. Furthermore, validation of the models and FE formulation for Taylor impact conditions through comparisons of experimental deformed profiles of Taylor specimens for Ti and Mo has been done. It is worth noting that for the first time, the extent of the zone of plastic deformation, change in geometry and the transition from transient to quasi-steady plastic wave propagation was captured with great fidelity. Furthermore, the model was used to gain understanding of the dynamic deformation process in terms of time evolution of the pressure, the extent of the plastically deformed zone, distribution of the local plastic strain rates, and when the transition to quasi-steady deformation occurs for different dynamic events. It was thus shown that this model has the potential to be used for virtual testing of complex systems.

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MS5-5

Prediction of four, six or eight ears in drawn cups of single-crystal aluminum sheets

Nitin Chandola, Oana Cazacu, Benoit Revil-Baudard

The new single crystal criterion developed by Cazacu, Revil and Chandola (2017) was implemented in a finite-element (FE) code and applied to forming of single-crystal cups of aluminum. Drawing simulations were conducted for circular single-crystal blanks of three different orientations:{100}〈001〉, {111 }〈1-10〉 and{112}〈1-10〉 using the same set of parameters for the single-crystal yield criterion. A strong influence of anisotropy (single-crystal orientation) on the earing profile is found. While for the{100}〈001〉 orientation it is predicted that four ears develop, for the {111 }〈1-10〉 and {111 }〈1-10〉 crystal orientations six and eight ears are predicted, respectively. The FE simulation results are consistent with experimental observations of Tucker (1961).

MS5-6

On the usage of a grain size sensitive crystal plasticity model in the spectral solver framework

Sebastian Hirsiger, Bekim Berisha, Christian Raemy Pavel Hora

Prediction of the yield loci based on crystal plasticity material models in combination with an efficient solver, the FFT-based spectral solver, is the main focus of this study. Results of the CP-based yield locus modeling are compared with the well-established macroscopic model YLD2000-2d for various materials; steel as well as aluminum alloys. For this purpose, uniaxial tensile tests in various directions as well as biaxial tests were performed. Further, the influence of grain size in crystal plasticity simulations is often neglected due to the fact that most grains are assumed to have similar size or the influence of grain size is directly mapped within material parameters. For materials containing significantly different grain sizes, this approach does not apply and therefore, a suitable model for crystal plasticity laws is needed. In the framework of this research, an adapted Hall-Petch phenomenological model is implemented in the crystal plasticity open-source code DAMASK. The spectral solver in combination with the phenomenological constitutive laws allows computing of numerical results in short time, which is a key factor for the development of new materials and industrial research.

MS5-7

Prediction of negative bulge in two point incremental forming of an asymmetric shape part

Mihaela Banu, Jaekwang Shin, Ankush Bansal, Randy Cheng, Maya Nath, Alan Taub, Brian Martinek

The bulging effect in incremental sheet forming (ISF) has been explained by the buildup of compressive stresses during forming resulting in the material at the center to bulge inward or outward. In this study, effect of step size on the formation of a bulge in an asymmetric shape in two point incremental forming (TPIF) is examined. Experimentally validated finite element models were developed to simulate the forming at both the macro scale, and using a finer mesh to generate the surface profile. The formation of the bulge is determined to be due to a combination of compressive stresses and an instability created by the material in the underformed area during the forming operation.

MS5-8

Prediction of tensile deformation behavior of Al-Li alloy 2060-T8 by computational homogenization-based crystal plasticity finite element method

Ali Abd El-Aty, Sangyul Ha, Shihong Zhang, Yong Xu

In current study, a computational homogenization-based crystal plasticity (CP) modelling was presented to determine the deformation behavior of a novel third-generation ALLi alloy 2060-T8 at room temperature, strain rate of 0.01 s^{-1} and various loading directions. The computational homogenization strategy used a representative volume element (RVE) which describes the real microstructure of AA2060-T8 sheet to consider the in-grains deformation behavior. Besides, a periodically boundary condition was modified to consider both deformation induced anisotropy and the geometrical anisotropy. The initial microstructures and microtextures of the AA2060-T8 sheet were determined by EBSD measurements, as well as used to build up the RVE model. The material parameters used in CP modelling was determined from the stress-strain curve obtained from the tensile test at strain rate of 0.001 s^{-1} and loading direction of 30° with

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reference to rolling direction. The results obtained from computational homogenisation strategy keep a remarkable agreement with the results determined from experimentation. In conclusion, the computational homogenization based CPFEM is able to predict the deformation behavior and capture the anisotropic response of AA2060-T8 sheet at various deformation conditions. The results determined from computational homogenisation keep a remarkable agreement with the results obtained from experimentation. In a conclusion, the computational homogenization based CPFEM is able to predict the deformation behaviour of the AA2060-T8 alloy at different forming conditions and illustrate the ability to capture the anisotropic mechanical response.

MS5-9

A multiscale model to incorporate texture evolution into phenomenological plasticity models

K Inal, CP Kohar, JL Bassani, RK Mishra

Crystal plasticity is a micromechanics-based model that is regularly used to simulate plastic spin during large deformation. Although crystal plasticity can provide an accurate description of local deformation behaviour, it is often computationally expensive and usually replaced by flow rule-based phenomenological models that do not capture this phenomenon. This work presents a phenomenological-based texture evolution (PBTE) model that allows for the enhancement of flow rule-based models to capture microstructural spin in a phenomenological manner. A numerical framework is presented for generating and calibrating the microstructural evolution for the PBTE model using crystal plasticity. The PBTE Model is calibrated and employed to predict the macroscopic mechanical response and the generated microstructural spin for single crystal FCC cube during non-proportional strain paths.

MS6 Sheet Metal Formability: in honor of Prof. Marciniak’s 100-year anniversary

MS6-1

Experimental and numerical investigations on determination of strain localization in sheet forming

Dorel Banabic, Dmytro Lumelskyj, Lucian Lazarescu, Jerzy Rojek

This work presents results of investigations on the determination of strain localization in sheet forming. Nakajima formability test has been chosen for the experimental studies and numerical analysis. The onset of localized necking has been determined using the criteria studied in the authors' earlier works, based on the analysis of the principal strains evolution in time. The first criterion is based on the analysis of the through-thickness thinning (through thickness strain) and its first time derivative in the most strained zone. The limit strain in the second method is determined by the maximum of the strain acceleration. Limit strains obtained from these criteria have been confronted with the experimental forming limit curve (FLC) evaluated according to modified Bragard method used in the ISO standard. The comparison shows that the first criterion predicts formability limits closer to the experimental FLC and second method predicts values of strains higher than FLC. These values are closer to the maximum strains measured before fracture appears in experiment. These investigations show that criteria based on the analysis of strain evolution used in numerical simulation and experimental studies allow us to determine strain localization.

MS6-2

The performance of Marciniak – Kuczinsky approach on prediction of plastic instability of metals subjected to complex loadings

Gabriela Vincze, Marilena Butuc

The objective of the present paper is to analyse the performance of Marciniak-Kuczinsky (MK) theory on the prediction of formability of sheet metals subjected to complex loadings. Advanced constitutive equations taking into account isotropic and anisotropic hardening are applied to describe the material mechanical behaviour under linear and complex loadings. A comparative study on their accuracy on predicting the forming limits for the studied material is performed. Two deep-drawing quality sheet metals are selected. Several strain path changes are taken into account. A good agreement between the theoretical and experimental results was obtained. MK theory is an efficient and valuable tool on the

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prediction of plastic flow localization of sheet metals under complex loadings when proper constitutive equations are used.

MS6-3

Phenomenological model for prediction of localised necking in multi-step sheet metal forming processes multi-step sheet metal forming processes

Klaus Drotleff, Mathias Liewald

Prediction of localised necking is crucial for cost, time and material efficient production of sheet metal components. Especially in multi-step forming operations, nonlinear strain paths occur due to complex part and tool geometry as well as changing loading conditions during the forming process. Today, prediction of localised necking for such components is often based on empirical knowledge of experienced forming specialists or specialised damage models particularly related to sheet metal materials. It is well known, that calibration of such damage models can be difficult, particularly for industrial applications. The model presented in this paper is a phenomenological approach for prediction of localised necking under varying loading conditions which is easy to calibrate. For the calibration procedure only 36 uniaxial tensile tests are needed. The model calibration and failure prediction was carried out for DP600 material with sheet thickness of 0.98 mm. An experimental forming component manufactured in three forming operations was used for validation of the model presented. Mathematical setup of the model, simulation approach as well as a comparison between numerical and experimental results will be given.

MS6-4

Evolution of plastic anisotropy and strain rate sensitivity

Junhe Lian, Fuhui Shen, Sebastian Muenstermann

In this study, it is aimed to formulate a constitutive model accounting for the evolving features of the plastic anisotropy, in terms of both stresses and r-values, and the strain rate sensitivity during the plastic deformation. For the model calibration and validation, a bcc ferritic steel is selected. The material parameters are calibrated by tensile experiments under different loading configurations and different strain rates. Nakajima tests are conducted to characterise the cold formability of the selected steel. The model prediction is compared with the experimental results and it is concluded that the formability prediction is significantly improved when considering the evolving features during the plastic deformation.

MS6-5

Multi-stage two point incremental sheet forming

Kai Han, Xiaoqiang Li , Dongsheng Li

In incremental sheet forming, the thickness of parts decreases with the sine law as the forming slope increases, resulting in serious thinning or even fracture of parts. For industrial products, extreme thinning of parts can not meet the design requirements, seriously affecting the application of incremental sheet forming in the industrial field. Multi-stage incremental sheet forming is found to effectively improve the thickness distribution of parts. For multi-stage two point incremental sheet forming, there are a great variety of multi-stage strategies, such as parallel linear tool-path strategy, parallel arcs tool-path strategy, variable angle straight lines tool-path strategy, and stretch-bend assist multi-stage strategy. However, which multi-stage strategy is the best multi-stage strategy is not conclusive. Therefore, in this paper, a square cone is selected to analyse the influence of tool-path strategy on thickness distribution. Then, the best multi-stage strategy is obtained by comparing the thickness distribution with different strategies. Finally, by analysing the change of strain condition with an increase in stage, the causes of different strategies for increasing the thickness distribution are obtained.

MS6-6

A microstructure based modelling of high strength steel sheet under stretch-bending

K. Achineethongkham, P. Thanakijkasem, V. Uthaisangsuk,

In the automotive industry, advanced high strength (AHS) steel sheets are widely used for various structural and safety parts in car body. Such AHS steels exhibit complex microstructures containing different phase constituents. The yield and tensile strength of these steel sheets are significantly increased, but the

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formability is very restricted due to earlier occurred local damages. Their fracture behaviours are thus strongly governed by the microstructure characteristics and interplays between various phases. Besides, the forming processes of AHS parts mostly showed a non-linear strain history, for which the conventional forming limit curve (FLC) could not be properly applied. In this work, stretch-bending tests were carried out for the AHS steel sheet grade 980 after subjected to different pre-strains. FE simulations on the micro-scale of the forming experiments were performed by using 2D representative volume element (RVE) model, which was generated from the real microstructure of examined steel. Hereby, local crack occurrences in the microstructure of steel were described. Furthermore, the FE results by using isotropic and kinematic hardening law were compared. Finally, the bending limits of steel grade 980 after varying pre-strains were predicted.

MS6-7

Prediction of the formability limit using damage mechanics

Gianluca Iannitti, Andrew Ruggiero, Nicola Bonora, Gabriel Testa, Domenico Gentile

Forming limit diagrams (FLD's) are used to evaluate the workability of metal sheets. These diagrams provide the failure locus at which plastic instability occurs and localized necking develops (commonly designated as the forming limit curve - FLC), and the failure loci at the onset of fracture by tension or by in-plane shear. In this work, the possibility to predict the FLD's using damage mechanics is presented. Following the approach proposed by Lemaitre [1], the fracture forming limit (FFL) for ductile metals is theoretically derived using the extended Bonora damage model (XBDM). The XBDM is used in numerical simulation with FEM of formability tests (Nakazima and Marciniak) to demonstrate the possibility to account correctly for necking development before fracture. The proposed model prediction was validated with available experimental data for high purity copper.

MS6-8

Influence of alloy chemistry on the texture evolution and plastic anisotropy of ultra-fine grained aluminum alloys

Abhijeet Dhal, M.S. Shunmugam, S.K. Panigrahi

In the present work, cryorolling was performed on both pure Al (AA1070) and Al-Mg alloy (AA5083). Cryorolled materials were subjected to same level thermal treatment. The deformation behaviour and anisotropic properties of these materials were extracted from uniaxial tensile test results. These properties were compared for base, cryorolled and heat treated conditions for both the materials. Compared to AA1070, AA5083 shows much improved strain hardening capability. This is attributed to its lower stacking fault energy and influence of incoherent Mg solute in the Al matrix. By controlled thermal treatment substantial ductility was also regained for AA5083, without much loss in its tensile strength. This behaviour is attributed to the presence of bimodal microstructure in AA5083, consisting of ultra-fine as well as coarse grains. Due to the preservation of rolling texture even at high annealing temperature, the anisotropic properties were also found to be much favourable in case of AA5083.

MS6-9

Toward development of optimum specimen designs and modeling of in-plane uniaxial compression testing of aluminum alloy 2024 and AISI 1008 steel sheet material

DK Banerjee, CA Calhoun, MA Iadicola, WE Luecke, TJ Foecke

Tension-compression testing is commonly conducted to understand and predict springback during a stamping process. However, large strains are generally difficult to achieve during the in-plane compression portion of the test. Proper specimen design and control of frictional forces are necessary for obtaining large strains. This paper describes extensive finite element analyses (FEA) and optimization studies (Phase 1) that were conducted to calibrate the model test assembly for three different buckling modes obtained in uniaxial compression tests of aluminum alloy 2024 and American Iron and Steel Institute (AISI) 1008 steel specimens. In addition to obtaining these three buckling modes correctly, calibrated FEA model predicted forces matched measured forces reasonably well. Also, a good agreement between computed and measured stress-strain data was demonstrated for one compression experiment. In Phase 2 of the

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optimization process, optimum specimen geometries will be developed by using these verified, optimum FEA model test assemblies in three types of compression buckling experiments.

MS7 Analysis of Sheet Metal Joining and Welding Phenomena

MS7-1

Simulation of fatigue crack growth in weld joint of thin structures using characteristic tensor

Hidekazu Murakawa

It is known that fatigue life of welded structures, such as automotive and ship structures, is greatly influenced by welding residual stress. In case of real structures, the orientation of the stresses produced by static load and that produced by repeated load and that of welding residual stress are generally different from each other and they form a highly complex multi axial stress states. On the other hand, the fatigue behaviour has been mostly studied for uniaxial stress state without residual stress. The crack growth rate is related to the stress intensity factor range DK such as in the Paris Low [1]. To predict the fatigue behaviour of real welded structures, the three dimensional stresses produced by static load, repeated load and welding must be rationally correlated with a scalar value DK . The author proposes a Characteristic Tensor which characterizes the singular stress field at crack tip and its invariant parameters, such as principal values or invariants which has similar form as strain energy density, are used to compute DK in a consistent manner. Its potential usefulness is demonstrated through simple examples.

MS7-2

The corrosion behavior of cold spray coating on 2219 aluminium alloy joints prepared by friction stir welding

Hua Zhang, Changyu Zhao, Bing Cui, Xuemei Yan, Chengliang Dou, Tongge Shao, Rui Pan

A compact coating was deposited on the surface of a friction stir welded 2219-T6 aluminum alloy joint via cold spraying for corrosion protection. The results showed that a relatively dense coating could be formed in the FSW joint surface. Corrosion resistance of the coating is pretty good with the average discharge potential of -0.638 V (vs. SCE) and corrosion current density is 7.034 $\mu A \cdot cm^{-2}$. Immersion tests in the exfoliation solution confirmed that the presence of coating significantly decreased the corrosion attack. The corrosion of coating begins with pitting, which is mainly at the coating porosity. It gradually developed into the intergranular corrosion and exfoliation corrosion ultimately.

MS7-3

Study on keyhole and melt flow behaviors of laser welding of aluminum under reduced ambient pressures

G C Peng, L Q Li, H B Xia, J F Gong

Laser welding of aluminum alloy under reduced ambient pressure can produce less porosity defects. In this paper, the effect of reduced ambient pressures on porosity was investigated by a combination of experimental and numerical method. A novel numerical model was proposed to describe the keyhole and melt flow behaviors under reduced ambient pressures. Numerical results showed that, compared with atmospheric pressure, reduced ambient pressure would produce a more stable keyhole. The vortex of melt flow in molten pool became unapparent and even disappeared under reduced ambient pressures. The flow velocity of the melt on the keyhole wall became faster under reduced ambient pressures. The difference between boiling point and melting point decreased under reduced ambient pressure, which made a contribution to the formation of a thinner keyhole wall and hence improved the stability of keyhole. Higher recoil pressure would be produced under reduced ambient pressures, which was responsible for the weakened vortex and enhanced melt flow velocity. The formation of porosity during laser welding process could be effectively inhibited based on the above combined effects.

