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Characterisation of the quasi-static flow and fracture behaviour of dual-phase steel sheets in a wide range of plane stress states

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ABSTRACT

An approach to characterise the flow and fracture behaviour with the help of a modified Miyauchi shear test, a uniaxial tensile test on standard, holed, waisted specimens as well as a hydraulic bulge test is presented. The modification of the Miyauchi specimen is related to the geometry of the shear zones. The new geometry helps suppress plastic strain concentration at the edges and increase deformation in the material interior, which allows for accurate fracture characterisation. With the help of the experimental and numerical tests analyses, the flow behaviour and equivalent plastic strain at fracture were estimated for two common cold-rolled dual-phase steels in a wide range of plane stress states. With the obtained data, the applicability of the phenomenological Johnson–Cook fracture model to describe the fracture behaviour of this material type is questioned and a need for a more extensive fracture behaviour characterisation and advanced modelling is shown.

1. Introduction

The use of the finite element analysis (FEA) helps minimise the material and energy consumption of a sheet forming process and assess the load-bearing capacity and crash behaviour of a formed part. The accuracy of FEA-based forming process design depends on mathematical models of the flow and fracture behaviour of the workpiece material. Provided an appropriate model chosen, the quality of the process simulation remains much influenced by the experimental material characterisation and model parameters determination. Considering the wide variety of new sheet materials that have been recently introduced, it becomes obvious that material characterisation should not only yield accurate material model parameters but also be easy to implement and fast to accomplish.

Nowadays, the available mathematical models describing the flow behaviour of traditional and new sheet materials and the related experimental procedures to determine the required parameters are well established and widely used both in the academia and industry [1]. On the contrary, the issue of accurate fracture modelling for sheet metal materials, especially of new advanced high-strength steels (AHSS), is currently being actively researched [2,3,4]. To assess the onset of fracture in FEA of sheet metal forming processes, the forming limit diagram (FLD) [5,6] has been long used to predict necking and crack failures [1,2]. According to the ISO 12004, the FLD is experimentally determined with

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the help of a bulge test on specimens of varying geometry. Due to the test design, the diagram is valid for linear tension-dominated deformation paths and a certain – rather narrow – range of stress states. Despite these limitations, the diagram yields acceptable fracture prediction for deep drawing, stretching, and stamping of conventional deep-drawing steels and – with some limitations – aluminium alloys and is widely used in industry [2]. However, necking or fracture caused by non-linear deformation paths or by shear-dominated deformation cannot be predicted with the help of the FLD. Moreover, fracture of AHSS is not accurately predicted in FEA based on the FLD approach [2]. Difficulties have been reported while determining FLD for some AHSS – e.g. dual-phase steels – due to the absence of necking prior to fracture [7].

Alternatively to the FLD, physically motivated or phenomenological modelling approaches can be used to predict the onset of cracking in plastically deforming metals [8,9]. With respect to simulation of sheet metal forming and crash, the model of Gurson extended by Tvergaard and Needleman is to be mentioned here [10], which is a physically motivated model. The coupling of progressing damage with the plasticity formulation realised in the model allows not only for fracture prediction due to forming but also for modelling of gradual material stiffness loss prior to fracture. The main shortcomings of the model are its strong mesh dependency [11] and its inaccuracy for shear-dominated stress states [12,13].

To avoid convergence difficulties due to stiffness loss accompaning damage accumulation and minimise the mesh dependency of the simulation results, one may alternatively use phenomenological fracture criteria uncoupled with the plasticity formulation [14], which can be expressed as follows:

$$\int_0^{\bar{\varepsilon}_{pl}{}^{f}} f(\boldsymbol{\sigma})\, d\bar{\varepsilon}_{pl} = C_{crit} \tag{1}$$

where $f(\boldsymbol{\sigma})$ is a predefined function of the stress state described by the stress tensor $\boldsymbol{\sigma}$, $\bar{\varepsilon}_{pl}$, $\bar{\varepsilon}_{pl}{}^{f}$ is the equivalent plastic strain and the equivalent plastic strain at fracture, C_{crit} is a material constant and stands for the material critical damage value, which leads to a crack. In numerical simulations, such models are usually implemented via a damage parameter $D \in [0;1]$, which is accumulated over simulation increments as follows:

