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Determination of ductile fracture criteria for bulk and PM materials

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Abstract

In the paper, calculation of the ductile fracture criteria for experimental materials as HSLA (high strength low alloy) steel, aluminium alloy EN AW 6082 T6 and powder metallurgy material ALUMIX 321 was carried out. Using ring and compression tests, it was possible to determine friction coefficient, stress-strain curves, constants for the Hollomon's equation, material workability and nCL (normalized Cockcroft-Latham) criteria. Moreover, the results from the nCL criteria calculations obtained from compression tests and numerical simulations were compared and verified. Numerical simulations were done by the Deform 3D software. It was confirmed that both methods provide similar results.

Key words: aluminium alloys, HSLA, physical simulations, mathematical simulation, Cockcroft-Latham fracture criterion

1. Introduction

In general, workability can be defined as an ability of the processed material to achieve a certain degree of deformation without a creation of defects. Hence, ductile fracture is a significant limitation influencing the productivity in metalworking processes. Therefore, early predicting the occurrence of ductile fracture in processed materials during metalworking operations has been attracted a lot of researchers [1–3]. Metal workability is one of the most important parameters considered during designing the forming operations. In order to prevent the plastic limits and improve the metalworking operations, forming limits have to be predicted correctly. A fracture forming limit diagram (FFLD) and ductile fracture criteria (e.g., Cockcroft-Latham (CL), Brozzo, McClintock, Oyane) were used as a tool to describe the material formability [1–6]. The FFLD is a suitable way to display the workability in a graphical illustration as well as display the threshold limit of principal strain when the material could be processed without a failure. Moreover, ductile fracture criteria are used to determine the threshold conditions for safe mechanical working. It is well-known that material ductile cracking is caused by the deformation predominantly effecting in the tensile direction. Hence, a CL ductile fracture criterion is mathematically described as follows [6]:

$$\mathrm{CL} = \int_0^{\bar{\varepsilon}_{\mathrm{fract}}} \sigma_1 \mathrm{d}\bar{\varepsilon}, \tag{1}$$

where σ_1 (MPa) is maximum principal tensile stress, $\bar{\varepsilon}_{\mathrm{fract}}$ (–) is equivalent strain to fracture, $\bar{\varepsilon}$ (–) is equivalent strain and CL (MPa) is Cockcroft-Latham damage value.

The CL criterion was used as a tool for predictions of fracture in materials as a steel, titan, aluminium, copper alloys [7–10]. Oh et al. [11] modified the CL criterion through normalizing the maximum principle tensile stress by the equivalent stress. This was defined as a normalized Cockcroft-Latham criterion [11]:

$$\mathrm{nCL} = \int_0^{\bar{\varepsilon}_{\mathrm{fract}}} \frac{\sigma_1}{\bar{\sigma}} \mathrm{d}\bar{\varepsilon}, \tag{2}$$

where $\bar{\sigma}$ (MPa) is effective stress and nCL (–) is normalized Cockcroft-Latham damage value.

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1 Table 1. Chemical composition and heat treatment conditions of experimental materials

Material	Chemical composition (wt.%)			Heat treatment – state
HSLA steel	Fe – 97 Mn – 1.3 P – 0.02	C – 0.1 Nb – 0.07 V – 0.11	Si – 0.2 Cr – 0.05 S – 0.01	as-received
EN AW 6082 T6	Al – 98.9 Mg – 0.24 Cu – 1.7	Si – 0.25 Fe – 0.34 Zn – 0.65	Mn – 0.42 Cr – 0.23 Ti – 0.04	T6 solution heat treated artificially aged
ALUMIX 321	Al – 98.1 Mg – 0.89 Cu – 0.26	Si – 0.53 Fe – 0.06 Zn – 0.03	Mn – 0.0 Cr – 0.00 Ti – 0.00	compacting pressure 400 MPa dewaxed at 400 °C for 60 min sintering in vacuum at 610 °C for 30 min cooling rate 6 °C sec^{-1}

The authors [12] described the analytical solution of Eq. (1) by formula as follows:

$$\mathrm{CL} = \frac{1+2a}{\sqrt{3(1+\alpha+\alpha^2)}} \frac{K\bar{\varepsilon}^{(n+1)}}{n+1} \frac{\varepsilon_z}{|\varepsilon_z|}, \tag{3}$$

where K (–) is strength index, n (–) is strain hardening exponent, $\alpha = \varepsilon_\Theta/\varepsilon_z$, ε_Θ is circumferential deformation, and ε_z is axial deformation.