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MS7-4

Effect of different coatings on the weldability of Al to steel

Junhao Sun, Zhuguo Li, Jian Huang, Rui Cao

The influence of different coatings on the weldability of Al/steel was assessed in this study. Different kinds of the coatings, which included pure zinc coating, Fe-Zn coating and without coating, were considered. The thickness of the coating was also studied. Different configuration of overlap and butt joint was used, and different welding methods including cold metal transfer (CMT) welding-brazing and laser welding-brazing with filler metal were investigated. Samples were fabricated and the weld appearance, microstructure and composition analyses of the joints were examined. It was found that the Al to steel without coating could not be welded due to the formation of large amount of brittle Fe-Al intermetallic compounds (IMC). The coating helped suppress the formation of IMC and a welding-brazing joint was produced. However, pure Zn coating enhanced the wetting of molten filler onto the solid steel substrate, but Fe-Zn coating barely enhanced the molten filler to wet the steel substrate. The coating with a thickness of 10-20 µm contributed to a better performance of Al/steel joint.

MS7-5

Simulation of welding thermal conduction and thermal stress using hybrid method of accelerated explicit and implicit FEM

Ninshu Ma, Kunio Narasaki

A hybrid method combining the accelerated explicit and the implicit FEM was developed for simulation of welding thermal stress. Furthermore, to reduce the computing time and keep the simulation accuracy, the hybrid modelling using solid elements around the welded zone and shell elements in the zone away from the welded zone is recommended. The applications of hybrid method and hybrid modelling to the simulation of welding thermal conduction, thermal stress and strain showed a good efficiency.

MS7-6

Numerical simulation of thermal supported self-pierce riveting of an ultra high-strength aluminium alloy

M Jäckel, S Maul, C Kraus, W-G Drossel

This paper will describe the experimental and numerical analysis of the thermal supported self-pierce riveting process of EN AW-6016 T4 into EN AW-7075 T6. In this regard, the experimental process analysis, the development of the simulation model and the evaluation of the FE simulation are discussed.

MS7-7

Numerical simulation and analysis of metal fused coating forming

Siyuan Xu, Zhengying Wei, Jun Du, Guangxi Zhao, Wei Liu

3D printing has been widely used for the forming of functional parts, and electron beam and laser are used as the heat source mostly, which is expensive and energy consuming [1]. Metal Fused coating process is a developing additive manufacturing technology, the high power heat source is eliminated and the material is not confined to powder and wire [2]. In this paper, computational fluid dynamics method [3] combined with fluid volume method are used to study the influence of process parameters on coating and morphology. Considering the material’s thermal physical properties change with temperature, the temperature history of feature positions and three-dimensional morphology are analysed. It is found that the differences of the melt spreading temperature histories of three key positions increase with the printing speed. The influence rules of different layer thickness and ratios of feeding speed to nozzle moving speed on bonding width, single-layer width and the ratio of bonding width to single-lane width are gained, which provides guidance to select the parameters in given process conditions.

MS7-8

Coupling analysis of molten pool during fused coating process with arc preheating

Guangxi Zhao, Jun Du, Zhengying Wei, Ruwei Geng, Siyuan Xu

Fused coating process with arc preheating is a new developing additive manufacturing technology. In addition to the high efficiency and low cost, it solves the spread difficulty of lightweight alloys such as

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aluminum alloy. In this paper, separating and coupling effect of driving forces exerted on weld molten pool caused by the arc is analyzed. Evolution of temperature field and flow field is described in detail. It is found that the magnitude order of the force's influence is surface tension>arc pressure> Lorenz force>drag force>buoyancy force. With the increase of the molten pool depth, the influence of the Lorentz force gradually increases and exceeds the surface tension at the bottom of the molten pool. Heat and mass transfer between the molten pool and externally added liquid metal is also calculated. External liquid metal rapidly flows into the molten pool at the moment of contact under the influence of surface tension and molecular affinity. Weld pool size and single pass morphology are measured and compared with the numerical simulation results to verify the accuracy of the model, and it turned out that the dimensional errors are all less than 10%.

MS7-9

An adaptive-domain-growth method for phase field simulation of dendrite growth in arc preheated fused-coating additive manufacturing

R W Geng, Z Y Wei, J Du, G X Zhao

A quantitative phase field (PF) model with adaptive-domain-growth method was developed to investigate the dendrite growth of the arc preheated fused-coating for 2024 aluminum alloy. A macroscopic numerical model was established to provide the solidification parameters of the molten pool. These solidification parameters such as temperature gradient, solidification speed were calculated from the macroscopic model and then fed into the phase field model to get the microstructure. Columnar dendrites can be found at the bottom of molten pool. Moreover, the micro segregation of Al-Cu alloy in arc preheated fused-coating process was studied by simulated and experimental results. The adaptive-domain-growth method is developed in phase field simulation which can improve the efficiency about 50%. The Electron Backscattered Diffraction (EBSD) and Energy Dispersive Spectrometer (EDS) tests were conducted on the fused-coating specimen, and the results were in good accordance with the simulations.

MS7-10

Interaction of laser beam, powder stream and molten pool in laser deposition processing with coaxial nozzle

Liqun Li, Yichen Huang

Powder-based laser deposition technology has widely used for parts coating, repairing and additive manufacturing. The quality and efficiency of laser deposition largely depends on the powder stream controlling. For some special laser deposition processing, such as ultra-high-speed laser cladding, inside laser cladding, FGM (Functionally Graded Materials) and MMC(Metal Matrix Composite) coating or parts manufacturing, the power stream controlling become more complex, because the powder melting behaviour is changed and varying proportion mix powder is used. In order to achieve the best feeding properties and highest powder efficiency aiming to different application requirement, the optimization of the nozzle geometry and controlling of powder flow are quite necessary. For this purpose, a comprehensive numerical model is developed to study the powder flow of coaxial nozzles, which include powder stream spatial distribution, flow rate, and trajectory. The powder stream convergence characteristics for different laser deposition application, and the interaction between laser beam, powder stream and molten pool are studied by numerical and experimental methods. The nozzle geometries, powder properties, and shield gas setting are optimized based on the understanding of the powder concentration distribution.

MS7-11

The effect of sheet metal anisotropy on the calibration of an equivalent model for clinched connections

A Breda, S Coppieters, T Kuwabara, D Debruyne

Clinching is a mechanical joining technique that involves severe local plastic deformation of two or more sheet metal parts using a punch and die. The local deformation results in a permanent mechanical interlock. It is widely applied as a reliable joining technique in automotive, heating, ventilation, air conditioning (HVAC) and general steel constructions and is still gaining interest. In FEA models of structures containing a

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large number of clinched joints, it is not computationally feasible to use detailed sub models of the joint. Therefore an equivalent model was proposed by Breda et al. to predict the force-displacement behaviour. This equivalent model was calibrated using a simple shear-lap and pull-out test. During the calibration step, some local effects due to the material properties are captured in the calibration parameters. This paper investigates the impact of the plastic material properties on this calibration method. The effect of strain hardening due to the bending process prior to pull-out testing, potential plastic anisotropy of the base material and their relation to the calibration parameters are investigated. This research has been validated with experimental results on mild deep drawing steel.

MS7-12

Welding distortion prediction and process optimization of turbine component by electron beam welding

Yichen Huang, Liqun Li, Bo Pan

A turbine component with 130 blades requests high dimensional precision to ensure the assembly requirements. The dimensional precision is significantly influenced by welding distortion. In this research work, welding distortion in the turbine component by electron beam welding was predicted through elastic finite element method based on inherent strain theory. The inherent strains of single blade welding joints with different welding process and fix condition were obtained through thermal elastic plastic finite element method calculation. The simulation results indicated coherence between the predicted and measured distortion value. The final welding distortion of turbine component in different assembly sequences were compared, by utilizing the inherent deformations of optimized single blade welding joints simulation. An optimized welding procedure and assembly sequence was proposed to reduce the welding distortion. The results verify that 180-degree symmetrical welding can significantly reduce the plastic deformation.

MS7-13

Numerical simulation and experimental validation of self-piercing riveting (SPR) of 6XXX aluminum alloys for automotive applications

Florian Hönsch, Josef Domitner, Christof Sommitsch, B Götzinger, M Kölz

Two-dimensional axisymmetric models of the self-piercing riveting (SPR) process consisting of punch, blank holder, die, rivet, upper blank and lower blank were built using the finite element software package simufact.formingTM. Three different joint configurations were modelled. An optical measurement system was used for capturing the actual geometries of both the die and the rivet which were then introduced into the simulation model. The stiffness of the riveting pliers was modelled as numerical spring. A combined model of Coulomb friction and shear friction was applied. Both friction coefficients were determined by inverse modelling. The deformation behaviour of the 6xxx aluminium alloy blanks to be joined was described with flow curves extrapolated from results of uniaxial tensile tests. In order to validate the results of the simulations self-piercing riveting experiments using 6xxx aluminium alloy blanks and coated steel rivets were conducted. Force-displacement curves of the punch were captured during the riveting process. Characteristic geometrical features of cross-sections of these joints including horizontal undercut of the rivet, bottom thickness of the lower blank and rivet head overlap were investigated using optical microscopy. The cross-sections of the self-piercing riveting joints obtained from simulations and experiments showed very good geometrical agreement, and just slight differences were observed between the force-displacement curves.

MS7-14

Investigating the influence of external restraint on welding distortion in thin-plate welded structures by means of numerical simulation technology

Dean Deng, Wei Liang

Welding-induced deformation not only degrades the fabrication accuracy of a welded structure but also decreases the productivity due to correction work. Accurate prediction of welding distortion will be helpful in controlling the dimension accuracy. In this study, the main objective is to clarify the influence of external

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restraint on welding distortion in three different thin-plate steel welded structures by means of numerical simulation technology. A two-step computational approach was employed to simulate welding distortion in each welded structure. In the first step, the thermal elastic plastic finite element method (T-E-P FEM) was used to obtain inherent deformation for each typical joint. In the second step, an elastic FEM based on inherent strain theory was used to compute welding deformation for three thin-plate panels with different thickness and shape. In addition, the effects of external restraint on welding deformation in a thin-plate panel with 5 mm thickness, a thin-plate panel with 10 mm thickness, and an asymmetric curved panel with 10 mm thickness were investigated.

MS7-15

Numerical analysis on stress evolution during GTA-additive manufacturing of thin-walled aluminum alloys

Zhida Ni, Sanbao Lin, Chunli Yang, Chenglei Fan, Jianxing Shi

GTA-Additive Manufacturing (GTA-AM) is one of the Wire Arc Additive Manufacturing (WAAM) technologies based on Gas Tungsten Arc Welding (GTAW). During the GTA-AM process, non-uniform heating, as well as rapid heating and cooling of deposited materials lead to inevitable temperature stress, while repeated remelting in subsequent deposition introduces complexity to the evolution of it. Finite element modeling was conducted in this work to investigate the stress evolution during the GTA-AM of thin-walled 5183-Al. Several thin-walled 5183-Al components with different bead widths are included to understand the influences brought about by geometry dimensions. Hole-drilling method is used to measure the residual stress of 5183-Al components manufactured by GTA-AM, which proves the reliability of this numerical model. Results of modeling show that the temperature stress is generated and released alternately and repeatedly as the deposition proceeds. The cycles of equivalent stress are in synchronization with the thermal cycles, in which equivalent stress reaches peak when temperature gets to its valley value. However, as the deposition layers pile up, the peak value of equivalent stress decreases gradually, and finally achieves stability after a certain layer. As for the influences of geometry dimensions, larger bead width results in higher level of stress due to much larger heat input as well as grater constraints.

MS7-16

Modeling of process parameters and sectional shape of sample in single-layer aingle-pass Sn63Pb37 fused coating additive manufacturing

Ren Chuanqi, Xin Wang, Du J, Wei Z Y, Bai H, Zhang S

Fused coating additive manufacturing is proposed to improve forming efficiency and material utilization. The forming property of single-layer single-pass is the basis of the process. The size of the sedimentary section is the smallest feature unit which includes the layer-height and pass-width. In this paper, the Design Expert 8.0.6 software is used to design the single-layer single-pass central composite experiment. In the reasonable parameters, the quadratic regression equations between the single layer cross-sectional size and process parameters were established by performing the second regression experiments. The misalignment and significance of the quadratic regression equations were checked and the non-significant variables in the regression model equation were excluded. The quantitative influences of main forming parameters on the single-layer single-pass cross-sectional size were finally analysed in detail.

MS7-17

Research on remelting phenomena and metal joining of fused-coating additive manufacturing

X. Wang, J. Du, Z. Y. Wei, G. X. Zhao, C. Q. Ren, S. Zhang

Metal fused-coating is a novel additive manufacturing technology used to building complex components. In order to determine good metallurgical bonding between layers, a two-dimensional model was established to predict the temperature needed to promote the metallurgical bonding of multi-layer specimens. The temperature of the cladding process was tracked and measured by the thermal imaging system. The influence of heat transfer on the forming characteristics of the fusion track was studied systematically. In addition, the maximum remelting depth of the liquid-solid interface was evaluated and the interlaminar bonding state was further confirmed by the formation of three-dimensional samples and optical

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microscopy images. This work may help to develop metal fused-coating to the produce effective process control and performance prediction.

MS8 Numerical Simulation of Locally Acting Sheet Manufacturing Processes

MS8-1

Experimental and numerical analysis of the flanging process by SPIF

Gabriel Centeno

J A López-Fernández, Andres Jesus Martinez-Donaire, Domingo Morales-Palma, Carpoforo Vallellano

This paper analyses the flangeability of AA2024-T3 sheets using single point incremental forming (SPIF). With this purpose, a series of process parameters is considered including flange length and width, tool radius and spindle speed. An initial experimental campaign is carried out for the evaluation of the limiting strain states of the flanges within the material forming limit diagram (FLD). Numerical modelling through finite element analysis (FEA) is used in order to provide a better understanding of the sheets flangeability and forming conditions that either allow manufacturing or lead to failure in this process using concave dies. The capability of the SPIF process to improve formability is discussed.

MS8-2

Experiments and simulation of shape and thickness evolution in multi-pass tube spinning

Biplov Kumar Roy, Yannis P. Korkolis, Yoshio Arai, Wakako Araki, Takafumi IIJIMA, Jin Kouyama

The primary objective of this study is to predict the geometric shape and thickness change during multi-pass tube spinning to a hemispherical shape. Interrupted spinning experiments are performed at room temperature on cylinders of 6061-O aluminum alloy. The shape and thickness after 2, 4, 6 and 8 spinning passes are measured. An axisymmetric finite element model of the tube spinning experiments is described. Uniaxial tensile tests are conducted for the development of the material model. The post-necking hardening curve of the material is identified using a hybrid experimental-numerical method. The stress-strain identified in this way is fitted to a combined Swift-Voce model. The results of the simulation are compared to the interrupted spinning experiments. Good agreement is obtained on the shape evolution in multi-pass spinning. The effect of roller paths on shape and thickness change during multi-pass tube spinning targeting a hemispherical shape with uniform thickness were predicted by axisymmetric modeling and validated with experimental results.

MS8-3

Study on spinning process of thin-walled curvilinear generatrix parts based on variable thickness blanks

Yixi Zhaon, Leitao Gao, Jinlong Song, Shuhui Li, Hao Wang

Large thinning ratio is a difficulty in spinning process of ellipsoid components, which needs to be solved to ensure the accuracy of parts. Based on the method of reverse deformation, two different variable thickness blanks were designed: (1) variable thickness blank based on thickness reduction of the conventional spinning process; (2) variable thickness blank based on sine rate of the shear spinning process. Then, the two methods were applied in the spinning simulation of ellipsoid thin-walled curvilinear parts with large diameter-thickness ratio. The results of simulation showed that variable thickness blank could significantly improve the forming quality of the forming parts.

MS8-4

Method to increase denting stiffness of car body skin panels

Martin Heckmann, Arndt R. Birkert, Markus Scholle, Marvin Sobhani, Birgit Awiszus, Harald Weiland

Induction of extrinsic stresses states may lead to significant increases of the denting stiffness of skin panels. For this purpose, the component needs to be produced in a dedicatedly malaligned shape. Forcing the part into its target geometry in the joining operation evokes said stress states and preserves them in the sheet. The approach discussed herein shall contribute to the reduction of sheet thickness and subsequent weight of skin panels without impairing the haptic quality of the car body.

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MS9 Material Modelling for Sheet Metal Forming Simulations

MS9-1

A discussion of the associated flow rule based on the FAY model and Nakajima tests

Niko Manopulo, Christian Raemy, Pavel Hora

Constitutive models based on a non-associated flow rule (non-AFR) have received increased attention due to their flexibility in capturing laboratory experiments. On the other hand, the recently proposed Fourier Asymmetric Yield (FAY) model enables the definition of convex yield functions with arbitrary complexity, which can be used in conjunction to an associated flow rule and nevertheless accurately match experimental data. The present contribution aims comparing AFR and non-AFR based approaches with respect to their ability in capturing measured strain fields in controlled Nakajima experiments. It is shown that a sufficiently flexible yield function is able of delivering accurate results without having to renounce to restrictions such as flow rule association or convexity. The analysis is carried out using two common deep drawing materials, namely an AA6016 and a steel grade DC05.

MS9-2

Effect of the plasticity model on the yield surface evolution after abrupt strain-path changes

Yanfeng Yang, Cyrille Baudouin, Tudor Balan

Abrupt strain path changes without elastic unloading have been used in the literature to investigate the yield surface of sheet metals, both experimentally and theoretically. Such pioneering studies emphasized an apparent non-normality of the plastic strain rate tensor with respect to the trace of the yield surface in stress space, following such a strain-path change. They inspired numerous subsequent developments of plasticity models including non - associated flow rules. In this paper, this type of abrupt strain-path changes is investigated using state-of-the-art plasticity models. The aim is to emphasize the respective contributions of elasticity, isotropic-kinematic hardening, and rate sensitivity, to the apparent violation of the normality condition. The results show that these classical ingredients of plasticity models significantly contribute to the apparent vertex and loss of normality. These effects are quantified for typical sheet metals subject to biaxial-to-shear orthogonal strain path change.

