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Sensitivity analysis of quantitative fracture criterion based on the results of the SICO test

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Abstract

Results of numerical simulation of the SICO test, including the resistance heating of samples and metal flow during the test, are described in this paper. The main goal of the work is the determination of the sensitivity of fracture criteria with respect to the test parameters: temperature, die velocity and material parameters—strain rate sensitivity, hardening coefficient, hardening exponent and temperature sensitivity coefficient. It was shown in earlier research that sensitivity analysis allowed the determination of the extent that the value of the fracture criterion changes with change of the SICO test parameters. Beyond this, the sensitivity analysis reveals which parameters interact with each other. This information is crucial for the inverse analysis if larger numbers of parameters are optimized. The present work is an extension of the authors' earlier research and the variance-based method with correlation ratios is used in the analysis. The results of this analysis contribute to development of more efficient optimization algorithms in the inverse method.

Keywords: SICO test; Fracture criteria; Latham and Cockcroft; Sensitivity; Correlations

1. Introduction

Formulation of a quantitative fracture criterion [1] for materials subjected to plastic deformation is essential for modeling of forming processes for materials characterized by low plasticity. In order to avoid the fracture during forming, it is necessary to determine precisely the material crack resistance and to use this knowledge to design process technological parameters, which prevent the fracture. Criteria based on computing stress and strain history, which are commonly used [1,2], give relatively good qualitative results but quantitative accuracy is often insufficient. It is generally due to difficulties with the determination of material parameters in fracture criteria. The problem of formulating a complex criterion, which gives qualitatively good results, is still open. This work is a continuation of earlier research on the design of the new fracture criterion in plastic processes, in which the SICO test was used as material testing method [3].

The SICO test [4–6] is commonly used to determine the tendency of materials to fracture during hot forming. The test is a hot workability technique with good reproducibility and the possibility of employment of large strains. Due to inhomogeneities of temperature, stress and strain fields in the test, quantitative interpretation produces certain problems [5]. A suggestion is made that application of the inverse analysis with a finite element solver for simulation of the SICO test is able to obtain values of the material parameters independently of the inhomogeneity of strains, stresses and temperatures. This suggestion is further explored in the present work. The particular objective of the work is determination of the sensitivity of the fracture criterion function with respect to the test parameters and properties of deformed material and investigation of correlation between them. The results of performed analysis is giving the grounds to design the critical value of fracture criterion as a function of appropriate test and material parameters. The critical value of the fracture criterion is responsible for the start of the fracture process.

2. Investigation methodology

The procedure is as follows:

1. SICO test—experiments.
2. Fracture criteria. Definition and implementation into the finite element code (simulator of SICO test).
3. Sensitivity analysis of fracture criteria.

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4. Inverse analysis. Determination of the coefficients in the fracture criteria.
5. Analysis of tendency to fracture. Fracture criteria with optimized coefficients are implemented into the finite element simulator of metal forming processes and analysis of tendency to fracture for selected forging operations is performed.

The particular objective of the present work is the determination of the sensitivity of the fracture criterion functions with respect to the test and material parameters and correlation between these coefficients and the chemical composition of the material (see point 3). As a result, the critical value of the fracture criterion is determined. Beyond the fracture criterion itself, the function is also implemented into the finite element code for the SICO test and forging operation simulations.

3. SICO test

The SICO test is divided into two stages: the resistance heating of the sample to get appropriate temperature field, and upsetting until fracture appears. View of the sample and temperature distribution at the cross section after the test are shown in Fig. 1. More details about the finite element simulations of SICO test are given in ref. [7].

The tests conditions were as follows: dimensions of the sample 10 mm × 86.4 mm; steel chemical composition, 0.21% C, 1.32% Mn, 0.23% Si and 0.2% Cu. Heat transfer coefficient for the tool–workpiece interface was assumed at 20 kW/(m^2K) for high pressure contact and 10 kW/(m^2K) for sides of the sample. Sample heating rate was 5 °C/s for about 230 s, stroke during upsetting was 16 mm.