$$D = \sum_i \frac{\Delta C_i}{C_{crit}} \tag{2}$$

Similar to the approach of (1) is the model proposed by Johnson and Cook (JC) [15]. However, in contract to (1), it provides some additional flexibility in specifying the influence of the stress state on fracture. This influence is taken into account via the equivalent plastic strain at fracture $\bar{\varepsilon}_{pl}{}^{f}$ defined as a continuous monotonic exponential function of the stress triaxiality $\sigma_H/\bar{\sigma}$ with three parameters. The stress triaxiality $\sigma_H/\bar{\sigma}$, which is the mean principal or hydrostatic stress divided by the von Mises equivalent stress, is in this case the mathematical representation of the stress state. Apart from the quasi-static description at room temperature, the model also accounts for the strain rate and temperature influence on the plastic strain to fracture:

$$\bar{\varepsilon}_{pl}{}^{f} = \left(D_1 + D_2 \exp\left[D_3 \frac{\sigma_H}{\bar{\sigma}}\right]\right) \times \left(1 + D_4 \ln \dot{\bar{\varepsilon}}^*\right) \times (1 + D_5 T_H) \tag{3}$$

where D_1–D_5 are the model parameters, $\dot{\bar{\varepsilon}}^* = \dot{\bar{\varepsilon}}/\dot{\bar{\varepsilon}}_0$ with $\dot{\bar{\varepsilon}}_0$ being the strain rate used to determine D_1–D_3 and D_5, $T_H = (T - T_R)/(T_M - T_R)$ is the homologous temperature with T, T_M, T_R being the test, melting, and reference temperature respectively. In numerical simulations, the model is realised based on the cumulative damage parameter $D \in [0;1]$ similar to (2):

$$D = \sum_i \frac{\bar{\varepsilon}_{pl}{}^{i}}{\bar{\varepsilon}_{pl}{}^{f}} \tag{4}$$

Fracture is assumed to occur, when $D = 1$. Due to its simple formulation and availability in commercial FE software – Abaqus/Explicit and LS-Dyna – the JC fracture model has been used to analyse highly dynamic sheet metal forming such as blanking [16] or crash [17].

The JC fracture model can be split into the quasi-static isothermal part as well as the strain rate and temperature dependent part. The first part reflects the well known fact that formability depends on the stress state and is the subject of the present study. The paper presents the results of this study, which was aimed at fracture behaviour characterisation and determination of D_1, D_2, D_3 for two common cold-rolled dual-phase sheet steels in the range of stress states of $\sigma_H/\bar{\sigma} \in [0;\ 0.67]$. To obtain sufficient fracture data in this range of the stress states, modified Miayuchi shear tests, tensile tests on standard, holed, and waisted specimens as well as hydraulic bulge tests were carried out. With the help of the experimental and numerical tests analyses, the flow behaviour and equivalent plastic strain at fracture $\bar{\varepsilon}_{pl}{}^{f}$ was estimated. With the obtained data, the applicability of the JC model to describe the fracture behaviour of this material type is questioned and a need for a more extensive material characterisation and advanced modelling is shown.

2. Material and methods

2.1. *Materials description*

Two cold-rolled hot-dip galvanised dual-phase steels for cold forming HCT600XD and HCT780XD both of 1.4 mm thick produced by Salzgitter Flachstahl GmbH, Germany were investigated. The chemical composition of the materials is given in Table 1.

Table 1 – Chemical composition of the studied materials determined via a melt analysis (max. wt%).

Material	C	Si	Mn	P	S	Al	Cr+Mo	Nb+Ti
HCT600XD	0.15	0.15	1.50	0.05	0.01	0.06	0.90	–
HCT780XD	0.17	0.30	2.00	0.05	0.01	0.08	1.00	0.05