MS9-3

A numerical scheme of convex yield function with continuous anisotropic hardening based on non-associated flow rule in FE analysis of sheet metal

Wencheng Liu, Bernard K Chen

A non-associated flow rule (NAFR) model is developed by adopting the convex function YLD-2004 as the yield stress function and the plastic potential function. The yield stress function coefficients are continuously updated which are associated with the change of directional uniaxial yield stress and biaxial yield stress to simulate the anisotropic hardening behaviour. That was achieved by implementing the numerical identification procedure of coefficients into stress integration procedure. The coefficients of plastic potential function are constant and identified by the uniaxial and biaxial r-value. This constitutive model is capable of describing anisotropic hardening and yield behaviour of strongly textured aluminium alloy sheet metal. In this paper, the model was implemented into the FE code via ABAQUS subroutine to predict the deep drawn cup earing and directional flow stresses of the AA5042-H2 aluminium alloy. The new anisotropic hardening model shows better agreement with experiments compared with the isotropic hardening model.

MS9-4

On the certification of positive and convex Gotoh's fourth-order yield function

Wei Tong

Gotoh proposed in 1977 a fourth-order homogeneous polynomial of three plane stress components as a yield function to model anisotropic yielding and plastic flow of sheet metals. The yield function admits up to eight experimental inputs from uniaxial tension tests and one measurement from an equal biaxial tension test for calibrating its nine material constants and can model the formation of up to eight ears in deep cup drawing. However, the superior Gotoh's yield function has not been widely adopted in sheet metal forming

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analyses in both academy and industry, especially outside Japan. One major concern is uncertain about the positivity and convexity of a calibrated Gotoh's yield function. Here the problem of certifying a calibrated Gotoh's yield function to be strictly positive and convex is first described and its resolutions are summarized based on some very recent research results. Algebraic necessary and sufficient conditions for a positive and convex Gotoh's yield function with only two non-zero stress components are first presented. Sufficient conditions in terms of semi-algebraic and algebraic inequalities for establishing the positivity and convexity of tri-component plane stress Gotoh's yield function are then summarized. Finally, the complete necessary and sufficient conditions for a positive and convex Gotoh's yield function in plane stress are realized as a fully numerical minimization problem. Examples of successfully applying those conditions in certifying positive and convex Gotoh's yield functions of various sheet metals are also given.

MS9-5

Description of non-linear unloading curve and closure of cyclic stress-strain loop based on Y-U model

Fusahito Yoshida

This paper proposes a cyclic elasto-plasticity model to describe non-linear unloading-reloading curves and closure of a cyclic stress-strain hysteresis loop based on the Yoshida-Uemori (Y-U) model. The nonlinear unloading stress-strain response is expressed by an equation for the stress-dependent Young's modulus in the yield surface. The closure of a cyclic stress-strain curve is described by automatically changing Y-U material parameters. The great advantage of the above approaches is that no additional parameters are needed.

MS9-6

Finite element calculations of hole expansion in a thin steel sheet with polynomial yield functions of four and six degrees

Seung-Yong Yang, Wei Tong, Mohammed Alharbi

A three-dimensional finite element simulation was used to study the anisotropic plasticity behavior of sheet metal forming. Both Gotoh's (fourth order) yield function and the more flexible sixth order polynomial yield functions with an associated flow rule were implemented as user material subroutines in the FE code ABAQUS. Parameter values in the yield functions were decided by fitting the yield stresses and plastic strain ratios along various directions of uniaxial and biaxial tension. To verify the FE implementation and to evaluate the modeling capabilities of the developed yield functions that were certified to be convex, the hole expansion experiment by Kuwabara et al.[1] was considered as the target example. The simulation results using the sixth order yield function showed a better agreement with the experimental results than those of lower order yield functions such as Hill's second order or Gotoh's fourth order yield functions.

MS9-7

High accuracy springback simulation by using material model considering the SD effect

Nobuyasu Noma, Koji Hashimoto, Taiki Maeda, Toshihiko Kuwabara

In order to enhance the accuracy of springback simulation, the strength differential (SD) effect, i.e., the difference in flow stress between tension and compression, of a high strength cold-rolled steel sheet with a tensile strength of 980 MPa is measured by means of in- plane tension-compression test apparatus. Bi-axial stress tests are also performed to measure the contour of plastic work of the test material. From those experimental results, the material model which can consider the SD effect is determined. Furthermore, this material model is implemented into commercial FEM code by using user-subroutine function. To check the validity of this model and established FEM analysis system, curvature-hat crush forming experiment is performed. By comparing the experimental result and forming simulation result, the accuracy of the material model which can consider the SD effect is validated. Consequently it is concluded that the use of material model which is capable of reproducing the SD effect is a must to enhance the accuracy of springback simulation.

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MS9-8

A plane stress yield function described by multi-segment spline curves and its application

Toshiro Amaishi, Hideo Tsutamori, Takeshi Nishiwaki, Takaaki Kimoto

Precise prediction of the material anisotropy is an important factor of an accurate sheet metal forming simulation. In order to describe the material anisotropy properly, many yield functions have been proposed. Hill '48 quadratic model is widely used. Barlat introduced Yld2000, which has a formulation using two linear transformations to represent a yield function. Vegter proposed a plane stress yield function based on the interpolation of multi-axial stress states by 2nd order Bezier curves. This model considers equi-biaxial, plane strain, uniaxial, and pure shear stress states as reference points of the yield surface. In this study, a plane stress yield function which is described by multi-segment spline curves is proposed. This model is able to consider an arbitrary number of multi-axial stress points and its normal directions on the yield surface. To show the applicability of the model, some simulation results of sheet metal forming are shown and its accuracy is discussed.

MS9-9

Evaluation of accuracies of phenomenological yield criteria for automotive Al sheets

Kangcai Yu, Zhenshan Liu, Cheng Liu, Pizhi Zhao

The anisotropic behavior of two typical cold rolled Al alloy sheets, AA5182-O and AA6016-T4, were investigated and used to predictive the yield surface by the well-known yield criteria: Hill90, Barlat89 and Barlat2000. Uniaxial tensile tests with axial and wide extensometers were carried out at different angles to the rolling direction (RD). Then the yield stress $\sigma\theta$ and anisotropic coefficient $r\theta$ were obtained. Biaxial tensile tests of cross-shaped specimens under certain liner loading paths were conducted on the well-designed biaxial tensile testing machine. The loading paths includes Fx:Fy =1:4, 2:4, 3:4, 4:4, 4:3, 4:2, 4:1. Yield stresses points (σx, σy) and their strain ratios in the yield locus plane can be obtained from the strain-stress curves of the biaxial tensile tests. Parts of tested values were used to determinate the yield locus according to different yield functions. All experimental data was used to evaluate the precisions of the yield functions by taking into account of the accuracy of $\sigma\theta$ and $r\theta$ and the yield stress and strain ratios of biaxial tensile tests.

MS9-10

Development of the user subroutine library "Unified Material Model Driver for Plasticity (UMMDp)" for various anisotropic yield Functions

Hideo Takizawa, Kai Oide, Kentaro Suzuki, Toshikazu Yamanashi, Takashi Inoue, Tetsuji Ida, Toru Nagai, Toshihiko Kuwabara

Many yield functions have been proposed in academia to describe the complicated shapes of yield surfaces of metals. However, many of the commercial FEM codes provide only classical yield functions. Moreover, it takes a long time for engineers to implement newly proposed yield functions to commercial FEM codes. The Japan Association for Nonlinear CAE (JANCAE), a non-profit organization, developed the Unified Material Model Driver for plasticity (UMMDp) subroutine suite with the cooperation of industry users of CAE and the engineers of software venders. This subroutine provides several anisotropic yield functions, and is applicable to most of the commercial FEM codes. The users can implement their own anisotropic yield functions easily using the UMMDp. This paper presents the basic framework of UMMDp and the development activities performed with many volunteers.

MS9-11

Development of plug-ins for bridging the variables between advanced finite element codes and 'UMMDp'

Tetsuji Ida, Hideo Takizawa, Toshihiko Kuwabara

For advanced finite element codes, we can add original material models by programming ourselves. On the other hand, as for implementation methods, we need unique technique in each advanced finite element codes, and there was a problem that it is difficult to implement unless we fully understand the procedure of these codes. Therefore, the Japan Association for Nonlinear CAE (JANCAE) has started to implement

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anisotropic yield functions independent of advanced finite element codes in its working group activities, and has created a subroutine library "UMMDp". The "UMMDp" library is connected to each advanced finite element codes with "plug-ins", and variables are bridged. In this report, we first explain the concept of "plug-ins" development and verification method in implementation. Next, we introduce some examples that we implemented "UMMDp" into the advanced finite element code “LS-DYNA” via the plug-ins. By comparing with the built-in yield function, we will explain that "plug-ins" is working properly and the usefulness of "UMMDp".

MS9-12

Implementation of anisotropic yield functions into the subroutine library "UMMDp"

Kai Oide, Hideo Takizawa, Toshihiko Kuwabara

To implement new yield functions into the user subroutines of advanced FE codes, professional skills and knowledge are required. The Japan Association for Nonlinear Computer Aided Engineering (JANCAE) has been acting as an organization that provides information and knowledge on finite element analysis (FEA) to the researchers and engineers in various positions involved in CAE. Since 2009, as one of the subcommittee activities for applying FEA to practical metal-forming problems, we have not only studied elastoplastic theory, but have also developed the Unified Material Model Driver for Plasticity (UMMDp), a user subroutine library. Basic yield functions, such as the von Mises and Hill's quadratic yield functions, which almost all advanced FE code already has, were implemented in the UMMDp as a basic study at its beginning of the development. Up to now, many anisotropic yield functions, including Yoshida's 6th-order polynomial, Barlat's Yld2000 and Yld2004, Comsa and Banabic's BBC2008, Cazacu's CPB2006, and Vegter's spline yield functions, have been implemented in the UMMDp, and it is possible to add a new yield function. In this presentation, the techniques for implementing yield functions in the UMMDp are explained. Moreover, the problem of BM1 in NUMISHEET 2016 is discussed as an example applying selected yield functions to the implementation procedure.

MS9-13

Practical examples of sheet metal forming simulations using the subroutine library 'UMMDp'

Tomokage Inoue, Hideo Takizawa, Toshihiko Kuwabara

With the common frame work of the user subroutine library, ‘UMMDp’, various constitutive models for metals have been implemented in several major commercial finite element (FE) codes. The implementation has been achieved by the material modeling working group of a non-profit organization, the Japan Association for Nonlinear CAE (JANCAE). Herein, we report the results of the finite element analyses on a typical metal forming problem solved using UMMDp. Moreover, since 2017, the CAE modeling working group has been tasked to provide more practical learning for the material models as well as extensive simulation knowledge. These activities are presented in this paper.

MS9-14

The application of crystal plasticity material files in stamping simulations

Bart Carleer, Philip Eyckens, Albert Van Bael, Matthias Sester, Dirk Roose, Jerzy Gawad

Representative material data are inevitable to execute accurate stamping simulations. These material data are generally generated by performing extensive mechanical material tests. In this research the generation and application of material data from a crystal plasticity-based multiscale model have been studied. The crystal plasticity model enables to generate detailed material properties which can be applied in various yield locus models. The evolution of the anisotropic properties during deformation can be readily taken into account with the crystal plasticity model. The generated material data have been applied in deep drawing simulations of a cross-die. The thickness distribution of the simulation has been compared with experiments. Results showed that crystal plasticity models are a viable alternative for material data generation, having as main advantage that extensive mechanical experiments are avoided.

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MS9-15

Prediction of mechanical response and microstructure evolution for 5000-Series Aluminum Alloy coupling visco-plastic self-consistent approach with finite element method

Andrew Ruggiero, Magnus Hörnqvist Colliander, Nicola Bonora, Domenico Gentile, Gianluca Iannitti, Gabriel Testa, A.H.S. Iyer

In the present work, a hybrid micro macro-approach was adopted to investigate the material behavior of the A5XXX-O object of the Benchmark 3 of Numisheet 2018. Starting from the provided uniaxial stress-strain curve and in house microstructure measurements, a mean field approach, by using the VPSC7c code, was used to perform numerical experiments in order to derive the anisotropic macroscopic behavior of the aluminum alloy. Then, at the macroscale, a constitutive model was built on coupling a non-quadratic yield surface function with a damage model developed in the framework of the continuum damage mechanics. Finally, by using MSC.Marc2017.1, finite element simulations of uniaxial and Nakajima bulging tests were performed with the purpose of obtaining the Fracture Forming Limit Curve for the aluminum alloy under investigation.

MS9-16

Experimental and numerical investigation of ironing in deep drawn parts

Alper Güner, Igor Burchitz, Bart Carleer, Marco Gösling

Majority of the industrially relevant deep drawn sheet metal parts undergoes an additional process after the drawing operations. Operations like flanging or hole extrusion are widely used especially in the automotive industry. In such industrial applications it is seen that process planers design the tools by using a clearance less than the sheet thickness. Due to this smaller gap between the forming steels and the post, sheet material is compressed in the thickness direction. This additional compression is definitely needed for collar forming and it is beneficial in flanging operations in terms of springback. Addition of compressive deformation state on flange regions reduces the bending effects on those parts. Ironing in sheet thickness direction is a challenging deformation state for numerical simulations. This effect can be modelled by 3D continuum elements. However, due to high computation times this solution is not feasible for industrial applications. On the other hand, shell elements are widely used in sheet metal forming problems due to their efficiency but the conventional shell elements cannot predict ironing effects since the formulation does not consider through-thickness deformation. In order to analyze the effect of ironing, cup drawing experiments were performed. Ironing level is controlled by changing the die diameter while keeping the punch diameter constant. DC04-SUPERMOD with 1.75 mm thickness was used in the experiments. The thickness distribution along the cup wall and height of the cups were measured after each operation. Same experimental procedure was modeled using new thick shell elements which accounts for the through-thickness deformation. Comparison with the experimental measurements show that the enhanced formulation of the shell elements can be used to simulate the ironing effects in deep drawn parts.

MS9-17

The evolution of mechanical properties of AISI 301 as a result of phase reversion heat treatment,experiment and modeling

Harm Kooiker, E.S. Perdahcioglu, Ton van den Boogaard

Laser heat treatments of metastable austenitic stainless steel AISI 301 are presented aiming to elucidate the relation between heat treatment, transformation and mechanical properties after heat treatment. It is assumed that the observed phase reversion of martensite to austenite is due to a diffusional transformation mechanism governed by nucleation and growth leading to submicron grains. Based on this assumption it is demonstrated that the reverse transformation can be successfully predicted by the proposed model. Subsequently the effect of the heat treatment on the hardness is reviewed. It is shown that the proposed hardness-model, in combination with the proposed isothermal transformation model, is in agreement with the observed behavior. Amongst others it is successfully predicted that the isothermaltransformation precedes the recrystallization of the retained austenite and that the post-heat treatment grain size has a large effect on the behavior through the Hall-Petch effect.

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MS9-18

Work-hardening behaviour of sheet steels in large strain regions and its simple approximation

Satoshi Shirakami
Yusuke Tsunemi , Tohru Yoshida , Toshihiko Kuwabara

The equivalent plastic strains in stretch flanging and bending frequently exceed the strain equivalent to the uniform elongation in uniaxial tension. However, the uniaxial tensile test does not directly provide the true-stress and true-strain relationship in this strain region. In this study, the simple shear tests and the hydraulic bulge tests of an interstitial free steel, and 590 and 980 MPa grade dual-phase high-strength steels were carried out to investigate the work-hardening behaviour, i.e., the relationship between equivalent stress and equivalent plastic strain as well as the evolution of instantaneous n-value, in such a large strain region. A parameter k that correlates stress and strain for a simple shear (or equi-biaxial stretching) to an uniaxial tension leads to a good agreement of stress-strain curves for these testing modes. It was also found that k is practically independent of strain region in the present study. The work-hardening behaviour obtained by a simple shear or bulge test well agrees with that by a uniaxial tensile test. On the other hands, work-hardening equations proposed by previous studies do not reproduce the evolution of instantaneous n-value, i.e., a strain dependency of the n-value, for the present steel grades. Thus, the authors propose a new work-hardening equation that can reproduce the strain dependency of the n-value for any steel grade in this study.

MS9-19

Biaxial deformation and martensitic transformation behavior observation on type 304 stainless sheet by biaxial bulge test

Shota Kusaka, Hiroshi Hamasaki, Eiichiro Ishimaru

Metallurgical characteristic phenomenon on type 304 stainless steel is the deformation induced martensitic transformation. To clarify the stress-strain curves and martensitic transformation behaviour, biaxial bulge test apparatus was developed. It enables to control the stress ratio of axial and circumference directions and equivalent plastic strain rate simultaneously. Biaxial bulge tests for uniaxial, equi-biaxial and plane strain cases were conducted at the constant temperature 20 ^{o}C. The obtained martensite volume fraction vs. equivalent stress curves for all the tests were well agreed, so that it can be said that the martensite volume fraction was predictable by the maximum austenite stress.

