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Ductile fracture prediction in cold forging process chains

P.F. Bariani (1)[a], S. Bruschi (2)[b,*], A. Ghiotti[a], M. Simionato[a]

[a] DIMEG, University of Padova, Via Venezia 1, 35131 Padova, Italy
[b] DIMS, University of Trento, Via Mesiano 77, 38050 Trento, Italy

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ABSTRACT

The paper presents a new approach for the prediction of ductile fracture occurrence in multi-stage cold forging process chains. The approach combines the fracture criterion proposed by Xue and Wierzbicky with a linear damage accumulation law. Thanks to this feature, the approach is capable of predicting both the location where the failure events occur under the action of external loading and the time they take to be generated. An application to the multi-stage cold forging of a C35 Torx-type socket screw carried out on a double-blow header is presented and results of predictions are compared with experimental observations.

1. Introduction

The onset of ductile fracture is the most severe constraint in designing and optimising process chains for metal parts, which are based on forming operations.

The separation of material in ductile fracture is only a final event, which is preceded by extensive plastic deformation and the formation of tiny voids, which then grow and coalesce, resulting in cracks that lead to fracture. As is the case with other microstructural phenomena that occur in the steps of forming process chains – such as strain and strain-rate hardening, crystallographic anisotropy and mechanical fibering, recovery and recrystallization, grain growth, and strain-induced ageing – the onset of ductile fracture is strongly affected by the thermal and mechanical histories that have been generated in the previous steps [1]. Therefore, in ductile fracture studies, the analyses of the different steps of the process chain must be effectively interconnected.

In cold forging process chains, the effects of the stress and strain histories stored during the process largely prevail over those of temperature- and time-related parameters in governing both the material response to deformation and the ductile fracture occurrence. On close examination, the loading and deformation in the workpiece material zones that are exposed to fracture risk may show complex paths (non-proportional and non-monotonic). The stress triaxiality varies from zone to zone and, for the same zone, during the deformation step, with stepwise variations especially at the changes from one process stage to the next.

Ductile fracture phenomena in cold forging operations have been extensively investigated by using different approaches and models. Depending on the approach, the models can be classified into three groups: *energy-based* models, *void growth* models and *Continuum Damage Mechanics (CDM) based* models. The models in the first group provide satisfactory results when they are applied to single-step operations where tensile stress states are predominant [2]. They are easy to use and calibrate, but they lack accuracy when they are applied to most cold forging operations where loading is more complex. *Void growth* models incorporate the dependence of damage on the stress triaxiality and are calibrated through tests that have to reproduce the same strain and stress conditions of the process. Although they provide greater validity than those in the first group, they are unable to predict fracture occurrence for the intermediate regimes of stress triaxiality where competing failure mechanisms work simultaneously [3,4]. *CDM-based* models can effectively predict fracture occurrence because they model damage evolution on a micro-scale and take account of rheological behaviour [5]. Calibrating these models requires experimental and numerical procedures that are complex and time-consuming, making it quite difficult to implement them.

In this paper, a new approach is presented, which is capable of accurately predicting ductile fracture occurrence in multi-stage cold forging process chains. The approach combines the fracture criterion proposed by Xue and Wierzbicky [6] with a linear damage accumulation law. According to the fracture criterion, the equivalent strain to fracture is evaluated as a function of both the stress triaxiality factor and the deviatoric stress parameters. By introducing the deviatoric parameter, the dependence of the strain to fracture from the stress state is captured, making the model applicable for any stress state and any failure mode. The restricted number of calibration tests and ease of performing the relevant standard experiments are a further advantage. The damage accumulation law makes it possible to track the continuous material damaging taking place within the individual deformation steps in the process chain. These features allow the approach presented in the paper to overcome the main limitations of the above-cited models.

The paper is organized in two main parts. In the first part, the approach underlying the development of the model and its main functional modules are illustrated. Then the paper focuses on the industrial application case. The material tested and the experiments carried out to calibrate the fracture criterion are presented

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* Corresponding author.
E-mail address: stefania.bruschi@ing.unitn.it (S. Bruschi).

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together with the results from the application of the model and their comparison with the experimental observations.

2. The approach

The major requirement that the predictive model has to meet is to predict damage evolution and fracture occurrence in the multi-stage cold forging processes with the complex loading and deformation paths that operate in industrial applications. Non-secondary feature of the model is the ease in its implementation and application, particularly with regard to calibration tests. With these requirements, the predictive model requires the joint use of complementary techniques, both numerical and experimental, organized in four functional modules which are devoted respectively to: (i) application of the fracture criterion, (ii) calculation of the damage accumulation, (iii) FE analysis of the process chain, and (iv) generation of the material data for process simulation and fracture criterion calibration. The four modules are described in the rest of this section.

