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Research Paper

Damage initiation and fracture loci for advanced high strength steel sheets taking into account anisotropic behaviour

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ABSTRACT

In this work, ductile failure loci for advanced high strength (AHS) steel sheet grade 780 and 1000 were determined by using a combined approach between experiments and FE simulations. Effects of anisotropic behaviour of the steels were considered. Tensile tests of sheet specimens with various geometries taken from the rolling, transverse and diagonal direction were performed. During the tests, the direct current potential drop (DCPD) method and digital image correlation (DIC) technique were applied for identifying damage initiation on the micro–scale and fracture occurrence of the steels, respectively, under different states of stress. Subsequently, FE simulations of the tensile tests were carried out and stress triaxialities, equivalent plastic strains and Lode angles were evaluated for the corresponding critical areas. Hereby, the von Mises, Hill's 48 and Yld2000–2d yield criteria coupled with the Swift hardening law were applied. The threshold values within the triaxiality range of 0–0.577 obtained from different samples were plotted as the 3D failure loci of the examined steels. The predicted damage initiation states were also verified by SEM analysis. Then, influences of different material orientations and yield functions on the shape alteration of the determined failure locus were studied. To investigate formability of the steel sheets the damage initiation and fracture loci were transformed to strain based forming limit curves (FLCs). Additional limiting strains for the shear stress region were here incorporated. Finally, a non–symmetric rectangular cup test was conducted for the investigated steels until fracture. Then, plastic strain distributions, strain paths of the critical areas and achieved drawing depths were evaluated by the FLCs. It was found that the proposed FLCs could fairly predict fracture incidence of the formed parts under shear deformation. Moreover, damage initiations were predicted at about 70% of the final drawing depth.

1. Introduction

Nowadays, the automotive industries have been rapidly grown up and investments are greatly increased due to much higher technological competitions. By the manufacturing of automotive parts and components, sheet metal forming technology belongs to one of the most important sections. To achieve lighter vehicles with reduced fuel consumption but improved safety performance advanced high strength (AHS) sheet steels have been progressively applied. Such steel grades exhibit superior strength and fair elongation when comparing with other low carbon steels with the same strength. However, these steels have still shown difficulties during their forming processes because of their complex microstructural characteristics and consequently unexpected failure behaviour. On the one hand, design of forming procedures, dies as well as part shapes and geometries needed to take into account this concern. On the other hand, small micro–cracks could occur in formed components and subsequently cause premature failure in operation or lowered durability. Therefore, methods or approaches for predicting damage occurrences of AHS steel parts during their forming processes with higher accuracies are necessary. Until now, various fracture criteria for ductile materials have been studied and developed. One of the mostly applied ductile fracture models was introduced by Gurson (1975). The model was developed on the basis of void nucleation and growth, which was supposed to be the main factor for causing failure in porous ductile materials, as reported in Gurson (1977). This model was further enhanced by Tvergaard (1981) and Tvergaard and Needleman (1984), in which secondary voids, which took place after a certain deformation, accelerated void coalescences and three adjusted parameters were included. It was shown that more precise prediction could be hereby achieved. The model proposed by

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Gurson (1977) and Tvergaard and Needleman (1984) has been widely applied to predict failure of ductile materials in many previous works. Besson et al. (2001) developed a damage model based on the Gurson–Tvergaard–Needleman (GTN) model for presenting the crack growth in round bars and plane strain specimens, which showed cup and cone fracture at the end. However, procedures for determining model parameters were not described. Also, the predictions provided by the model were not verified with any experimental results. One crucial concern of the GTN model has been the large number of material parameters and extensive identification procedures. This led to a limitation in industrial applications. Faleskog et al. (1998) and Gao et al. (1998) used cell model as a predictive tool for nonlinear fracture analysis of the examined material. A key feature of this computational model was the description of material in front of the crack represented by a layer of similarly–sized cubic cells. Each cell contained a spherical void of initial volume fraction of f_0 and subsequently resulted in void growth and coalescence as defined by the GTN model. The micromechanics model was firstly calibrated taking into account both strain hardening and strength of the material. Then, the model was successfully applied to predict load, displacement and crack growth histories in specimens considering two crack geometries with different crack tip constraints and crack resistance behavior. Lemaitre (1985) presented an integrated model of ductile plastic damage, which was developed on a thermodynamic and effective stress concept. It was shown that the damage was linear with equivalent strain and was largely influenced by the triaxiality. Its validity range was limited by the assumption of isotropic plasticity, isotropic damage and constant triaxiality ratio during loading. Dhar et al. (2000) applied Lemaitre's model in large deformation elastic–plastic FE simulations for studying mode I ductile fracture in AISI1095 steel. It was stated that the proposed criterion is acceptable by predicting the critical load for crack growth initiation in the material. The ductile fracture process was directly influenced by both the plastic strain and triaxiality. Chaboche (1993) proposed another phenomenological approach of continuum damage mechanics for describing fracture processes of elastic solids under consideration of anisotropic and unilateral damage. Hereby, anisotropic damage was basically assumed and tensorial damage variables were introduced. A relationship between small crack occurrences and strain direction was examined. Hammi et al. (2003) described anisotropic ductile damage behaviour of Al–Si–Mg alloys. The developed damage–plasticity coupling model was based on the effective stress concept, in which effects of damage tensors on the deviatoric and hydrostatic part were taken into account. Therefore, the induced damage anisotropy was mainly driven by the void nucleation as a function of the plastic strain rate tensor.