MS9-20

Finite element analysis of AHS steel under dynamic loading using a micromechanical modelling

Tachawut Chiyatan, P. Karin, N. Ohtake, V. Uthaisangsuk

Currently, advanced high strength (AHS) steel sheets have been increasingly used in the automotive structural parts, where improved crashworthiness and lightweight design are required at the same time. Such steel sheets provide an excellent combination between high strength and great energy absorption. Most AHS steels exhibit microstructures containing several phases and constituents with different morphologies and mechanical properties. In this work, the dual phase (DP) steel grade 780 was investigated under dynamic tensile loading by means of a finite element modelling on the micro-scale. A representative volume element (RVE) model was applied to take into account the effects of microstructure characteristics on the mechanical behaviour of steel sheets at high strain rates. For the RVE modelling, the Johnson-Cook constitutive model was applied to describe the stress-strain response, whereas the Johnson-Cook damage model and damage locus were employed for predicting failure development of each individual phases of examined steel. The RVE simulations were performed under varying strain rates and states of stress and the results were subsequently compared.

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MS9-21

Parameter calibration for a shear modified GTN damage model and its application to forming limited prediction

Liang Ying, Wenquan Liu, Minghua Dai, Ping Hu, Dantong Wang

Damage evolution is an unavoidable problem in the forming process of sheet metal, and an improper forming technology may cause ductile fracture of the final parts. The damage mechanics theory can give great insight to the failure mechanism and the numerical simulation using damage model can provide a new way to predict the fracture behaviour for sheet metal. The shear modified GTN model by Nahshon and Hutchinson with a piecewise interpolation function was applied, which can capture the damage evolution under both low and high stress triaxiality. Then, a method combined numerical simulation and optimization algorithm was adopted to calibrate the damage-related parameters. Furthermore, the shear modified model was used to predict the forming limit of a high strength steel 22MnB5. With the help of digital image correlation technique (DIC), both the strain field and forming limit curve obtained by the numerical simulation were compared with the experimental ones, and satisfactory results are obtained.

MS9-22

Simulation of electrohydraulic free forming of DP600 sheets using a modified Rousselier damage model

Iman Sari Sarraf, Daniel E. Green

Electrohydraulic forming (EHF) is a high-energy rate pulsed forming process in which the expansion of the plasma channel formed by the discharge of electrical energy between two electrodes immersed in water results in the high-velocity forming of the sheet material. This process is shown to have the capability of increasing the formability of sheet materials beyond conventional limits and being applicable to less ductile materials. In this work, DP600 sheet specimens were deformed in uniaxial tension, plane strain and biaxial tension using electrohydraulic free forming (EHFF). A modified Rousselier ductile damage model was then employed to predict the forming and damage behaviour of these specimens deformed along each strain path. This modified Rousselier model includes a modified Johnson-Cook hardening model as well as a void nucleation function and a void coalescence criterion. The limiting strains, the distribution of the scalar damage variable and the final damage morphology obtained from the numerical simulations were compared to the experimental results in order to evaluate the accuracy of the proposed micromechanical damage model. It is shown that predicted strains,damage accumulation and the final damage geometry of DP600 sheet specimens using the modified Rousselier model are in good agreement with experimental results as well as with those predicted by other phenomenological constitutive models.

MS9-23

Generalisation of Hill's yield function for planar plastic anisotropy

Rui Cardoso, Mayo Adetoro

In this paper we present a new generalised quadratic yield function for plane stress analysis for the description of the plastic anisotropy of metals and also for the study of the asymmetric behaviour in tension-compression typical of the Hexagonal Closed-Pack (HCP) materials. The new yield function has a quadratic form in the stress tensor and it simultaneously predicts accurately the r-values and directional flow stresses. It also describes very well the biaxial symmetric stress state which is fundamental for the accurate modelling of aluminium alloys. The new quadratic yield function represents the non-symmetric biaxial stress state by performing a linear interpolation from pure uni-axial loading to a biaxial symmetric stress state. The most advanced yield functions for plastic planar anisotropy characterise very well the bi-axial symmetric stress region by using experimental flow stresses for the symmetric bi-axial stressstate. However, the behaviour of the alloy between the uni-axial stress state and the symmetric bi-axial stress state is still not very well characterised. In this new yield function that behaviour can be assessed from interpolation from the uni-axial stress state into the symmetric bi-axial stress state until experimental yield locus tting is achieved within a reasonable tolerance in that region. The main advantages of this new yield function is that it can be used for the modelling of metals with any crystallographic structure (BCC, FCC or HCP), it only has five anisotropic coefficients and also that it is a simple quadratic yield criterion that is able

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to accurately reproduce the plastic anisotropy of metals whilst using an associated flow rule. In the results and discussion we validate the yield locus for FCC and HCP alloys and we apply the new yield function in a cup drawing simulation for the assessment of the cup earing profile.

MS9-24

Earing prediction of AA 2008-T4 with anisotropic Drucker yield function based on the second and third stress invariants

Saijun Zhang, Yanshan Lou, Jeong Whan Yoon

This paper applies anisotropic Drucker yield function [14] (Lou and Yoon, 2018, Int. J. Plasticity 101, 125-55) to predict earing profile after cup deep drawing of AA 2008-T4. The new yield function is implemented into ABAQUS/Explicit using semi-implicit integration algorithm to calculate the increment of plastic strain. Both associated and non-associated flow rules are incorporated in this study. The predicted anisotropy and cup height profile are compared with the experimental results and those predicted from the Hill48, Yld91 and Yld2004-18p yield functions. It is observed that the earing profile predicted from the new yield function shows high accuracy. The computation time is also compared to investigate the computation cost of different yield functions. The comparison reveals that it takes the shortest time for the Hill48 function, the anisotropic Drucker yield function reduces 30%~40% of computation cost compared with the Yld91 and Yld2004-18p functions. It is concluded from the simulation of cup deep drawing that the new yield function can provide high accurate numerical analysis of plastic deformation for anisotropic metals with competitive computation cost.

MS9-25

Influence of hardening functions on earing prediction in cup drawing of AA3104 aluminum alloy sheet

Hideaki Fukumasu, Toshihiko Kuwabara, Hideo Takizawa, Akinori Yamanaka

The accuracy of cup drawing simulation of aluminum alloy sheets strongly depends on the hardening and yield functions used in the simulation. In this study, stress-strain curves for an AA3104 aluminum alloy sheet were measured by uniaxial tensile and rolling tensile tests to identify parameters for various hardening functions. In addition, in-plane uniaxial tensile, biaxial tensile, and combined tension-compression tests were carried out to measure the successive contours of plastic work in the stress space and the directions of plastic strain rates under linear stress paths. The anisotropic coefficients, α_1-α_8, and exponent M of the Yld2000-2d yield function were determined so that the mean square error of the analytical yield locus from the measured plastic work contour was minimized. Finite element simulations of cup drawing of the aluminum alloy sheet were carried out using the determined parameters for hardening functions and the Yld2000-2d yield function implemented in LS-DYNA. By comparing the simulation results with the results of cup drawing experiments, the effects of the hardening functions on the accuracy of earing profile prediction were investigated.

MS9-26

An alternative procedure to identify stress-strain relation for DP980 sheet over a large strain range

Quoc Tuan Pham, Young Suk Kim

In sheet metal forming, the standard uniaxial tensile test is a well-established testing method used to achieve stress-strain relation or flow curve for examined material. In agreement with the development of material science, the number of forming processes that exceeded the maximum uniform strain observed in a uniaxial tensile test is myriad. To obtain the relationship between stresses and strains over a large range of deformation, extrapolation of a common hardening model (Swift model or Voce model) is only accepted for some specific materials. Therefore, expensive calibrating methods, such as inverse finite element analysis and virtual field method, are widely used to identify the flow curve for recently developed sheet materials, for example, advanced high strength steels or aluminium alloys. This study presents an alternative procedure to identify the flow curve for sheet metals by using the extrapolation method. Key to the success of this procedure is using the Kim-Tuan hardening model, a newly developed hardening model

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proposed by the authors. The examined material is DP980 sheet that is tested material in Benchmark 01 of the NUMISHEET 2018 conference. To verify the accuracy of the calibrated flow curve, this curve is imported into a finite element analysis for a uniaxial tensile specimen and computational loading forces according to gauge length displacement are compared with experimental observation supported from the Benchmark's data.

MS10 Springback, Elasticity and Time Effects in Forming

MS10-1

Spring-back prediction based on a rate-dependent isotropic-kinematic hardening model and its experimental verification

Hoon Huh, Geunsu Joo

This paper deals with spring-back prediction with a rate-dependent isotropic-kinematic hardening model with tension/compression in high speed U-draw-bending tests. In order to verify the validity of the present model, spring-back simulation is carried out and its results are compared with experimental results. A rate-dependent isotropic-kinematic hardening model has been proposed by combining the rate-dependent function of material parameters and the Chaboche type model for the TWIP980 steel sheet under tension and compression. The proposed model can accommodate the strain rate effect on the material properties by providing rate-dependent hardening curves under loading and reverse loading condition. This change of the rate-dependent material properties is important to predict spring-back under high speed deformation in practical sheet metal forming undergoing tension and compression during the deep-drawing forming. High speed U-draw-bending tests have been performed to investigate the strain rate effect on spring-back of the TWIP980 steel sheet after draw-bending at intermediate strain rates of up to a hundred per second. The experimental results have been compared with simulation results of high speed U-draw-bending and spring-back analysis with four hardening cases: isotropic; isotropic-kinematic; rate-dependent isotropic; rate-dependent isotropic-kinematic hardening models. It is demonstrated with the comparison that the rate-dependent isotropic-kinematic hardening model proposed provides the best prediction of spring-back after U-draw-bending at intermediate strain rates among the four hardening cases.

MS10-2

The effect of loading modes on springback behaviour of austenitic stainless steels sheets in three points bending

Yong Xu, Xiaosong Zhang, Shihong Zhang, Ali Abd El-Aty

The paper aims at investigating the bending deformation behavior and springback of austenitic stainless steel sheet (AISI 304) at room temperature and under different loading modes using experimentation and finite element simulation. Three bending experiments under both monotonic and pulsating loading were accomplished on AISI 304 sheets with thickness of 2mm in order to determine and calculate the variation of springback under different bending angles. Besides, ABAQUS finite element code was used for simulating the bending process in order to validate the results obtained from experimentation. From simulation, the equivalent strain in the bending section of the maximum deformation position of the specimen was measured and analyzed. According to the strain value, the uniaxial tensile test at room temperature was designed and carried out. The monotonic loading and cyclic loading and unloading which is similar to pulsating loading were selected. Through the stress-strain curve obtained, the elastic modulus of the stainless steel under two loading modes were calculated respectively. The XRD methods was used to calculate the deformation induced martensite content in the specimen under different loading modes and bending angle. The experimental results showed that the specimen under the condition of pulsating loading have smaller amount of springback. It's concluded that the pulsating loading mode can increase the fraction of martensitic phase induced by deformation in austenitic stainless steel sheet, then resulting in the enhancement of transformation induced plasticity effect (TRIP). It lead to the improvement of elastic modulus of material, which reduced the springback behavior after bending process.

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MS10-3

Investigation on strain dependent elastic behavior for accurate springback analysis

Simon Vitzthum, Matthias Eder, Christoph Hartmann, Wolfram Volk

In the field of metal forming the effect of springback is of great importance and is one of the research areas. The amount of springback depends substantially on the materials' elastic behavior and the degree of strain hardening. Former studies showed that Young's modulus is influenced by strain hardening and thus detailed knowledge about this correlation is necessary. For an accurate description of strain dependent Young's modulus, a generally valid and consistent formulation in terms of continuum mechanics is required. To reconsider existing formulations, a close examination of the additive decomposition of elastic and plastic strains is necessary that is revealed within this study. Cyclic tensile tests with mild steel DX56 are performed to investigate the strain dependency of Young's modulus experimentally. The theoretically derived formulation is applied to the experimental results. On this basis different determination methods for identifying Young's modulus are utilized and finally analyzed in terms of springback prediction. Finally a new strategy to predict springback is proposed.

MS10-4

Kinematic hardening performance of 5052 aluminum alloy subjected to cyclic compression-tension

Haiyan Yu, Ping Xu, Huiru Shi, Huiqi Yu, You Wang

In order to study the kinematic hardening performance of 5052 aluminium alloy, experiments of cyclic compression-tension were conducted in this work. The kinematic hardening performance including the Bauschinger effect, transient hardening and permanentsoftening shown by the forward-reverse stress-strain curves was discussed. The famous Yoshida-Uemori hardening model was adopted to characterize the kinematic hardening behaviour of AA5052. The parameters in Yoshida-Uemori hardening model were identified with an inverse method composed by experiments, finite element simulation and optimization. Experiments of cyclic loading-unloading uniaxial tension were also performed to identify the degradation of the elastic modulus of AA5052 with the plastic strain. U-bending springback simulation using the Yoshida-Uemori hardening model was conducted. The results showed that the investigated AA5052 has strong Bauschinger effect, transient hardening and permanent softening. The percentage of elastic modulus degradation could reach 16.7% at 8.8% plastic strain. The Yoshida-Uemori hardening model can capture the kinematic hardening behaviour of AA5052 very well.

MS10-5

A constitutive law based on the self-consistent homogenization theory for improved springback simulation of a dual-phase steel

A.H. van den Boogaard, A. Torkabadi, E.S. Perdahcioglu

It has been widely observed that below the flow stress of a plastically deformed material the stress–strain response of the material does not obey the linear relation assumed in classical elasto-plastic models. As a matter of fact, a closer observation indicates that the stress–strain response of the material is nonlinear upon unloading. This results in a larger strain recovery than predicted by the linear elastic law which consequently results in an error in springback prediction. Furthermore, when the material undergoes compression after tension, it exhibits Bauschinger effect, transient behavior and permanent softening. The accuracy of the springback prediction is dependent on the capability of the model in capturing the above mentioned phenomena. In this work a constitutive law based on the self-consistent homogenization method is developed. In this model the stress inhomogeneity in the material is realized through considering a distribution in yielding of individual material fractions. The model was calibrated using stress–strain curves obtained from tension–compression experiments. The model has shown to be capable of predicting the nonlinear unloading behavior and the Bauschinger effect while maintaining computational efficiency for FEM simulations.

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MS10-6

Effect of pre-strain on creep behavior of titanium alloy sheets and springback simulation

Yuan Chen, Shuhui Li, Ji He, Yue Ma

This paper discusses the effect of pre-strain on the creep behaviour and constitutive modelling of titanium alloy Ti-3Al-5Mo-5V-8Cr sheets. A set of uniaxial tensile creep tests at different pre-strains and different stresses were carried out to analyse the creep behaviour of titanium alloy sheets. The results show that pre-strains have significant influence on the creep behaviour which was opposite to the effect of stress. And based on the experiment results, a modified Garofalo creep constitutive model was established which can illustrate the creep aging behaviour of titanium alloy Ti-3Al-5Mo-5V-8Cr sheet at 500°C under different stresses and different pre-strains very well.

MS10-7

Crystal-plasticity finite-element simulation of time-dependent springback in a commercially-pure titanium sheet

Takayuki Hama, T. Sakai, Y.P. Korkolis, H. Takuda

A crystal-plasticity finite-element method was used to examine the deformation mechanism of time-dependent springback in a commercially-pure titanium sheet. To reproduce the viscoplastic behavior of the sheet, the material parameters were calibrated to reproduce the strain-rate dependency of the stress-strain curve under uniaxial tension. A two-dimensional draw bending process was simulated and the change in the sidewall curvature was evaluated. The simulation results showed that the curvature increased with the elapsed time after unloading, consistent with experimental results reported elsewhere. The deformation mechanism during the process was discussed in terms of evolution of stress and relative activities of slip and twinning systems.

MS10-8

Investigation on stress relaxation behavior of high-strength steel sheets based on elasto-viscoplasticity

Masato Takamura, K Murasawa, Y Kusuda, Y Suzuki, T Hakoyama, Y Ikeda, Y Otake, T Hama, S Suzuki

Stress relaxation is the phenomenon where stress of materials decreases under constant strain. In several previous studies, it was found that the stress relaxation makes uniform elongation larger, showing a possibility that this phenomenon can be utilized to increase the forming limit in combination with the flexible slide motion of a servo press. However, the stress relaxation phenomenon has not yet been sufficiently clarified. Authors previously investigated the stress relaxation behavior by applying several models where stress relaxation was described as an elasto-viscoplasticity behavior. However, a unified and quantitative description of strain rate sensitivity of flow stress and stress relaxation has not been sufficiently studied. In this study, we investigated the influence of strain, strain rate and relaxation time on stress relaxation phenomena of high strength steel sheets. Strain rate sensitivity of flow stress was modelled with m-power law. Stress relaxation behavior was also successfully approximated by a model derived from the m-power law with the parameters obtained by strain rate sensitivity tests, which suggests that both the strain rate sensitivity and the stress relaxation were based on a unified elasto-viscoplasticity. The mechanisms of stress relaxation was also discussed through numerical analyses.