Strains in vertical and circumferential directions were evaluated according to the following equations:

$$\varepsilon_\Theta = \ln\left(\frac{d_1}{d_0}\right), \tag{4}$$

$$\varepsilon_z = \ln\left(\frac{h_1}{h_0}\right) \quad . \tag{5}$$

Forming criteria (3) were modified by the values of effective stress (measured in the moment, when a crack appeared) as follows:

$$\mathrm{nCL} = \frac{1+2a}{\sqrt{3(1+\alpha+\alpha^2)}} \frac{K\bar{\varepsilon}^{(n+1)}}{n+1} \frac{\varepsilon_z}{|\varepsilon_z|} \frac{1}{\bar{\sigma}_{\mathrm{fract}}}, \tag{6}$$

where $\bar{\sigma}_{\mathrm{fract}}$ (MPa) is effective fracture stress.

It is well known that the nCL criterion and forming limits are dependent on similar material parameters. Microstructural features as a grain size and non-metallic inclusion content have a significant effect on a critical value of the damage [13]. Beside other criteria, the nCL criterion is one of the most suitable ways to predict the fracture initiation for compression and extrusion conditions [14–16]. However, it is not suitable to apply the criterion in high strain rate conditions [17].

Nowadays, finite element methods (FEM) have been often used for an analysis of plastic deformation processes. FEM provide useful data about metalworking processes and their limits [18–23]. The knowledge of the ductile fracture criteria is highly advantageous for mathematical simulations [24–26]. An accuracy of the calculations depends on correct fitting the boundary conditions of the technological process. Hence, ductile fracture criteria have been nowadays used in mathematical modelling to optimize technological processes. To recognize the ductile fracture criteria in laboratory conditions, the experimental compression, tension and torsion testing tests have been carried out [15].

The main purpose of this paper was to determine the critical values of the nCL criteria for selected materials. Critical values of the nCL criteria were calculated and verified using the Deform 3D software, as well.

2. Experimental materials and methods

As experimental materials, there were used two types of materials: "bulk" represented by high strength low alloy steel (HSLA) and EN AW 6082 T6 (aluminium alloy), "PM" (powder metallurgy) represented by ALUMIX 321 (aluminium alloy). Chemical composition and heat treatment conditions of experimental materials are given in Table 1 (it is obvious that ALUMIX 321 and EN AW 6082 T6 have similar chemical composition).

The compression test was carried out on hydraulic equipment with maximum force 1000 kN at room temperature with 0.2 mm s^{-1} compression speed. Initial parameters of the sample were: D = 10 mm, H = 10 mm. The test was finished in the moment when a first crack on the sample's surface emerged. Moreover, to recognize the influence of friction, smooth and rough anvils were used. The contact friction coefficient was calculated according to [27], through the

Table 2. Material parameters of experimental materials

Material	Holloman's equation: $\sigma = K\,\varepsilon^n$	r	K	n
HSLA steel	$\sigma = 940\ \varepsilon^{0.15}$	0.92	940	0.15
EN AW 6082 T6	$\sigma = 421\ \varepsilon^{0.045}$	0.93	421	0.045
ALUMIX 321	$\sigma = 330\ \varepsilon^{0.19}$	0.95	330	0.19

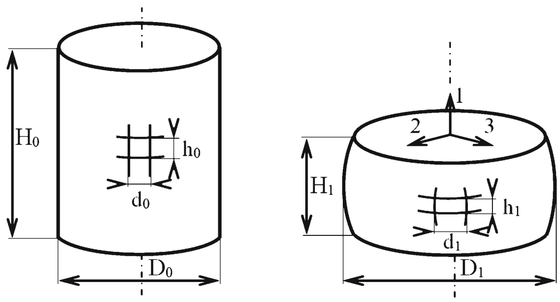

Fig. 1. Schematic diagram of an experimental sample with a deformation marker.

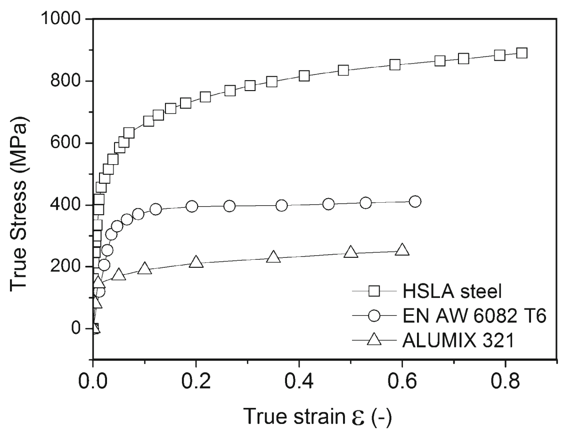

Fig. 2. Compressive stress vs. strain curves.