For sheet metal forming, Behrens et al. (2012) reported an approach using experimental and numerical analyses for characterizing flow and fracture behaviour of cold rolled dual phase (DP) steels under a wide range of plane stress states. A modified Miyauchi shear test was here carried out, in which plastic strain localization at the sample edges was noticeably reduced. Therefore, shear fracture behaviour, which was critical for deformed steel sheets, could be more precisely examined. Björklund and Nilsson (2014) clearly reported that failure in ductile sheet metals was principally induced by tensile fractures, shear fractures or localized instability. The state of stress occurred during plastic deformation of DP steel sheets strongly affected their failure mechanisms, which was verified by scanning electron microscope (SEM). Furthermore, FE simulations were performed to determine effective plastic strains at failure as a function of the average stress triaxiality and average Lode parameter. Generally, shear test has been frequently used for sheet metals in order to achieve large deformations without plastic instability. Yin et al. (2014) developed different shear tests for extensively investigating material behavior under shear conditions. In this work, results of the shear test proposed by Miyauchi, using sample according to the ASTM standard and an in–plane torsion test were compared. Here, a unique overview of the most commonly used shear tests for sheet metal characterization was provided.

Otherwise, various failure criteria and approaches have been also developed for predicting damage and fracture of sheet materials. However, in the case of sheet metal parts with complex geometries or made of higher steel grades, more accurate tool or criterion is yet needed for the manufacturing process. Bao and Wierzbicki (2004) emphasized that stress triaxiality was the most important factor, which governed ductile fracture initiation, beside the strain magnitude. A series of tests including upsetting tests, shear tests and tensile tests of an aluminum alloy was carried out. Based on experimental and numerical results it was observed that fracture mode of the material could be divided into three distinct regions. For negative stress triaxialities, fracture was governed by shear deformation. For large stress triaxialities, void evolution was the dominant failure mode. At low stress triaxialities between the two regimes, a combination of shear fracture and void growth was found. Bai and Wierzbicki (2010) applied the Mohr–Coulomb (M–C) fracture criterion for describing ductile fracture of isotropic crack–free solids. It was shown that the hydrostatic pressure and Lode angle parameter significantly controlled fracture appearance of ductile metals. In this work, the M–C criterion was transformed to the spherical coordinate system containing the axes of equivalent strain to fracture, stress triaxiality and normalized Lode angle parameter. An aluminum alloy and high strength steel grade TRIP690 were used to calibrate and validate the proposed fracture model. It was found that the fracture locus could precisely predict material ductility in dependence on the stress triaxiality. For conventional deep drawing steel sheets, necking has been the dominant failure mode. Nevertheless, AHS steel sheets showed a typical shear fracture, which could not be simply predicted by the forming limit curve (FLC). Li et al. (2010) applied the fracture locus, which was represented on the plane of the equivalent strain to fracture and the stress triaxiality, to predict crack initiation and propagation of the AHS steel grade HCT690T during a series of deep drawing–punch test. This fracture locus was based on the modified Mohr–Coulomb fracture criterion (MMC). Furthermore, the 2D fracture locus was transformed to the space of principal strains with two new branches, which exhibited the formation of shear–induced fracture. Gruben et al. (2011) studied the fracture behaviour of AHS steel sheet under quasi–static loading conditions. The fracture occurrences were characterized by using the digital image correlation (DIC) technique in combination with FE simulations of various mechanical tests. Hereby, a method for determining the stress triaxiality and Lode angle parameter based on the DIC measurements was shown.

On the other hand, Lian et al. (2012) reported that the onset of damage and subsequent damage evolution were the key factors in the application of AHS steel sheets. Therefore, a microscopic description for describing the damage onset was necessary by the modeling of ductile damage. In this study, a non–quadratic yield function with consideration of the Lode angle effect was applied. It was found that this model could predict the plastic behaviour of the examined steel more precisely than the conventional J2 plasticity model. Note that only isotropic material behaviour was yet assumed for the calculations. Additionally, a phenomenological criterion, which incorporated influences of the stress triaxiality and Lode angle parameter, was introduced for describing the damage initiation of the steel. The stress state significantly affected the ductile crack initiation locus. Later, investigation of damage initiation on the micro–scale of DP steel under various stress states was done by Lian et al. (2014) by means of a numerical method based on representative volume element (RVE) FE simulations on the microstructural level. Hereby, the plastic strain localization was used as the criterion for damage initiation in the RVE modeling without any other damage models or imperfections. It was stated that the local damage initiation also showed the dependency on both stress triaxiality and Lode angle. Sirinakorn et al. (2015) investigated influences of microstructure characteristics on forming limits behaviour of DP steel sheets. Hereby, micromechanics models were applied to predict failure occurrence in the microstructures by considering plastic instability due