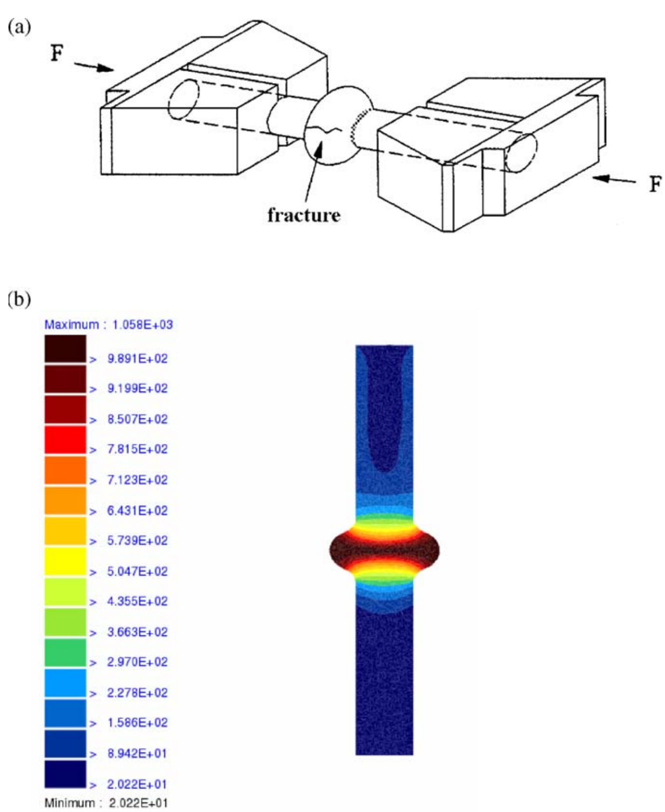

Fig. 1. SICO test, view of the tools and the sample (a) and temperature distribution at the cross section of the sample after the test (b).

4. Sensitivity analysis

The objective of this analysis is the evaluation of how sensitive parameters in various fracture criteria are (normalized Latham and Cockcroft, Latham and Cockcroft [2] and Oyane et al. [1]) with respect to the SICO test parameters and to the material parameters. Evaluation of the sensitivity will supply the information, which, in the further investigation, will make the inverse analysis of SICO test more efficient. As mentioned, the criteria are based on the assumption that the fracture occurs when the integral of stresses with respect to strain exceeds the limiting value.

Normalized Latham and Cockcroft criterion:

$$\chi_{\mathrm{nLC}} = \int_0^{\varepsilon_{\mathrm{i}}(t)} \frac{\sigma_1}{\sigma_0}\,\mathrm{d}\varepsilon_{\mathrm{i}}(t) \geq C \tag{1}$$

Latham and Cockcroft criterion:

$$\chi_{\mathrm{LC}} = \int_0^{\varepsilon_{\mathrm{i}}(t)} \sigma_1\,\mathrm{d}\varepsilon_{\mathrm{i}}(t) \geq C \tag{2}$$

Oyane criterion:

$$\chi_{\mathrm{Oyane}} = \int_0^{\varepsilon_{\mathrm{i}}(t)} \left(1 + A\frac{\sigma}{\sigma_{\mathrm{i}}}\right)\mathrm{d}\varepsilon_{\mathrm{i}}(t) \geq C \tag{3}$$

where ε_{i} is the effective strain, σ_{h} the hydrostatic stress, σ_{i} the effective stress, σ_1 the maximum principal stress, σ_0 the yield stress and C is the critical value of integral.

Values of parameters and fracture criteria were estimated for circumferential strain in the SICO test equal to 0.65. The independent variables of the process in the analysis were:

- temperature at the time of fracture (T);
- die velocity (v);

and variables describing material properties were:

- strain rate sensitivity (m);
- hardening coefficient (K_0) in the consistency parameter in FORGE 3 code;
- temperature sensitivity coefficient (β);
- hardening exponent (n).

Since the FORGE 3 commercial code was used for simulations, all the above material parameters are the coefficients in the Norton–Hoff flow rule [8]:

$$\sigma_0 = \sqrt{3}^{(1+m)} K_0 \varepsilon^n\,\mathrm{e}^{(-\beta T)} \dot{\varepsilon}^m \tag{4}$$

In the analysis, the fracture criteria were calculated as a maximum fracture criterion value χ_i in the whole volume of the sample:

$$\chi_i^{\max} = \max_V \chi_i, \qquad i \in \{\mathrm{Oyane},\ \mathrm{LC},\ \mathrm{nLC}\} \tag{5}$$