2.1. The fracture criterion

According to the ductile fracture criterion proposed by Xue and Wierzbicky [5], fracture is postulated to occur when the accumulated equivalent plastic strain, modified by the function of the stress triaxiality T and the deviatoric state parameter X, reaches a limiting value equal to one (for the definition of T and X please refer to the original reference [6], where the two parameters are named η and ξ, respectively). With the introduction of the two stress parameters, the fracture criterion can be adequately applied to deformation conditions with any stress state and to any failure mode as well. Moreover, the fracture locus can be conveniently represented in the stress domain.

In the case of material behaviour obeying the Hollomon rheological law, the upper and lower limits of the fracture locus can be correlated through the Tresca failure hypothesis [7]. The equivalent strain at fracture ε_f, valid for any value of the stress triaxiality T, can then be expressed by Eq. (1):

$$\frac{\bar{\varepsilon}_f}{\bar{\varepsilon}_1} = \left[\frac{\sin(\pi/3)}{\sin((2\pi - \arccos\ X)/3)}\right]^{1/n} \tag{1}$$

where $\bar{\varepsilon}_1$ is the upper limit of the fracture locus. Assuming $\bar{\varepsilon}_1$ to be an exponential function of the stress triaxiality factor T [8], Eq. (1) becomes the fracture locus represented by Eq. (2):

$$\bar{\varepsilon}_f = C_1 e^{-C_2 T}\left[\frac{\sin(\pi/3)}{\sin((2\pi - \arccos\ X)/3)}\right]^{1/n} \tag{2}$$

where C_1 and C_2 are material constants to be calculated through tests aimed to calibrate the fracture criterion (see Section 2.4) and n is the exponent in the Hollomon power law. Therefore, the material fracture locus can be fully determined as a function of any stress state expressed in terms of the stress triaxiality factor T and the deviatoric stress parameter X.

2.2. The damage accumulation law

The accumulation of the material damage in the deformation steps of the process chain is tracked by a linear damage accumulation law. According to this law, the additional damage introduced at each time step in the process chain numerical simulation is defined by [6]:

$$D = \int_0^{\varepsilon_f} \frac{1}{\bar{\varepsilon}_f(T,X)} d\bar{\varepsilon} \tag{3}$$

where $\bar{\varepsilon}_f(T,X)$ represents the material fracture locus of Eq. (2). The time derivative of Eq. (2) is implemented into the numerical code used for the process chain simulation by compiling a user routine whose flow chart is shown in Fig. 1. The material failure is postulated to occur when the damage parameter D reaches the unit value.

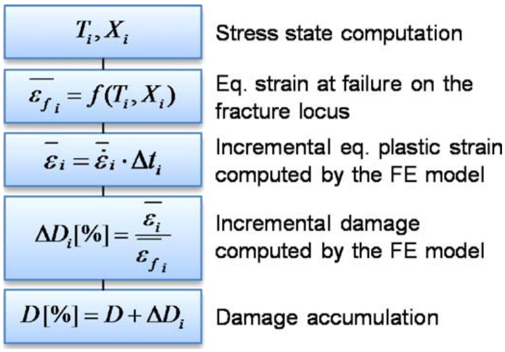

Fig. 1. Flow-chart of the damage accumulation routine.

2.3. The FE model of the process chain

The main task of the FE model of the cold forging process chain is to provide an accurate analysis of the stress- and strain-related parameters inside the workpiece material in the different stages of the process chain. The damage law described in Section 2.2 is implemented in the FE model. In this way, the damage accumulated inside the individual stages of the process chain is calculated and the accumulated damage is transferred from one step to the next.

2.4. Tests for model calibration

Rheological and workability tests are utilized to identify the material constants C_1, C_2 and n in Eq. (1). In particular, compression tests are used to determine the material flow behaviour and to calculate the strength coefficient and the exponent of the Hollomon power law. Tensile and torsion tests are used to identify the constants C_1 and C_2. The two constants are calculated by comparing the results measured in the experimental tests with the corresponding values calculated through numerical simulations of the same tests, and therefore are independent from the particular reference process, but only material dependent. Details are given in Section 3.1, where the tests carried out for the application case are presented.

3. Application case

The application case refers to the multi-stage cold forging of a Torx-type socket screw carried out on a double blow header (Fig. 2). The material is a 6.5 mm diameter wire of carbon steel C35. After straightening on a roll straightening unit, the wire is cropped to the required length and then forged. The two forging steps consist in a preliminary heading followed by the piercing of the Torx socket combined with the calibration of the screw head. A ductile fracture regularly occurs in the last forming stage at one of the six points of the star-shaped cavity (Fig. 2d and lower part of Fig. 6). It is important to note that the material zone where fracture occurs has already been damaged and separated during the cropping operation. In the forging sequence, the same material undergoes complex loading with medium-high values of stress triaxiality, which shows stepwise changes when the blank moves from one forming stage to the following.

Fig. 2. Forging sequence for a C35 Torx-type socket screw.