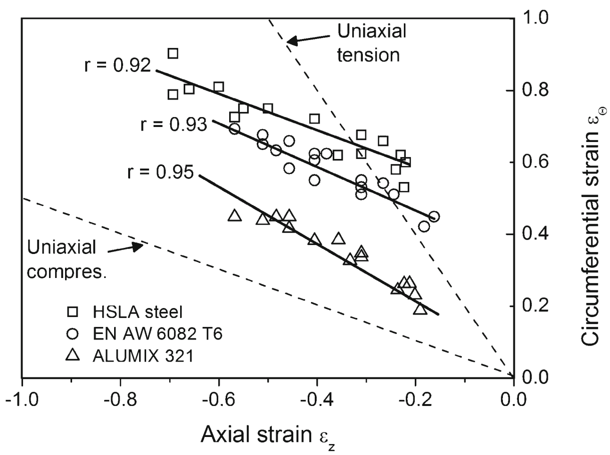

Fig. 3. Forming limit diagram.

ring compression tests which were carried out at room temperature. The friction coefficient by a shear model was calculated at 0.18, 0.35 for smooth and rough anvils, respectively. To recognize the deformation in an axial and radial direction, the network ($h_0 \times b_0 = 3 \times 3\,\mathrm{mm}^2$) was drawn along the sample's surface, as is illustrated in Fig. 1.

To calculate and verify critical values of the nCL criteria, as the first there was used numerical Eq. (6), and as the second method of numerical simulations. The material characteristics and processing conditions (temperature, strain, strain rate, friction coefficient and sample geometric dimensions) from experimental compression test served as an incoming data in numerical simulations. In numerical simulations, a sample was defined as a rigid-plastic material. Material flow data was determined using stress-strain curves which were obtained from the compression test. The finite element mesh included 8000 elements.

3. Results and discussion

A schematic illustration of the measured data from compression tests is given in Fig. 2. As seen in Fig. 2, HSLA shows high strength and provides significant axial deformation without cracking. The fracture forming limit diagram describing the dependence between compressive and tensile strains calculated from the compression test data and by Eqs. (4) and (5) under different friction conditions is given in Fig. 3. From the diagram, there is obvious that HSLA and ALUMIX 321 provide high and low workability, respectively.

The parameters of Holloman's equations were derived by using regression analysis (Table 2). The constants were applied in Eq. (6) to calculate the critical nCL value and used as input data for mathematical simulations.

The features of samples after experimental testing (compression and mathematical simulation) are displayed in Fig. 4. On the left, there are samples where the first crack was observed on the surface (shown by darts). An initial stage of the crack formation starts from the sample centre and continues to the edge in 45° angle to a force. According to the values of nCL calculated by Eq. (6), there is obvious that HSLA steel

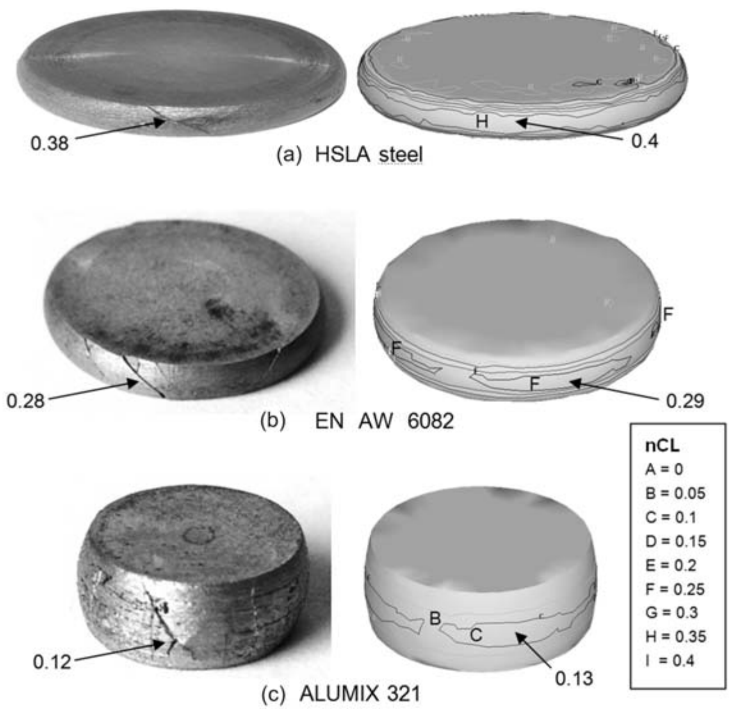

Fig. 4. Schematic illustration of samples from laboratory experiments and mathematical simulations: HSLA steel (a), EN AW 6082 T6 (b), ALUMIX 321 (c).