MS10-9

Numerical simulation of forming and springback of ultra-thin copper alloy sheets

Sandrine Thuillier, C.H. Pham, P.Y. Manach

This study deals with forming and springback of U-shaped channels made of copper alloy thin sheets. Three materials are considered: pure Cu, copper-beryllium CuBe2 and copper-iron CuFe2P alloys. All these materials are supplied under sheets of thickness around 0.1 mm. Their mechanical behavior is investigated in monotonic uniaxial tension, loading-unloading sequences in tension and simple shear, in order to highlight the hardening, the evolution of the unloading slope with plastic strain and the magnitude of Bauschinger's effect. Then, drawing of U-shaped elongated parts is performed; to enhance 3D springback, a misalignment of the blank with respect to the punch, die and blank-holder is deliberately applied. The

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geometry after tool removal is measured by laser scanning, to quantify the magnitude of springback. The twisting parameter, defined as the ratio of the total angle variation between two extreme sections over the distance between the two same sections, is strongly dependent on the material, with a small value of 8° m^{-1} for CuBe2, an intermediate value of 28° m^{-1} for pure Cu and a high value of 45° m^{-1} for CuFe2P. The relationship between 2D springback and twisting is highlighted.

MS10-10

Analysis of anisotropic effects in single point incremental forming

Venkata Reddy N, Rakesh Lingam, Praveen Konka, Kishor Kalathiya, Shamshoddin Shaik

Incremental Sheet Forming (ISF) has great potential to form complex sheet metal parts without using component specific tooling. Formability in ISF process is higher than the conventional forming processes but achieving good geometrical accuracy is a challenging task. Anisotropy of material causes variation of thickness with respect to rolling direction, which effects stiffness, spring-back and accuracy. Variation of thickness and spring-back with rolling direction is studied using experimental and numerical analysis for a conical geometry formed using extra deep drawing steel having high anisotropy. Comparison of anisotropy and isotropy is done using numerical analysis. Results showed that, thickness is low in the direction with low ratio of width to thickness strain (r-value), resulting in higher spring-back. This directional property has to be considered in tool path design to enhance the accuracy. When material is assumed to be isotropic, variation of thickness and spring-back with respect to direction is insignificant.

MS10-11

Accurate prediction of springback after coining operation

Alper Güner, Bart Carleer, Igor Burchitz, Marco Gösling

A common approach used to reduce springback in flanging operations is to apply additional coining around the bent regions. In this strategy, the sheet metal part is compressed between two rigid dies having a clearance less than the sheet thickness. The aim is to bring additional compressive stresses especially around bending dominated regions. These stresses are slightly larger than the current yield stress of the material. By this way, the dominant bending stress state is reduced leading to less springback. The shell elements which are the state of the art in productive utilization of finite element simulations lack the ability to consider normal deformation which occurs during coining. Hence, it is not possible for process planners to decide on the degree of coining and to predict the springback results beforehand. In order to address this problem a set of experiments were performed, whereby deep drawn cups were coined around the punch radius region and cup bottom. To investigate the changed state of residual stresses, drawn cups were cut into halves and springback was measured. The same procedure was also simulated with the new thick shell elements which are improved to incorporate the normal stresses in thickness direction. It was seen that, by the help of this enhancement, the springback prediction is improved as compared to the conventional shell elements.

MS10-12

Effect of warm forming on formability and springback of aluminum alloy brazing sheet

Michael Worswick, Kyu Bin Han, Ryan George, Sooky Winkler

This paper investigates the effect of warm forming (up to 350 °C) on the formability and springback behavior of AA3003/AA4045 brazing sheet (0.2 mm gauge) for two temper conditions: O-and H24-temper. The key objective is to utilize warm forming to form aggressive geometries and control the springback to improve the part flatness which enables the use of harder temper material with improved strength. Simulations and experiments are performed considering heated dies at several different temperatures up to 350 °C and the blanks are pre-heated in the dies. The geometry under study is referred as a surrogate heat-exchanger component (SHC) and contains complex features found on commercial automotive thermal management systems. An in-depth springback characterization was completed for a wide range of forming process parameters such as: temperature, punch load, sheet direction, and holding time. Numerical simulations were also performed to predict the springback behavior and were compared to the experiments. There were no clear results showing improvement in formability using the warm forming

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process. However, increased temperatures (above 250 °C) offered significant improvement in springback for the harder H24 material temper.

MS10-13

Guideline to optimize the convergence behaviour of the geometrical springback compensation

Arndt Birkert, B. Hartmann, M. Nowack, M. Scholle, M. Straub

The need for car body structures of higher strength and at the same time lower weight results in serious challenges for the stamping process. To produce accurate parts at the end the stamping dies must be adjusted more or less by the amount of the springback in the opposite direction. Which stamping dies out of a multistage die set need to be adjusted, and how great the respective adjustment needs to be, is still quite often defined by practical experience and trial-and-error. Normally a certain number of compensation iterations based on the same compensation strategy must be realized and in addition to that, even the compensation strategy itself must be modified in some iterations in order to achieve accurate parts within tolerance. In contrast to the today still convenient trial-and-error optimization approach, a compensation guideline has been developed. Key content is the influence of the relevant compensation parameters, such as the measuring reference system (measurement system) including clamping of the parts (orientation of the springback part relative to the target part) and the amount of the compensation in the different stages (compensation factor and compensation strategy).

MS10-14

Evaluation of all springback aspects through a success story on Ford Cargo Truck Door Opening Part

Fatih onhon, Cem Bilgili

Springback remains as a challenge in the automotive stamping industry. Use of different new materials for lightweighting purposes like aluminium, HSS and AHSS increase studies on that subject. Moreover, constraint timings and cost reduction targets require robust strategies on springback prediction and its compensation. In this paper, the industrial approach to this issue is told through a successful large scale case study where various applied methods are mentioned for accurate springback prediction and effective compensation.On the prediction side, this includes hardening curve, yield criteria, FLC, friction, drawbeads, spacers, blankholder model, blank properties, thickness, material grade, clamping concepts, mesh parameters. On the compensation side, strategies are playing an important role and also certainly validation. For the validation, so called, full cycle simulations are performed. Full cycle simulations must be carefully evaluated due to many noise factors.

MS11 Advanced Simulation and Material Characterization for Micro Metal Forming

MS11-1

Development of in-situ observation methods of surface roughening behavior by hand-size stretching test for metal foils

Tsuyoshi Furushima, Yutaro Hirose

It is known that the surface roughness on the free surface increases with increasing plastic strain. When the size of material is scaling down in to micro scale, the ratio of surface roughness to the thickness becomes large in micro metal forming compared with macro-scale forming. Thus, the surface roughening behavior of metal foils is an important factor in micro metal forming. To clarify the surface roughening behavior of the metal foils, in-situ observation is required under bi-axial tension state. In this study, the method of in-situ observation of surface roughening during plastic deformation is developed. The hand-size stretching test is developed and installed on the confocal laser micro scope which can evaluate quantitative 3D profile of surface with high resolution. The effect of strain state such as equi-biaxial on surface roughening behavior is investigated experimentally. By using developed in-situ observation method, it became possible to evaluate the process of changing the surface under various strain states.

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MS11-2

Crystal plasticity finite-element analysis of surface roughening behaviour in biaxial stretching of steel sheets

Masahiro Kubo, Takayuki Hama, Yusuke Tsunemi, Yoshiaki Nakazawa, Hirohiko Takuda

Because of the increasing demand for automobile outer panels with sharper streamlines, prevention of surface roughening during press forming is important to obtain outer panels with better surfaces. It is crucial to examine the effects of deformation-mode on surface roughening, because steel sheets are subjected to various deformation modes during press forming. Moreover, surface roughening behaviour of interstitial free (IF) steels, which are now commonly utilized for fabricating outer panels, has not been studied enough. In this study, surface roughening behaviours of IF steel under various deformation modes were simulated by crystal plasticity finite-element analysis (CPFEA). First, the validation of a CPFEA model was carried out for investigating the stress-strain relationships in simple shear deformation and for studying changes in crystal orientations during biaxial tension. Then, the influence of microstructures on surface roughening was investigated. The results showed that surface roughening was larger for plane-strain tension than for equi-biaxial tension in IF steels. To predict surface roughening, it is essential to consider the difference of deformation resistance between crystals and the distribution of crystal orientations in the thickness direction.

MS11-3

Deformation-induced surface roughening of an Al-Mg alloy

Yannis Korkolis, Paul Knysh, Kanta Sasaki, Tsuyoshi Furushima, Marko Knezevic

We analyze the deformation-induced surface roughening of an Al-Mg alloy. One aspect of our work is an effort to model the exact roughening behavior of a mesoscale-size specimen that contains a small number of grains. Such a specimen is obtained using prestrain, recrystallization annealing and subsequent machining. It contains one layer of grains through the thickness and is tested under uniaxial tension. A laser confocal microscope is then used in order to measure the surface profile of a deformed specimen. We apply crystal plasticity finite element method to a voxel model of a given specimen. The exact arrangement of grains in the voxel model is reconstructed from a pair of electron backscatter diffraction (EBSD) scans using a custom-developed shape interpolation procedure. The material properties of the Al-Mg alloy are found using an efficient black-box optimizer. The exact shape of the deformed specimen wasn't fully captured, however results on average surface roughness show good matching between model and experiment.

MS11-4

Design of a reverse deep drawing experiment enhancing strain path changes

Pierre-yves Manach, Nejia Ayachi, Noamen Guermazi, Sandrine Thuillier

To evaluate a priori the amount of strain path changes in forming processes in order to adjust the complexity of constitutive equations, it is necessary to develop forming tests at the laboratory scale sensitive to strain paths changes. In this work, a micro-forming experiment is designed in order to perform reverse deep drawing tests on ultra-thin metallic sheets, typically 0.1 mm-thick copper alloys. This experiment is supposed to be set on a Zwick-Roell BUP 200 device. The work presents the design of the device and the evolution of strain path changes occurring during both stages of the process. The experimental results obtained after both stages (force-displacement, thickness) are presented. Finally, a sensitivity analysis of a strain path change indicator is proposed through the numerical simulation of the reverse deep drawing test by varying the geometry of the tools.

MS12 Friction and Wear in Sheet Metal Forming

MS12-1

Friction in sheet metal forming: forming simulations of dies in try-out

Johan Hol, Mats Sigvant, Johan Pilthammar, Jan Harmen Wiebenga, Toni Chezan, Bart Carleer, Ton van den Boogaard

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The quality of sheet metal formed parts is strongly dependent on the tribology and friction conditions that are acting in the actual forming process. This paper focuses on the tribology conditions during early try-out of dies for new car models. The motivation for the study is that the majority of the forming simulations at Volvo Cars are performed to secure the die tryout, i.e. solve as many problems as possible in forming simulations before the final design of the die and milling of the casting. In the current study, three closure parts for the new Volvo V60 model have been analysed with both Coulomb and TriboForm friction models. The simulation results from the different friction models are compared using thickness measurements of real parts, and 3D geometry scanning data of the parts. Results show the improved prediction capability of forming simulations when using the TriboForm friction model, demonstrating the ability to accurately describe try-out conditions in sheet metal forming simulations.

MS12-2

Data-driven modelling in the era of Industry 4.0: A case study of friction modelling in sheet metal forming simulations

Sravan Tatipala, Johan Wall, Christian M Johansson, Mats Sigvant

With growing demands on quality of produced parts, concepts like zero-defect manufacturing are gaining increasing importance. As one of the means to achieve this, industries strive to attain the ability to control product/process parameters through connected manufacturing technologies and model-based control systems that utilize process/machine data for predicting optimum system conditions without human intervention. Present work demonstrates an automated approach to process in-line measured data of tribology conditions and incorporate it within sheet metal forming (SMF) simulations to enhance the prediction accuracy while reducing overall modelling effort. The automated procedure is realized using a client-server model with an in-house developed application as the server and numerical computing platform/commercial CAD software as clients. Firstly, the server launches the computing platform for processing measured data from the production line. Based on this analysis, the client then executes CAD software for modifying the blank model thereby enabling assignment of localized friction conditions. Finally, the modified blank geometry and accompanied friction values is incorporated into SMF simulations. The presented procedure reduces time required for setting up SMF simulations as well as improving the prediction accuracy. In addition to outlining suggestions for future work, paper concludes by discussing the importance of the presented procedure and its significance in the context of Industry 4.0.

MS12-3

Temperature dependent micromechanics-based friction model for cold stamping processes

Chao Wang, Javad Hazrati, M. B. (Matthijn) De Rooij, Mark Veldhuis, B. Aha, Emmanuel Georgiou, Dirk Drees, A.H. (Ton) van den Boogaard

Temperature rise in cold stamping processes due to frictional heating and plastic deformation of sheet metal alters the tool-sheet metal tribosystem. This is more prominent in forming advanced high strength steels and multi-stage forming operations where the temperature on the tool surface can rise significantly. The rise in temperature directly affects the friction due to break down of lubricant, change in physical properties of tribolayers and material behavior. This can result in formability issues such as workpiece-splitting, etc. Therefore, it is important to account for temperature effects on friction in sheet metal forming analyses. In this study, the temperature effect was included in a micromechanics-based friction model which allows calculation of local friction coefficients as a function of contact pressure, bulk strain and relative sliding velocity. The temperature influence on friction was introduced through material behavior of sheet metal, viscosity of lubricant and shear strength of boundary layer in the micromechanics-based model. The model validation has been done by comparing the calculated fractional real contact area with the experimental results. The model can be used in formability analyses and to predict optimum stamping press parameters such as the blank holder force and the press speed.

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MS12-4

Temperature analysis during the drawing of an aluminum cylindrical cup

Luis Menezes, Vasco M. Simões, Diogo M. Neto, Marta C. Oliveira, José L. Alves, Hervé Laurent

Both the plastic deformation and the friction forces generate heat in sheet metal forming processes. This yields a temperature rise on the blank and tools, which is mainly dictated by the blank properties and the press speed. Although modest values of temperature rise yield negligible changes in the mechanical behavior of metals, the lubricant properties are rather influenced by the temperature. Thus, the deep drawing of an aluminum cylindrical cup was selected to evaluate, experimentally and numerically, the temperature variation of the forming tools and blank at room temperature. Different values of punch speed are compared to evaluate the impact of the heat losses to the environment. The experimental results show that the temperature rise on the die surface is higher than 9 ^{o}C when the punch speed is 10 mm/s. The temperature is underestimated by the finite element model due to the isothermal conditions imposed on the forming tools.

MS12-5

Strategies for increasing the accuracy of sheet metal forming finite element models

Toni Chezan, Tushar Khandeparkar, Jeroen van Beeck, Mats Sigvant

Accurate modelling of sheet metal forming can contribute significantly to reduction of lead time and development costs in manufacturing industries. The current way to improve the finite element model accuracy is to combine advanced constitutive material models and advanced tribological models. For model validation purposes the geometry of the forming tools needs to be updated and the most relevant parameters of the forming press needs to be incorporated. The addition of a simple and easier to control model test can offer additional information on difficult to characterize parameters of the industrial process. The industrial validation case presented in this paper demonstrates that the Tata Steel constitutive material model has similar prediction capability as the state of the art material model used at Volvo Cars for regular process development for automotive parts production. In both industrial and model tests the tribological system appears to affect significantly the overall model accuracy. The model tests suggests that further work is needed in order to improve the tribological model description at high contact pressure and high strain levels.

MS12-6

Study of frictional contact conditions in the hole expansion test

Diogo Neto, Pedro Barros, Marta Oliveira, José Alves, Luís Menezes

The adoption of advanced high-strength steels is growing in the automotive industry due to their good strength-to-weight ratio. However, the frictional contact conditions differ from the ones arising in mild steels due to the high values of contact pressure. The objective of this study is the detailed numerical analysis of the frictional contact conditions in the hole expansion test. The Coulomb friction law is adopted in the finite element model, using different values for the (constant) friction coefficient, as well as a pressure dependent friction coefficient. The increase of the friction coefficient leads to an increase of the punch force and a slight decrease of the hole expansion. The results show that increasing the friction coefficient postpones the onset of necking, but the localization does not change.

MS12-7

Evaluation of surface asperity based contact friction models under different conditions

K.J Lee, M.G. Lee

Finite element (FE) simulation has been often used to optimize sheet metal forming process. In order to increase predictive capability for the formability and springback of sheet metals in the FE simulations, advanced numerical techniques and constitutive models have been regarded as critical issues and thus investigated by numerous researchers. However, most of the sheet metal forming simulations employed the Coulomb friction law with a constant value, which in fact is known to be a function of contract pressure, surface quality and sliding velocity. In this study, the asperity based friction model proposed by Westeneng [1], as one of most promising microscale models, was investigated and evaluated by introducing different

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contact assumptions. Modified friction model was evaluated for estimating the friction coefficient under different variables influencing the frictional condition.

MS12-8

Modeling of contact zones in air bending of sheet metals

Josef Domitner, R Eckhard, D Schweinzer, H Leumüller, B Heller, C Sommitsch

Reducing unfavorable surface imprints, so-called "bending marks", at the contact zones between the tools and the workpiece is a major objective in air bending of sheet metals. In this work basic numerical investigations of the contact zones were performed in order to study the mechanisms of bending mark formation. For that purpose a numerical model was created using the finite element software Abaqus. The two-dimensional model included the punch, the V-shaped die, the die insert and the steel sheet which has to be bent. All of these parts were treated as deformable. The elasto-plastic material properties required as input for the simulations were captured with uniaxial tensile tests. The influence of different insert materials on the plastic strain field inside the steel sheet was investigated. Air bending experiments were conducted for validating the results of the numerical simulations.

