PHYSICAL AND NUMERICAL DETERMINATION OF WORKABILITY IN ALUMINIUM ALLOYS

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Abstract
To prevent any failure or fracture in materials during a forming process, the study of material workability is a crucial task. In this paper, the workability of two different aluminium alloys was described through Cockcroft - Latham ductile fracture criteria and forming limit diagrams. Moreover, the experiments have been carried out using compression tests and finite element methods and there was able to compare and verify the physical and numerical approaches. According to the results, there was found out that physical and numerical models are advantageous tools to describe the material workability during forming processes and the optimal data are obtained when both approaches are working together.

Keywords: EN AW 6082, EN AW 7075, ductile fracture criteria, forming limit diagram, compression tests, FEM

1 Introduction
Aluminium alloys provide some advantageous properties which make them attractive for many industrial applications. Within aluminium alloys forming processes, there is very important whether deformation can be carried out in safe conditions, means without any failure or fracture of the processed material (workability). Thus, in metalworking industry, there is a need for predicting and preventing fracture which has a significant influence on the quality of products. Hence, understanding the conditions in which a ductile fracture (occurrence of internal or surface fracture in the sample) emerges is a key task in most bulk metal - forming processes [1].
Nowadays, there exist a lot of criteria based on various hypotheses which have been proposed empirically as well as theoretically [2, 3]. As there is well known that the forming limit of metals strongly depends on stress and strain, ductile fracture criteria as a Freudenthal, Cockcroft - Latham (CL), Brozzo, McClintock, Oyane type [2-6] have been successfully used to the numerical description (expression) of material workability with focus on stress and strain.
Generally, great stress and strain are being developed during the processing through severe plastic deformation (SPD) methods which have been nowadays successfully used to refining the material internal structure to the submicrometer range (ultrafine-grained structure). Ultrafine-grained (UFG) materials provide improved properties in comparison to their counterparts (processed by classical methods) [7-11] however sufficient emphasis on the material workability during SPD processing has to be ensured.

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Besides, for a graphic representation illustrating the limits of the principal strain which it may suffer without failure in a forming process there have been used forming limit diagrams [12].
It is obvious that these criteria are very helpful on a design the metal - forming process without failure. According to the cumulative damage theory, Cockcroft and Latham developed a model describing a critical value of the tensile strain energy per unit volume, which has been successfully applied in a lot of processes as extrusion, rolling [2, 3, 13-15]. Cockcroft - Latham criterion [3, 13, 14] is expressed as an amount of work to the ratio of maximum tensile stress carries out through the applied equivalent strain in a metal - working process;

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

where: σ_1 [MPa] - maximum principal tensile stress,
$\bar{\varepsilon}_{fract}$ [-] - equivalent strain to fracture,
$\bar{\varepsilon}$ [-] - equivalent strain,
CL [MPa] - Cockcroft-Latham damage value.

Oh et al. [16] modified a CL criterion through normalizing the maximum principle tensile stress by the equivalent stress. That was defined as a normalized Cockcroft-Latham criterion [16]:

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

where: $\bar{\sigma}$ [MPa] - effective stress,
nCL [-] - normalized Cockcroft - Latham damage value.

The authors [17] defined a solution for eq. (1) by formula as follows:

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

where: K [-] - strength index,
n [-] - strain hardening exponent,
$\alpha = \varepsilon_\Theta / \varepsilon z$, ε_Θ - circumferential deformation, ε_Z - axial deformation.

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

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

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

Forming criteria [17] were modified through values of the effective stress (measured in the moment, when a crack appeared) as follows:

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

where: $\bar{\sigma}_{fract}$ [MPa] - effective fracture stress.

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Recognizing the ductile fracture criteria is also highly advantageous in mathematical modelling that has been used to optimalize technological processes [18-20]. Finite element methods (FEM) are numerical methods used for the analysis of metal-forming processes that are aimed to predict stress and strain fields and material flow [12]. The accuracy in calculations depends on the correct fitting of boundary conditions. To evaluate the ductile fracture criteria, experimental testing methods based on compression, tension and torsion have been applied in laboratory conditions [21].
The main aim of this study was to determine and verify critical values of the nCL criteria for two different Al-based alloys through methods of physical and numerical simulations.

2 Experimental materials and methods

As experimental materials, there were used two different types of Al-based alloys with the marking EN AW 6082 and EN AW 6082 7075, both in a T6 heat treatment state. All samples were compressed using the hydraulic system at room temperature with speed of the equipment movement of 0.2 mm/s and initial parameters of samples: D_0=10 mm, H_0=10 mm. In the moment when the first crack was emerged, testing turned off. Moreover, to verify the influence of friction, anvils with different roughnesses were used. The contact friction was determined through ring compression tests (at room temperature) and calculated according to the [22]. By the shear model, there was recognized friction of 0.18, 0.35 for smooth and rough anvil surfaces, respectively. Changes in the deformation at the sample's surface was investigated in axial and radial direction using the grid with parameters of h_0xd_0=3x3 mm, as is shown in **Fig. 1**.