is resistant to high deformation (before the first crack was appeared) what implies high ductility. Further, EN AW 6082 T6 shows lower workability than HSLA, what comes from its artificially aged state. Moreover, ALUMIX 321 provides the lowest ductility also confirmed by the earliest crack formation in comparison to the above mentioned experimental materials.

On the right in Fig. 4, there is schematic illustration of samples and calculated values of the nCL criteria resulting from numerical simulations. The darts are showing the areas where the highest values of the nCL were achieved. According to the laboratory experiment, the highest values of the nCL are seen on the sample circumference what implies that numerical simulations were carried out correctly. The highest nCL values obtained from laboratory and numerical simulations can be considered as critical. Additional deformation would lead to cracking.

Critical values of the nCL criteria and differences between data calculated from laboratory compression test and numerical simulations are shown in Fig. 5. There is seen high similarity in the obtained values (in particular, bulk HSLA and EN AW 6082 T6). For each material, the deviation was only 3.5 and 5.2 %, respectively. ALUMIX 321 showed the deviation at 8.3 %. That could be explained through porosity that is typical for PM materials. It is well known that pores act as crack initiators, as was also shown in [28–29]. Moreover, porosity has a significant influence on the stress distribution. As the stress is inhomogeneously distributed across the sample it can lead to reduction

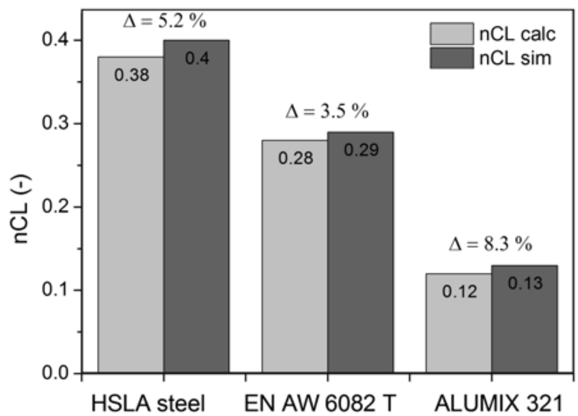

Fig. 5. Comparison of calculated and simulated nCL values.

of the effective load bearing area [30–33].

The nCL critical value for HSLA was calculated 0.38–0.4, it was compared to that for AISI 1040 carbon steel with similar chemical composition. For AISI 1040 carbon steel, authors propose the nCL critical value at 0.35 [4]. Even, another criteria were used and verified, however, authors imply that the nCL criterion is one of the most suitable ones. Further, the nCL criterion for EN AW 6082 T6 was 0.28–0.29, what is similar to [34], where a critical value of the nCL criterion was established as 0.3. Besides, authors of [35] were involved in the study of EN AW 6082 subjected to ECAP (equal channel angular pressing). According to their study, after the first ECAP pass, calculated nCL values were in the range 0.3–0.5. Similar results were obtained in an experimental study [36] which was also focused on ALUMIX 321. According to [36], calculated nCL value for material processed by ECAR (equal channel angular rolling) was helpful to predict the fracture formation. The values of ductile fracture criteria obtained from experimental studies together with data from finite element simulations can be applied successfully to predict the material workability during metalworking processes, what was also confirmed in [25, 37].

4. Conclusions

According to the literature review as well as physical and numerical simulations carried out on HSLA, EN AW 6082 T6 and ALUMIX 321, following can be summarized:

– in terms of determination of the nCL criteria, physical and numerical simulations showed the high joint similarity,

– experimental compression test together with mathematical calculations could be used as a suitable tool to calculate the critical nCL values,

– FEM simulations carried out through the Deform 3D software provide the data about critical values of nCL criteria, however, no indications about the direction and the nature of material failure,

– to evaluate the nCL criterion from numerical simulations, there is necessary to verify data in real experimental conditions on samples with identical material characteristics.

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