GS0 Advanced Technology for Sheet Metal Forming

GS0-1

Recent developments in multi-disciplinary applications of stamping simulation

Subir Roy

Traditionally stamping simulation has focused on assessment of manufacturability at early product design phase and for process validation at the downstream phase. In the recent years, there has been an increasing trend towards expanding the scope of stamping simulation to integrate with other CAE domains such as structural CAE, composite materials, fatigue, safety, optimization, CFD, casting and lately 3D printing. The enablers are, highly streamlined graphical user interfaces for modeling and visualization combined with accurate, robust and scalable multi-physics solvers. In this talk, industrial case studies are presented on topography optimization and initialization of sheet metal parts with manufacturing results to improve structural stiffness, process optimization of complex stampings via highly scalable and accurate explicit analyses, topology optimization and manufacturability of stamping die structures, and thermo-forming of composite materials.

GS0-2

Validation of the stoning method by numerical and experimental investigation of outer panels with and without surface deflections

Annika Weinschenk, Wolfram Volk

Surface deflections have a negative effect on the appearance of exterior body panels in the automotive industry. They occur during springback and depend on part geometry and stress states. To detect whether a produced part has surface deflections, inspection methods, such as stoning, are applied. If the part has surface deflections, the tool geometry is modified in an iterative process until no more surface deflections are detected on the produced part. Besides stoning of physical parts, surface deflections can also be detected in post-processing of a finite element simulation by use of a numerical stoning method. The advantage is that the design of the tool can be modified before it is manufactured. However, the appearance of detected surface deflections depends on the software used and its settings. Therefore, the accuracy of surface deflections detected in simulations is worth investigating. This paper describes surface deflections detected by stoning method in experiments and compares them with the numerical results from AutoForm. In doing so, the influence of the numerical settings on the appearance of the surface deflections is analyzed. For this study, various parts with door handle pockets are produced. By changing the shape of the blank, and as a consequence, also the stress state, it is possible to generate parts with surface deflections of different sizes or parts without surface deflections. A blank of AA6016 with a sheet thickness of 1.0 mm is used. The results show that it is possible to detect surface deflections in simulations accurately if suitable settings are chosen. The meshing has a significant influence on the detected surface deflection whereas the draw bead model has less of an effect.

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GS0-3

Cellular automaton calculation for dynamic recrystallization

Seung-Yong Yang, Jeoung-Han Kim

Since the mechanical behavior of superalloys can be optimized by tailoring the microstructure, the evolution of microstructure should be carefully controlled by thermo-mechanical treatments. To study the microstructure evolution of Ni-Cr-Fe based 718 alloy during hot forging, computational simulation and microstructure prediction model can be combined with experimental observation. It is necessary to establish a microstructure prediction model considering the recrystallization during the hot working process. In this work, cellular automaton (CA) method was used to simulate the dynamic recrystallization phenomena of 718 alloy during hot compression. The strain rate and temperature were considered as the processing variables. CA stress strain curves were compared with the experimental results and the prediction for the grain nucleation and growth were presented.

GS1 Composites

GS1-1

Deformation behavior analysis based on matrix/yarn sliding friction model of woven fabric green composite under simple tension

Ken-ichi Manabe, Jun-ichi Ozaki, Naoya Kobayashi , Kihei Tsutsumi

Finite element (FE) model of woven fabric green composites considering matrix/yarn sliding friction is adopted to simulate deformation behavior under simple tension in this study. In this model, certain gap were created on the interface between yarn and matrix, wrap and weft yarns. Each interface could contact and interact each other through deformation process. The interaction can be generated by the sliding friction contact surface. The deformation simulation under simple tension was carried out using a commercial explicit dynamic FE code, LS-DYNA. To clarify the obvious deformation behavior and a surface unevenness configuration on the composite, tensile deformation behavior was simulated for woven fabric green composite with fiber orientation θ=45° to tensile direction. The validation of the FE model with a gap was confirmed compared with the FE models having a gap and non-gap at the interface.

GS1-2

Influence of temperature on in-plane and out-of-plane mechanical behaviour of GFRP composite

Michael Grubenmann, Jörg Heingärtner, Pavel Hora, Daniele Bassan

In this work, the challenges in forming of glass-fibre reinforced PA6, from experimental material characterization and parameter identification to numerical modelling using Finite Element Analyses (FEA) is reviewed and results are presented. Mechanical in-plane behaviour is characterized by tensile and bias extension tests. Out-of-plane characteristics are determined using the cantilever test. The constitutive model is set-up using LS-DYNA^{TM}, in which the fibre and matrix properties are considered separately. Therefore separate tensile experiments with unreinforced PA6 are performed. FEA is used to model the tensile and cantilever tests in which the strain-stress curves, influence of displacement on shearing angle and different approaches in modelling the bending stiffness are compared. The advantages and drawbacks of the model are shown and discussed. It is shown that the conducted experiments can be reproduced by using the implemented material model and reasonably good results are achieved.

GS1-3

Numerical modeling of thermoplastic resin behavior for thermoforming of laminates composed of non-crimp fabrics

Juan Pedro Berro Ramirez, Hariharasudhan Palaniswamy, Subir Roi

Although composite materials have been used for many years in aeronautic and defense industries, the interest in the automotive industry has grown only recently. However, since they are expensive, aeronautic materials cannot be directly used for automotive and new woven fiber composites are being developed such as Non-Crimp Fabrics (NCF) with thermoplastic resin. Woven fiber composite material properties depend on many parameters such as non-linearity of tensile stiffness in yarn direction, shearing effect

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between fibers, temperature and strain rate dependency. Numerical simulation becomes a helpful tool which can be used to estimate the risk of defects after forming. A reliable characterization of resin behavior with respect to the process temperature and speed will allow users to optimize the process and reduce development cycles. In this study, we investigate a method to model a NCF thermoplastic composite taking into account both thermal and strain rate dependency using the non-linear finite element solver RADIOSS®. A new multi-layer property is used to model the NCF resin and fabric components. Fibers are modeled with a hyper-elastic anisotropic fabric material model available in RADIOSS, and the resin is modelled as an elastoplastic thermal and strain-rate dependent material. The laminate behavior is characterized using data from Bias tests in two different directions and validated process simulation. A numerical study is used to show the influence of process temperature and speed on the final shape and presence of defects.

GS2 Fracture and Damage

GS2-1

Extension of the DF2015 criterion into an anisotropic ductile fracture criterion

Yanshan Lou, Jeong Whan Yoon

The paper extends the recently proposed ductile fracture criterion of DF2016 (Lou, Chen, Clausmeyer, Tekkaya and Yoon, 2017. Modeling of ductile fracture from shear to balanced biaxial tension for sheet metals. International Journal of Solids and Structures 112, 169- 184) to consider the anisotropic ductile fracture behaviour of sheet metals. The DF2016 criterion is coupled with the Hill48 yield function to model the anisotropy in ductile fracture. For the verification purpose, experiments are conducted for AA6082-T6 sheet with a thickness of 1.0 mm in various loading conditions: in-plane shear, uniaxial tension, plane strain tension, and the balanced biaxial tension. Tests are carried out in the rolling direction, diagonal direction and transverse direction. Fracture strains are measured by digital image correlation along different loading directions. The anisotropic fracture of the sheet is modelled by the DF2016 criterion by incorporating an anisotropic yield function. The predicted anisotropic fracture loci are compared with experimental results in shear, uniaxial tension, plane strain tension and balanced biaxial tension. The comparison demonstrates that the anisotropic DF2016 criterion accurately models the anisotropic fracture behaviour of AA6082-T6 sheet in wide loading conditions from shear to balanced biaxial tension.

GS2-2

Identification method of an advanced constitutive law for nickel-based alloy Haynes 230 used in solar receivers

Anne Habraken, Helene Morch, Laurent Duchene

A model to study panels of thin tubes of Haynes 230 nickel alloy used in solar receivers has been developed. The thermo-mechanical behavior of these tubes is simulated using an advanced model capable of representing specific characteristics such as viscosity, kinematic and cyclic hardening, static recovery, or dynamic recovery. The constitutive law implemented is a finite-element visco-plastic model based on the work of Chaboche. Due to its complexity, the model uses a significant number of parameters that need to be identified at several temperatures. The aim of this article is to define an efficient method for the identification of the parameters of this Chaboche model adapted to cyclic thermo-mechanical loading.

GS2-3

A new strain-based method to determine GTN parameters for thin stainless steel foil

Peng Zhang, Michael Pereira, Bernard Rolfe, Daniel Wilkosz, B Abeyrathna, Matthias Weiss

In this work, tensile tests were carried out on the 316L foil with a thickness of 0.1 mm to calibrate the Gurson–Tvergaard–Needleman (GTN) model. Two calibration methods were compared for calibrating the same test data. The common approach is to use iterative finite element simulations to fit the experimental load-displacement curve. A new strain-based approach, which uses strain data obtained by a Digital Image Correlation (DIC) system, is presented here. It uses a stress-return-mapping algorithm to reconstruct the fracture related state variable, i.e., the accumulated void volume fraction. Fracture is predicted when the critical void fraction is reached at the measured fracture moment. The study shows that the new approach

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gives similar fracture model parameters compared to the common method, but with significantly higher computational efficiency.

GS2-4

On the effect of stress state on the failure limits of hole-flanged parts formed by SPIF

Andres Jesus Martinez-Donaire, D Morales-Palma, M Borrego, G Centeno and C Vallellano

Single Point Incremental Forming (SPIF) is a novel and flexible forming technology that has been used in the last few years to obtain a variety of customized sheet parts. One of the most valuable advantages of this process is its ability to suppress the localized necking of the sheet, allowing a stable plastic deformation up to the ductile fracture of the sheet. Traditionally the fracture in sheet metal forming is characterized by the conventional Fracture Forming Limit (FFL) curve, obtained with Nakazima or Marziniak tests. However, in many cases the SPIF processes exhibit fracture strains clearly above the conventional FFL, showing an unexpected gain of formability. It is well known that ductile fracture in metals is highly affected by the stress state in the material. Therefore, among others, this fact could contribute to explain the experimental differences observed in the FFL obtained by conventional and incremental operations. The present work develops a numerical model in ANSYS to study the mechanics of the fracture process during the incremental deformation operation. The simulations focus on the hole-flanging operation by SPIF in AA7075-O metal sheets of 1.6mm thickness, recently experimentally analysed by the authors. Different configurations of pre-cut hole diameters are simulated. The evolution of the strain paths and the hydrostatic stress in the SPIF process are analysed and discussed. These variables help to explain the apparent enhancement of formability observed in SPIF processes beyond the conventional FFL curve.

GS2-5

Failure prediction in incremental sheet forming based on Lemaitre damage model

K Narasimhan, Abhishek Kumar, Abhishek Kumar Singh, Amber Shrivastva, Sushil Mishra

Single Point Incremental Forming (SPIF) is a dieless forming process. In this process sheet is clamped on its periphery and a hemispherical tool clamped on a CNC (Computer Numeric Control) machine applies small incremental pressure to deform the sheet in three dimensional component. During the process, strain increases on successive steps of forming and it is much above the conventional forming limit. These higher strains lead to excessive thinning which eventually results in failure. The aim of this work is to revisit the failure analysis in SPIF and study the effect of tool diameter on the failure. Finite element method (FEM) is used for the analysis of the process and a truncated cone is simulated using different tool diameter. For failure prediction, Lemaitre damage model, based on continuum damage mechanics, has been numerically implemented in FE software Abaqus/Explicit using user subroutine. Further, the results from numerical analysis such as strain evolution in deformation zone and thickness reduction are analysed.

GS2-6

Damage mechanics modelling of material separation in self-pierce riveting (SPR) process

Nicola Bonora, G. Iannitti, G. Testa, and A. Ruggiero

In numerical simulation of self-pierce riveting process (SRP) material separation criteria plays a critical role. In most of published works, material failure is simulated using numerical techniques, such as erosion criteria, that are calibrated on available experimental results. The lack of material based criteria strongly limits the use of numerical simulation as effective investigative tool for manufacturing process parameters assessment. In this work, damage mechanics is used to determine failure conditions in SRP considering dissimilar material sheets. In particular, the extended Bonora Damage Model (XBDM), which account for both void growth and void sheeting, was used. Damage model parameters for metal sheets have been determined independently and successively used in the simulation of SRP process. Results were compared with available experimental data.

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GS2-7

Measurement of local necking in tensile test of mild steel sheet for forming numerical simulation

Daisuke Shimizu, Susumu Takahashi, Hideyuki Sunaga, Masato Takamura, Shunsuke Mihara, Eiichiro Oohashi

Plate forging can be applied to the reduction of the forming time and costs of parts which have large thickness and complex shape. In many cases, the surface quality of the shearing portions is very important when their surfaces slide along those of other parts. The research and development of analytical methods for evaluating the surface condition of shear deformed parts are underway. Fracture in plastic working is generally ductile fracture. Therefore, studies on the analysis of fracture in material tensile tests are advanced. In this report, starting point of local necking is thought as starting point of fracture. Three methods are examined to find the starting point of local necking for mild steel sheets. Among these methods, the measurement method using the laser displacement mater is the most accurate.

GS2-8

Numerical investigations on a framework for fracture prediction in metal forming with a material model based on stress-rate dependence and non-associated flow rule

Tetsuo Oya, Jun Yanagimoto, Koichi Ito, Gen Uemura, Naomichi Mori

In this paper, the proposed framework for fracture prediction during sheet metal forming is explained and some numerical investigations are presented to demonstrate the effectiveness of this method. In particular, the role of parameters that affects the forming limit curves, which are represented by the initiation of local bifurcation in each stress rate, are examined; namely, anisotropic parameters and the KC value, which means a stress-rate dependence, and other material properties. The newly proposed concept of forming limit diagram is used to evaluate the formability of the concerned material and working process.

GS2-9

Material characterization and fracture prediction with advanced constitutive model and polar EPS fracture diagram for AA 3104-H19

Robert Dick, Yanshan Lou, Shunying Zhang, Jeong-Whan Yoon

Material characterizations for plasticity and fracture have been conducted from uniaxial tensile tests, bi-axial bulge test, and disk compression test for a beverage can AA3104-H19 material. The results from the experimental tests are used to determine material coefficients for the Yld2004-18p model [1]. Finite element simulations are developed to evaluate the predicted earing profile. Excellent agreement with the experimental data for eight ears exhibited in AA3014-H19 is achieved using the Yld2004-18p constitutive model. Further mechanical tests are also conducted on the AA3104-H19 to generate fracture data under different stress triaxiality conditions. Tensile tests are performed on the samples with a central hole and notched specimens to achieve tensile and plane-strain conditions. A specially designed torsion test of a double bridge specimen is conducted to generate the points near pure shear conditions. The Nakajima test is also utilized to produce a bi-axial tension condition. The data from the experiments is used to generate the fracture locus in the principal strain space. Mapping from the principal strain space to Polar Effective Plastic Strain (PEPS) space is accomplished for a general yield function. Finite element modeling is used to validate the fracture diagram in the polar space. A hole expansion demonstrates the accuracy of the PEPS fracture theory for the direction for onset of failure.

GS2-10

Development of the crack-line-update method for two-dimensional piercing simulations

Takashi Matsuno, Masato Takamura, Shunsuke Mihara, Takayuki Koda, Kaori Tsujioka

We have developed the crack-line-update method for two-dimensional piercing simulations by a finite element method. This method is combined with a remeshing process involving an outer line and meshing. By using the crack-line-update method, crack lines, which are derived from a stress and strain analysis of the high-damage regions, are added to the outer line in every remeshing step. In this paper, we compare the simulations between the mesh deletion and crack-line-update methods. The crack-line-update method

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successfully simulated the arresting of cracks during the piercing process, whereas the mesh deletion method could not express such fracture behavior.

GS2-11

Finite element analysis of blanking operation of magnesium alloy (AZ31) sheet using ductile fracture criteria and its experimental verification at various temperatures

Piemaan Fazily, Jeahyeong Yu, Chang-Whan Lee

This study focuses on modeling and analyzing sheet blanking process of Magnesium alloy sheet (AZ31) using finite element method at various temperatures. The computational analysis is then compared with the results obtained through the experimental setup. In the finite element model fracture initiation and the shape of the blanked edge are influenced by the value of critical damage criteria (C). The value of critical criteria is determined and compared using the ductile fracture criteria proposed by various researchers by varying various process parameters and temperature. The effect of temperature and process parameters on the geometry of the blanked edge including burr, fracture zone, shear surface and rollover has been investigated. Moreover, numerical predictions were compared with the experimental results.

GS3 Material Testing

GS3-1

Prediction of flow stress curve of metallic foam using compressible constitutive equation

Hiroshi Utsunomiya, Yohei Noguchi, Woo-Young Kim, Ryo Matsumoto

For industrial applications of metallic foams, it is demanded to develop the forming processes and technologies [1]. However, deformation of metallic foams is complicated due to changes in apparent density and volume during the process so that numerical prediction of the deformation is not easy. Compressible plastic constitutive equations with dependence on hydrostatic pressure have been used. In literature, the initial apparent density of the workpiece was considered, while change in apparent density during the process was rarely considered. Therefore the prediction is not applicable to heavy industrial forming Deformation of metallic foams in forming processes is complicated due to large volume change so that the prediction is not easy. In this study, cylindrical billets of open-cell type nickel foam were compressed uniaxially. Multi-step compression tests were also conducted to reveal changes in apparent density and diameter during the compression. For numerical prediction, Oyane’s yield criterion and the associated flow rule were assumed. With considering volume change in the compression, incremental analysis was performed. Changes in apparent density, diameter and flow stress curves were successfully reproduced with constants a=2.12, m=0.3 and n=2.0.

GS3-2

Cruciform specimen design for large plastic strain during biaxial tensile testing

Yong Hou, Junying Min, Jianping Lin, John E. Carsley, Thomas B. Stoughton

The cruciform biaxial tensile test can be used to map the hardening evolution of the yield surface over a wide range of loading paths, which is useful for calibrating and validating the advanced material models. However, when cruciform specimens following ISO Standard 16842 are used, equivalent plastic strain in the gauge region is limited to only ~0.03 for DP590. In this study, a new method was developed to strengthen the arms of ISO Standard cruciform specimen in order to achieve greater plastic deformation in the gauge region. Arm strength of cruciform specimens was enhanced by laser deposition of thickening layers using materials compatible with the base metal. Furthermore, the slit geometry in the arms was adjusted to improve strain distribution and delay fracture. To verify the proposed method, cruciform specimens of different base materials (Cr4, DP590, DP780 and DP980) were tested in a biaxial tensile testing system with the aid of digital image correlation (DIC) techniques to characterize the strain fields within the gauge region. The laser-deposition-affected zones were negligible for the base materials according to optical microscopy. For DP590, the laser deposition method provided an increase of equivalent plastic strain in the gauge region from ~0.03 to ~0.11 for various loading paths. Consequently, evolution of an experimental yield locus was obtained at equivalent plastic strains up to ~0.11 for DP590. Continuing work with Cr4, DP780

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and DP980 materials increased equivalent plastic strains to different degrees under nearly plane strain conditions (biaxial force ratio of 1:2).

GS3-3

Improvement of the drawing ratio of the anisotropic material behaviour under near plane strain conditions for DP600 characterized in elliptic hydraulic bulge test

Matthias Lenzen, Marion Merklein

The plane strain condition is one of the most frequent reasons for failure in a deep drawing process. State of the art material models do not consider this strain state in FE simulations. Since there is only the notched tensile test to determine the first principal stress, an improved testing setup is needed to characterize the first and second principal stresses up to high deformations to determine the material behaviour under plane strain conditions. Within this contribution, an innovative testing setup is used, which induces a near plane strain regime in the specimen with an elliptical hydraulic bulge test. Experiments are carried out in rolling and transversal direction for DP600. Based on the experiments, stress and stain based material characteristics are evaluated. For validation of the setup, square cups are deep drawn, which have a plane strain area at the drawing radius which causes cracking under this strain state. Due to the highly directional dependent material behaviour, the drawing ratio can be increased by considering the anisotropic material behaviour by cutting the blank in an optimized position according to the rolling direction.

GS3-4

Examination of evaluation method of uniaxial compressive property of cold-formed duplex embossed sheet metal by FEM analysis

Takashi Iizuka, Wuyang Liu

The utilization of applying periodic configurations to flat sheet metal will become a good method to enhance functional and mechanical properties. Especially, these periodic convexities and concavities of sheet metals are very good in enhancing functional property, such as heat radiation, improving of heat diffusivity, sound insulation and so on. In addition, this particular shape can also increase bending rigidity. In order to promote development of industrial technology for forming such sheet metals, it is necessary to offer information on the plastic feature of them. Here, this study focuses on sheet metal forming properties of a duplex embossed sheet, which has periodic convexities and concavities. And FEM analysis was carried out to attempt to conduct the uniaxial compression test used duplex embossed sheet by Blank holder force method which was got some inspirations from the method reported by Prof. Kuwabara. Based on analytical results, comparing the strain-stress responses and the equivalent strain maps which were obtained from uniaxial tension to those from uniaxial compression, it was found that embossing periodic structure itself had tension-compression asymmetry (SD effect).

GS3-5

Ductile failure under combined tension and shear

S Kyriakides, K Chen, M Scales

Recent tension-torsion experiments on Al-6061-T6 tubes have shown that strains inside localization zones that precede failure are much higher than previously reported. Furthermore, contrary to some other results, the measured strain at failure monotonically decreases as the triaxiality increases. This paper will review these results and subsequently present numerical simulations that demonstrate that suitably calibrated plasticity models can reproduce the measured deformations. The strains in the simulations approach the values measured at failure without the introduction of damage.

GS3-6

Influence of zinc coating on anisotropic mechanical properties of hot dip galvanized steel sheet DP600

G Li, X Y Long, S S Cui, Q W Huang, Z P Chen, S H Tan

The influence of zinc coating on the anisotropic mechanical properties of hot dip galvanized steel sheet DP600 is studied by tensile test. The results show that zinc coating makes the yield strength of the steel plate decrease, but has no obvious influence on the hardening index. Compared with the bare steel sheet,

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in the direction of R00 direction parallel to the rolling direction, the tensile strength and yield strength of galvanized steel sheet decrease, while the elongation and thickness anisotropy coefficient increase. After comprehensive analysis, it is found that the plastic deformation ability has decreased in the direction of R00 direction. and the plastic deformation ability decreases after comprehensive analysis. In the R90 direction, the mechanical property parameters of galvanized sheet all increased, and zinc coating improves the plastic deformation ability of the steel sheet. However, in the R45 direction, the variation extent of the mechanical property parameters of galvanized steel sheet is between R00 and R90. Therefore, the influence of zinc coating on the mechanical properties of steel plate is closely related with the rolling direction, which also illustrates that the adhesion strength between the galvanized layer and steel plate substrate is affected by the surface microstructure of rolled steel sheet.

GS3-7

Characterization of mechanical properties and formability of a superplastic Al-Mg alloy

Omid Majidi, Mohammad Jahazi, Nicolas Bombardier

In order to develop a reliable constitutive model for predicting formability and springback of sheet metals during superplastic forming (SPF) and quick plastic forming (QPF), characterization of elastic-plastic behavior, as well as formability of the material is essential. In the present study, the module of elasticity, uniaxial flow behavior and anisotropy, as well as the forming limit curve (FLC) of one of an SPF/QPF grade AA5083 was investigated. The variation of Young's modulus with temperature was measured from the uniaxial tensile tests for four temperatures ranging from 25 to 500 °C. The impact of temperature and strain rate on the flow behavior of the material was investigated via uniaxial tensile tests for three temperatures (420, 450, and 480°C) and at three strain rates (0.001, 0.01, and 0.1 s^{-1}). The dependency of the flow stress on the material orientation with respect to the rolling direction (0, 45, and 90°) was assessed using uniaxial tensile tests at a constant temperature. In addition, the evolution of plastic anisotropy with plastic strain and strain rate was assessed by measuring the Lankford coefficient (r-value). Finally, the FLC of the material at 450 °C was characterized according to Nakazima tests procedure for three strain paths (i.e. uniaxial tension, plane strain, and biaxial tension).

GS3-8

Characterisation of high strain rate material behaviour for high-speed forming and cutting applications

Marc Tulke, Christian Scheffler, Verena Psyk, Maik Linnemann, Dirk Landgrebe, Alexander Brosius

Determination of the material behaviour for high speed forming processes is challenging due to high process velocity and small specimen geometry in experimental analysis. This paper proposes two different material characterisation concepts for high strain rates at 10^3 s^{-1} and higher, namely a pneumatically device and an electromagnetically accelerated hammer, for obtaining experimental values. Furthermore, two measuring principles of the hammer velocity and displacement are presented and compared. The authors describe a measurement system with an acceleration sensor for the pneumatic device and a shadowing principle for the electromagnetically driven concept. Using the measured data, material parameters are iteratively adapted in an optimisation procedure until an objective function, comparing the difference between numerical and experimental results, is satisfied. In this case the parameter identification is applied on a strain rate dependent flow curve approximation based on Johnson-Cook.

GS3-9

Evaluation of tension-compression asymmetry of a low-carbon steel sheet using a modified classical compression test method

Takayuki Koizumi, Mitsutoshi Kuroda

A modified classical compression test method was used to examine in-plane tension-compression asymmetry in a low carbon steel sheet. In this compression test method, interfacial friction between the compression platens and specimen surfaces was significantly reduced by use of polycrystalline diamond plates installed on the compression dies. Furthermore, crosshead displacement of the universal testing machine, which inherently includes deflection of the machine itself, was corrected to the net deformation of the specimen based on a series spring model. Consequently, precision of the compressive strains

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obtained with the present test method is equivalent to that attained in the standard tension tests using wire strain gauges. For tension and compression tests performed at in-plane directions of 0°, 45° and 90° relative to the rolling direction (RD), significant tension-compression asymmetry (i.e. strength differential effect (SDE)) was observed. In all the mechanical tests in the three testing directions, flow stresses in tension tests were smaller than those in compression tests.

GS3-10

Sheet thickness reduction influence on fracture strain determination

Miroslav Urbanek, Pedram Farahnak, Martin Rund, Jan Dzugan

Standardly, the FLC curve [11] is determined based on ISO12004 according to Nakajima test or Marciniak test [1]. There are two basic influences: the friction between the punch and the specimen and at the same time the pushing the punch on the specimen, which affects the strain distribution over the sheet thickness [17]. The main disadvantage of these tests is the measurement of the linear deformation paths only, but the real forming processes are usually formed in multiple steps processes and the loading path is strongly non-linear. The current trend for sheets formability assessment is investigation of non-linear deformation paths performed on cruciform specimens [2, 3] or using a combination of Marciniak and Nakajima tests [6], [7]. The cruciform specimens should have reduced thickness in the central part in order to assure main plastic deformation and fracture in this region [18]. However, there are indications that the thickness reduction can influence results of the formability assessment. The main goal of this present paper, is experimental investigation of effect of local material thickness reduction on FLC and on Fracture Forming Limit Curve (FFLC). The cruciform specimens with a reduced thickness is investigated with the use of the biaxial stand without friction and pushing the punch. All results are compared to the FLC values.

GS3-11

Material testing in support of the development and calibration of material models for forming simulations

A. Gilat, J. Seidt

Material testing at various strain rates, temperatures and loading conditions provides data that is used for the development and calibration of constitutive equations (material models) that are utilized in numerical simulations of sheet metal forming. In general, the testing can be divided into characterization tests and validation tests. In characterization tests basic material properties (e.g. yield stress, ultimate stress, failure strain) are determined from a test in which a material coupon is loaded under a well-defined condition (stress, strain rate, temperature, etc.). The data is used for determining the values of parameters in plasticity and failure models. In validation tests a material specimen or a small component is loaded with a more complicated, but well defined, loadings. The test is numerically simulated and the calculated quantities (forces, deformation, failure, temperature, etc.) are compared with measurements. The recent development of the Digital Image Correlation (DIC) technique for full-field measurement of deformation has extended the useful data that can be extracted from traditional characterization tests and provide means for developing new experiments that can be used for obtaining more accurate material models. This paper reviews the advantages of using DIC in traditional tests and presents several new recently developed testing configurations for material coupons and small components. Many of these tests have been used during in the development of a failure surface that gives the equivalent plastic strain to failure as a function of stress triaxiality and the Lode parameter.

GS4 Innovative Forming Methods

GS4-1

Double sided incremental forming: capabilities and challenges

N V Reddy, R Lingam

Incremental Sheet Forming (ISF) is gaining importance because of its flexibility to form customized/low volume sheet metal parts. Out of different variants of ISF, Double Sided Incremental Forming (DSIF) is most flexible variant which uses two tools, one to form the geometry and the other to provide local support.

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Complex geometries with features on both sides of sheet can be formed in single setup by changing the roles of forming and supporting tools based on the geometrical characteristics. This article presents the evolution of DSIF process, machines, methodologies and strategies to form complex geometries and their prediction. A multi-stage methodology is attempted to enhance the accuracy of large components is presented. Results show that the accuracy of a 250 mm × 250 mm size conical component is enhanced by 50% (maximum error reduced from 2.9 mm to 1.4 mm) using two-stage forming.

GS4-2

Electromagnetically assisted sheet metal stamping with non-disposable foil coils

Ming Jin, Min Wan, Anlin Long, Wenping Wang, Xiangdong Wu

Coil in electromagnetic forming (EMF) process commonly requires high strength and long longevity to be robust enough to accommodate great input energy that makes the coil difficult and costly to be manufactured. However, foil coils, in most cases, utilized for part calibration, vaporized for shearing, welding and embossing are less consuming in both time and outlay, easier to be fabricated and replaced, but are mostly disposable. Therefore, the purpose of this paper is to study feasibility of utilizing non-disposable foil coils in EMF process via forming the part (150 mm × 150 mm) with hyperbolic curve like cross-section feature with 1 mm thickness AA 2524-T3 aluminum alloy sheet. Copper foil of 0.5 mm, 1 mm thickness, wrapped in polyimide insulation foil are used as coils in two steps of a quasi-static two-mould-closing pre-forming and EMF process. Besides, practical orthogonal tests are deployed to explore these coils' forming performance and find the factors' influential sequence to obtain appropriate process parameters. Results of loose coupling simulation with selected parameters, using ANSYS APDL macro and ABAQUS keywords will be presented and compared with formed components corresponding to simulation load steps. Eventually, formability of sheet component under conditions of diverse charging voltage, foil thickness, foil layers and number of loading repetition and longevity of these coils were experimentally investigated. And the study demonstrates that this technique can be used to improve sheet metal stamping process.

GS4-3

Numerical and experimental investigation on tube hot gas forming process for UHSS

Yulong Ge, Pengzhi Cheng, Yong Xia, Qing Zhou

Ultra-high strength steels (UHSS) have been regarded as one of the most attractive alternatives for lightweight parts in automotive industry. In this study, the tube hot gas forming process is introduced to implement high temperatures forming for UHSS tubular components. In the proposed process, the tube blank is first heated up to 900°C for several minutes to achieve homogeneous austenitization and then quickly transferred to a press for forming. Nitrogen gas replaces? water in traditional hydro-forming process as media to apply internal pressure in a heated tube. To enhance the energy absorption capability of the components, a one-step quenching and partitioning (Q&P) process is conducted by the die cooling during deforming simultaneously to increase the elongation and ductility of the material. Moreover, a numerical investigation on a tube component fabricated from 22MnB5 steel is performed. The temperature distribution and microstructure evolutions are studied, which demonstrates the forming quantity advantages of tube gas forming process.

GS4-4

Characterization of ultra-fine grained AA 6061 alloy sheets processed through two different severe plastic deformation techniques

Kandarp Changela, K. Hariharan, D. Ravi Kumar

Al-Mg-Si (AA 6061) was subjected to two different severe plastic deformation (SPD) routes of cryorolling (CYR) and constrained groove pressing (CGP) to investigate their effect on mechanical properties and microstructure. In both the routes, large amount of plastic strains are applied in sheet metal blanks to obtain ultrafine grained structure. Solutionized AA 6061 alloy sheets have been cryorolled to reduce the thickness from 6.5 mm to 1 mm (true strain 1.87). Samples of this alloy with 3 mm thickness have been subjected to CGP with an equivalent plastic strain of 1.16. The CGP samples have been subsequently cold rolled to reduce the thickness to 1 mm (67% reduction) so that the mechanical properties and

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microstructure from both the routes could be compared with the samples of same thickness. Microstructure of the deformed samples was characterized by optical microscopy and X-ray diffraction to investigate grain refinement and its influence on mechanical properties. From the results, it has been found that CGP followed by cold rolling is also a suitable process to produce UFG Al alloy sheets with mechanical properties similar to those of cryorolled sheets.

GS4-5

Experimental investigation of novel impact hydroforming technology on sheet metal formability

Yan Ma, Shi-hong Zhang, Yong Xu, Ali Abd El-Aty, Dayong Chen, Yanling Shang, Guoqing Chen, Artur Igorevich Pokrovsky

The present article aims at investigating the effect of impact hydroforming (high strain rate forming) on the formability of AA5A06. In comparison, traditional hydroforming is also conducted. The formability of AA5A06 is investigated trough hydro-bulge test at room temperature and strain rate range 4.67×10^{-3}-3.18×10^{3} s^{-1}. The results show that the effective fracture equal-biaxial strain was not increased monotonically by increasing the impact velocity. There exists an optimal impact velocity, under which velocity the maximum effective fracture strain of biaxial zone increases by 62.18% compared with the quasi-static condition. It is concluded that mpact hydroforming is an effective forming technology to achieve high formability and to form complex parts with low plasticity metals. In this paper the equi-biaxial strain of FLC is also theoretically calculated by Swift and M-K models. The plastic anisotropy is also taken into account during this calculation by introducing the anisotropy yield criteria, which is seldom discussed in the dynamic field. The results show that the M-K model is more suitable for calculating equi-biaxial strain of AA5A06 at high strain rate.

GS4-6

Case studies on chain-die forming for AHSS

Chunhui Yang, Raju Majji, Yang Xiang, Scott Ding

In this study, three case studies were conducted to develop a reliable finite element-based numerical model of Chain-die Forming (CDF) with AHSS. These simulations demonstrated the effectiveness of this forming process while capturing the mechanical behaviours of AHSS. The numerical modelling and simulations serve as Computer Aided Engineering (CAE) tools which determined tool geometries and control unwanted spring back. An automotive martensitic steel DOCOL 1400M from SAAB was adopted for this research as a typical AHSS material, which has a yielding strength of 1,150 MPa and a tensile strength of 1400-1600 MPa. There were three case studies involved (a) Case Study – 1: Forming AHSS 60o section; (b) Case Study – 2: Forming AHSS 90° section; and (c) Case Study – 3: Forming top-hat section. All three cases were conducted to achieve desired profiles in minimum number of passes without defects. Validation and verification of the CDF process were further demonstrated based on these case studies. According to the numerical and experimental results obtained, Chain-die Forming (CDF) can be considered as an affordable, sustainable and environmental friendly manufacturing process.

GS4-7

Comparison of thickness variation in multistage deep drawing of a stator motor housing by experimental and simulation methods

BHARGAVA MARRAPU, ROHIT PATIL, KOTESWARA RAO Jakkula, ARUN SHETTY

The objective of the present work is to study the thickness variation in multistage deep drawing of a stator motor housing by experimental and simulation methods. The final component of a stator motor housing is formed in five stages. The stator motor housing component in each stage is divided into different regions like punch flat region, punch radius region, wall surface and die flange region. The thickness variation is studied in all these regions to meet the required specifications. The thickness at each region is measured using an ultrasonic device. Finite element method (FEM) simulations were performed to predict the thickness of the stator motor housing at different regions. It was found that the simulated thickness at different regions is very close to experimental results and the experimental thickness variation in the stator motor housing was within the specification limits. A progressive tool is developed to reduce the process to form the stator motor housing so that production time can be saved and higher numbers of components

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can be produced. The stator motor housing is manufactured using this progressive tool and thickness is measured at the different regions.

GS4-8

Developing a progressive draw with ironing tool for manufacturing a solenoid casing

ROHIT PATIL, BHARGAVA MARRAPU, NAVEEN CHAND MANDADAPU, KOTESWARA RAO JAKKULA, ARUN SHETTY

The present paper focuses on developing a progressive draw with ironing process for production of solenoid casings with the main aim of reducing the number of presses required to form the component thereby reducing the cost of the component and enhancing the productivity rate. The material used for the present study is extra deep drawing (EDD) steel. In progressive draw with ironing tool, the first draw operation takes place followed by the ironing operation in a single tool. The progressive draw with ironing tool consists of three different die inserts planned one below the other in single station. The solenoid casing is manufactured by using this progressive draw with ironing tool and the thickness is measured at the dome and wall regions using an ultrasonic thinning measuring device. Tensile tests were performed for EDD steel according to ASTM standards and mechanical properties were evaluated. Finite element method (FEM) simulations were performed using the mechanical properties evaluated from tensile tests to predict the thickness at the dome and wall regions by using the progressive draw with ironing tool. It is found that the simulated thickness is close to experimental results. It is also found that the surface finish on the component has improved and die life has increased due to use of internal lubrication with coolant supplied.

GS5 Process Design and Optimization

GS5-1

Drawbead uplift force analytical model for deep drawing operations

Eneko Saenz de Argandoña, Imanol Gil, Lander Galdos, Joseba Mendiguren, Nagore Otegi

Drawbead uplift force calculation has been an open issue among the deep drawing tool maker and software developers in the last years. Starting from the original work of Stoughton (1988) many have been the models presented in order to improve the predictions. However, still nowadays, the main deep drawing software are not able to accurately predict the uplift force and clear example of that are the intensive effort of the software developers in that topic as well as the conversion factors used by the main OEM when acquiring a new tool. In this work, a new semi-analytic model of drawbead closing force calculation is presented. The model is not only able to predict the uplift force for different steps of the closing (very useful for the set-up process) but it has been validated when using a high strength steel (DP780) for different drawbead configuration.

GS5-2

Study of V-bending deformation characteristics of magnesium alloy sheet in warm forming

Hyun Woo Kim, Jea Hyeong Yu , Chang-Whan Lee

Magnesium alloys have low elongation at room temperature. Warm forming is a common method used for forming of magnesium alloy sheets. In the V-bending process, the bending deformation of magnesium alloy sheet due to effect of strain rate is different at the room temperature and 250°C. The bending behaviour at 250°C makes the radius of curvature of sheet larger than the punch radius. The results of V-bending deformation of magnesium alloy sheet in warm forming were investigated both experimentally and numerically. Three-point contact occurred due to effect of strain rate at 250°C

GS5-3

A software package for toolpath generation and process simulation of incremental sheet forming

Michael C Elford, Jaro Hokkanen, Andrew J E Stephan

Incremental Sheet Forming (ISF) is a CNC based forming method whereby parts are formed one layer at a time using a blunt moving forming tool (stylus). Whilst forming times can be on the order of hours for large parts, the absence of expensive metal tooling makes this an attractive technology for low volume part

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production or prototyping. The long forming time can however present a significant challenge for traditional simulation software due to the amount of physical time which must be simulated. Previous NUMISHEET benchmarks [1] have shown that simulations of even twenty minutes of physical forming can require anywhere from hours to weeks of computational effort. This presentation will introduce a dedicated ISF software package, the 'ISF-Toolkit', which has been designed as a companion to the ISF manufacturing process. An example geometry will be used to demonstrate the toolpath generation and simulation capabilities of the software. With respect to the simulation capability, the software is linked to three high speed Graphics Processing Unit (GPU) based solvers. The results of running the three solvers for the example geometry will be compared to the experimental results obtained using an Amino DLNC-PC ISF machine.

GS5-4

Intermediate shapes for incremental sheet forming

William Daniel

Incremental sheet forming has limitations such as when forming a steep wall angle with a small radius tool. These limits need to be anticipated by using a multistage strategy with intermediate shapes, that avoids excessive strains. In designing methods to smooth a formed shape to achieve an intermediate shape, work on digital image processing is informative. In particular, K. Crane [6] and others have used solution of Poisson's diffusion equation to obtain a smoothing of a surface. An alternative approach labelled false elasticity smoothing to estimate intermediate shapes is presented here. Two parameters control smoothing of the final shape: one to scale back curvatures and one to scale back membrane strains. Membrane strains are estimated to give nodal forces. The curvature tensor at any element centre is estimated from the final shape to predict nodal moments. Scaling back moments will reduce local curvature, and scaling back forces will reduce the membrane strains. An elastic finite element solution predicts an intermediate shape, typically giving priority to reducing the local peak curvatures. This can be repeated until the sheet is flattened. The application of this approach to trial geometries is presented, and the choice of smoothing parameters discussed.

GS5-5

Numerical investigation of a new sheet metal shear cutting tool design to increase the part quality by superposed compression stress

Sergei Senn, Mathias Liewald

Nowadays, a major criterion for the quality of shear cut workpieces is characterised by a smooth final cutting surface. Normally, this surface only can be manufactured by using fine cutting or trimming technology. Major disadvantage of these processes is the complex tooling design caused by a double-acting press and corresponding tool layout. Content of this numerical study is to investigate the impact of a new sheet metal cutting tool design to increase the clean-cut portion in conventional shear cutting of high strength steel (DP600). Using FEA-Software DEFORM 2D, the models of fine cutting, conventional cutting and cutting with new tool design were mapped by comparing cutting surface results and stress distribution in the shearing zone. The main criterion of the optimization of tool design focuses on an enlarged clean-cut area along the cutting surface compared to conventional shear cutting. This study is based on the design of experiments (DOE) using Latin-Hypercube-Variation of the factors cutting clearance, die radius, punch radius, punch velocity, part holder force and special geometry designs to identify and to optimise new tool geometry. New tool design shows a significant increase of clear-cut surface up to 73% compared to conventional cutting surfaces disclosing 35% when using tools according to standard design rules. Using this new punch design, it is possible to shear high strength steels revealing a noticeably performed shearing surface quality.

GS5-6

Energy efficient roll forming processes through numerical simulations

Tilman Traub, Peter Groche

Due to ongoing efforts to mitigate climate change especially large scale manufacturing methods such as roll forming have to be optimized with respect to energy consumption. The required amount of drive power in

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roll forming is strongly affected by the rotational velocity of the tools. Due to the contoured shape of the rolls resulting in varying circumferential speed, the relative speed between tool and blank sheet can be positive, negative or zero. In consequence, neighboring sections of the same forming roll can accelerate or decelerate the blank sheet. Inappropriate speed ratios between different shafts cause some shafts to decelerate the blank sheet while other shafts have to compensate this deceleration and waste energy. Presently, the rotational speed of the shafts is mainly chosen based on the operator's experience leading to a high risk of an energy inefficient process setup. This paper demonstrates how numerical simulations can optimize the energy demand in roll forming and validates the results experimentally. The drive power for each individual shaft is minimized by balancing accelerating and decelerating tool sections. Thus, the optimal rotational velocity for each shaft is derived. The numerical simulation predicts an energy saving potential of 50 %. However, due to limited control accuracy only 14 % could be realized in experiments to date.

GS5-7

Numerical study on the thickness homogenization in hole-flanging by SPIF

Domingo Morales-Palma, Marcos Borrego, Andrés J. Martínez-Donaire, J. A. López-Fernández,Gabriel Centeno, Carpóforo Vallellano

Incremental sheet forming is a novel technology that has signicant benets compared to conventional forming. However, it is a time-consuming process that is usually carried out in several forming stages to homogenize deformation and avoid material failure. In hole-anging operations by SPIF, a single-stage strategy might provide functional anges in considerably less time, however a non-uniform thickness is obtained along the ange. This work proposes a two-stage process as the best strategy to increase production rate, and an optimization methodology to produce a homogeneous thickness distribution of the flange. The procedure is used to automate the design process of parts and tool trajectories by CAD/CAM, and validate the optimal forming strategy by FEA.

GS5-8

Analyses of press formability of CFRP sheet considering the fiber kinking and the ductile behavior of resin

Takahiro Hayashi, Tetsuo Oya

Establishment of a press forming method of carbon fiber reinforced plastic (CFRP) is desired. However, fundamental research on a ductility improving mechanism of CFRP is still insufficient. Since unidirectional CFRP shows different characteristics in compression and tensile deformation, accurate expression in both characteristics is necessary to investigate factors that affect formability. To express fiber kinking and ductile behavior of resin, a microscale model that separated fiber and resin was made. The fiber part in FEM model was tilted as initial misalignment and Gurson-Tvergaard-Needleman (GTN) model was applied to the resin part. To investigate the influence of design parameters such as temperature and initial void fraction on formability, this study performed tensile, compression and bending analyses by changing the resin temperature and initial void fraction. Results of compression analysis showed that the higher the temperature and initial void fraction, the earlier fiber kinking occurrence. Bending analysis showed a similar tendency. These results are physically reasonable. Therefore, these numerical experiments confirmed that the model used in this research is valid for studying factors that affect formability.

GS5-9

Metamodel-based methods to verify the feasibility of a process control in deep drawing

David Harsch, Jörg Heingärtner, Yasar Renkci, Pavel Hora

In production of deep drawn sheet metal parts it is often challenging to achieve a robust process. Especially in the production of kitchen sinks made out of stainless steel, the fluctuation of the process and material properties often lead to robustness problems. Therefore, numerical simulations are used to detect critical regions. By means of a series of finite element simulations with variable noise and design parameters, metamodels are computed for each quality criterion. Based on the metamodels, the influences of changing noise variables on the individual quality features are identified. To keep a constant product quality, the process settings (design parameters) should be adjusted. By means of new metamodel-based methods, the

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controllability of quality features is verified for user-defined production scenarios and visualised for each design and noise parameter. Thus it is possible to identify which design parameters are indispensable to control the desired quality feature and if it is controllable depending on the actual values of the noise variables. Furthermore the controllability of the entire part is analysed by using draw-in measurements for the feedback loop. Thereby it is possible to simulate, based on the metamodels, the effects of a series production, such as the heating of the tools during the first dozen of parts. Hence, the feasibility of a process control can be verified before realisation in order to optimize the concept of process control or even the process design.

GS5-10

Investigation on stretch forming process of thick double-curved aluminium alloy component

Xiaoxing Li, Taotao Fang, Yulong Ge, Xiaoxing Li

Stretch forming process is extensively employed to manufacture aluminium alloys aircraft panel part which possesses large size. These panels usually have a various double curvatures geometric contour. A stretch forming process is proposed to make this part. It indicates that this process which is optimized by research work can be used to manufacture the thick aluminium panel possessing double curved contour with high accuracy. Furtherly in help of the optimization of process parameters by this research work, the manufacturing process may be simplified by means of reducing the forming steps. This stretch forming process has been applied in industry manufacturing. This method is feasible for further stretch process design.

GS5-11

Stamping parameters optimization of a AA5754 A-pillar by response surface methodology

Ming dong Huang, Chao Li, Lei Fu, Li Li, Cheng Liu

In this paper, an A-pillar was selected as an example to investigate the effect of stamping parameters on the parts forming quality of AA5754 sheet. A finite element model was established using commercial stamping software PAMSTAMP2G. Barlat2000 yield function was used to describe yield behavior of the material. Stamping experiment was conducted to validate the reliability of the model. The studied parameters are blankholder force (100-700 KN) and drawbead's geometrical variables, including two fillet radii R1 (8-12 mm), R2 (4-8 mm) and the height of drawbead D (2-6 mm). The central composite experiment design method has been employed to design the simulation matrix. In order to obtain stamped parts with optimal forming quality, response surface methodology was used to establish the relationship between stamping parameters and forming quality (rupture and springback). The non-domination sorting genetic algorithms II (NSGA-II) was adopted to conduct an optimal calculation of the models. A pareto optimal solution set in the solution space was obtained. A reasonable optimized scheme was selected. The optimum blankholder force is found to be 700 KN with the drawbead's geometrical parameters R1, R2 and D of 12 mm, 6.6 mm and 3.8 mm, respectively.

GS6 Numerical Methods

GS6-1

Microstructure-based multiscale approach to obtain mechanical property of duplex stainless steel according to ICME concept

Mototeru Oba, Sukeharu Nomoto, Kazuki Mori, Akinori Yamanaka

We have proposed a microstructure-based multiscale simulation framework based on Integrated Computational Material Engineering (ICME) concept and applied it to the simulation of hot rolling process of a duplex stainless steel. In the study, the finite element simulation of the hot rolling process is performed. The mechanical property of a slab is calculated on the basis of its underlying solidified microstructures, which are simulated by the multi-phase field method coupled with CALPHAD thermodynamic database. The properties of constituent phases in the solidified microstructure is obtained by the first-principles calculation, the molecular dynamics simulation and nano-indentation tests. The mathematical homogenization method is used to calculate the property of slab based on the microstructure. This paper reviews the application of the multiscale simulation framework to a SUS304 duplex stainless steel.

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GS6-2

Efficient Isogeometric shell element with through-thickness stretch: application to incremental sheet forming

Jaro Hokkanen, Dorival Pedroso, Michael Elford, Andrew Stephan, Yunpeng Zhang

An isogeometric shell element with through-thickness stretch is applied to a two-point incremental forming problem. The shell element supports full three-dimensional constitutive laws and therefore does not make the plane stress assumption. An anisotropic material model is implemented to account for the sheet rolling direction. Automatically adjusting penalty stiffness is proposed for modeling the contact between the stylus tool and the sheet, whereas the die contact algorithm uses traditional constant penalty stiffness. A comparison is made between experimental results as well as results from a conventional shell formulation.

GS6-3

Automatic calibration of 3D anisotropic yield criteria using a parallel evolutionary algorithm

Yunpeng Zhang, Dorival Pedroso, Andrew Stephan, Michael Elford

Advanced 3D non-quadratic anisotropic yield criteria are usually required to describe highly anisotropic materials such as aluminium alloys. One issue related to the advanced anisotropic yield criteria is that they often require the identification of many parameters that are difficult to calibrate. An automatic and reliable technique for the determination of the coefficients of 3D anisotropic yield criteria is presented here. The error between predictions and experimental data is minimised by finding the yield criteria coefficients using a modification of the evolutionary algorithm described in (Pedroso et al. 2017 Applied Soft Computing 61 995-1012). The method is implemented for parallel computation to both speed up calculations and to make sure the results are consistent after several runs. The results show that the proposed method can produce good coefficients for the 3D anisotropic yield criteria.

GS6-4

A GPU based explicit solid-shell finite element solver

Andrew Stephan, William Daniel, Michael Elford

In this work we present a co-rotational/updated Lagrangian, strain-rate based explicit finite element code which uses hexahedral solid-shell tri-linear elements, intended for simulation of the incremental sheet forming (ISF) process. This element is based heavily on the elements described in [1, 2, 3]: it is under-integrated with a single stack of stress integration points in the thickness direction passing through the elements center; it uses Assumed Natural Strain (ANS) interpolates for the thickness and transverse shear strains; it uses a single parameter Enhanced Assumed Strain (EAS) for the thickness strain; and it selectively scales the mass in the through thickness direction to increase the stable time-step. We combine these methods with a hypo-elastic constitutive model to simulate the ISF process. Initial results obtained with a GPU implementation of the element are presented.

GS6-5

Investigation of blank bow defect after roller leveller by finite element analysis

Kirill Trusov, Petr Mishnev, Eduard Garber, Natalia Bolobanova, Dmitry Nushtaev

Sheet metal often shows curvature, shape defects and internal (residual) stresses which are not complying with the increasing requirements for the quality needed for customers. Roller levelling is one of the ways to flatten a metal sheets. The setting up of such machines is extremely complex and mainly depends on the operator's experience. The main objective of this paper is investigation of adjustable parameters of roller leveller together with elastic-plastic material behaviour on the internal stresses formation. High and unbalanced values of residual stresses lead to blank bow defects in a final product. In this study, numerical finite element (FE) 2D-model of roller levelling process is proposed to use. Properties of the material were determined experimentally. The blank bow magnitude was simulated and compared with experimental results and have a good accuracy for FE prediction.

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