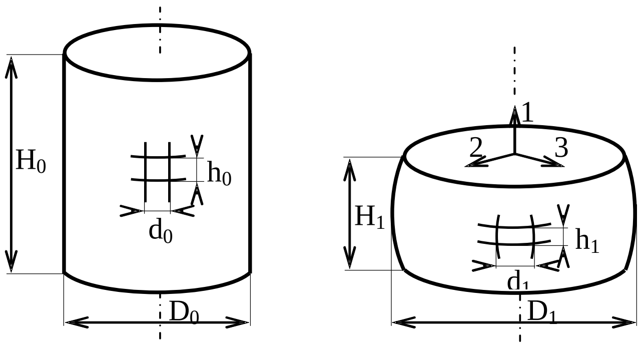

Fig. 1 Schematic illustration of upset tests showing the grids for strain measurement

In order to determine critical values of nCL criteria and moreover to compare, two methods were applied. First, the nCl was calculated by eq. (6), second using finite element methods (FEM) through Deform 3D software. Findings from the laboratory experiments (temperature, strain, strain rate, friction and sample geometric parameters) served as an input to numerical simulations (FEM). The samples were defined as a rigid-plastic material. Material flow data was determined from the stress-strain curves and the finite element mesh included 8000 elements.

3 Results

The stress-strain curves for experimental materials were obtained from the low speed compression test at room temperature.

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From **Fig. 2**, it can be seen that both materials have a similar progress in the engineering strain and engineering stress. Moreover, according to the compressive stress-strain curves (Fig. 2), there is obvious that both materials show high ductility, however EN AW 7075 provides higher strength than EN AW 6082.

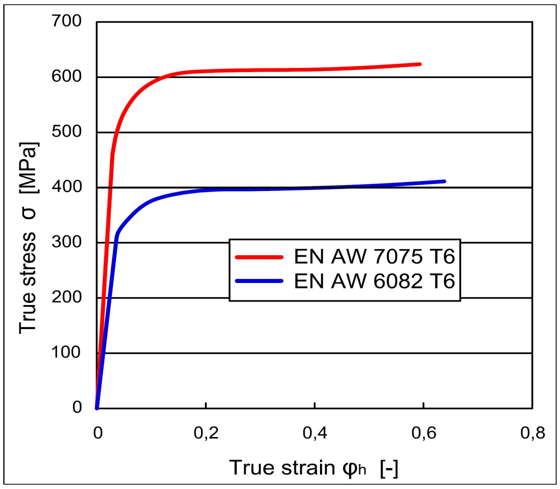

Fig. 2 Compressive stress - strain curves

For a numerical description of stress-strain curves from **Fig. 2**, there was used the Holloman's equation in the following form:

$$\sigma = \mathrm{K}.\varepsilon^{\mathrm{n}} \tag{7.}$$

Correlation coefficients for both tested materials were derived through regression analysis and together with Holloman's regression equations are given in **Table 1**. Constants from Holloman's regression equations were substituted to eq. (6) for calculation of the critical nCL value and used as incoming data for numerical simulations.

Table 1 Material characteristics of both materials

Material	Hollomon's regression eq. [MPa]	Correlation coefficient I_{yx}[-]
EN AW 6082 T6	$\sigma = 421 \cdot \varepsilon^{0.045}$	0.93
EN AW 7075 T6	$\sigma = 673 \cdot \varepsilon^{0.040}$	0.96

Surface strains (ε_θ, ε_z) determined experimentally for the geometric mid-sectional grid of the samples undergoing deformation are plotted in **Fig. 3**. Fracture forming limit diagram illustrated in Fig. 3 describes critical compressive and tensile strains from the compression test carried out in different friction conditions and determined according to eq. (4, 5). From the dependences, there was higher workability in EN AW 6082 than in EN AW 7075.
Theoretical predictions of the fracture criteria were computed using the finite element program Deform 3D. Critical values of the nCL criteria and differences between data calculated from laboratory compression test and numerical simulations are shown in **Fig. 4**. High similarity in obtained values is visible.

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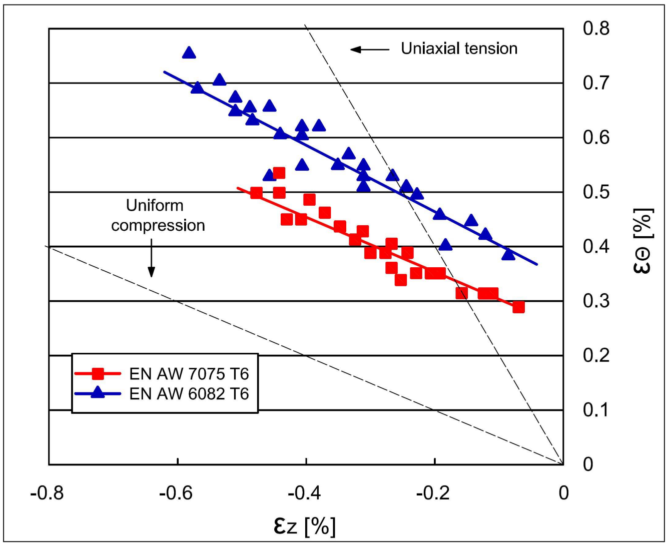

Fig. 3 Forming limit diagram

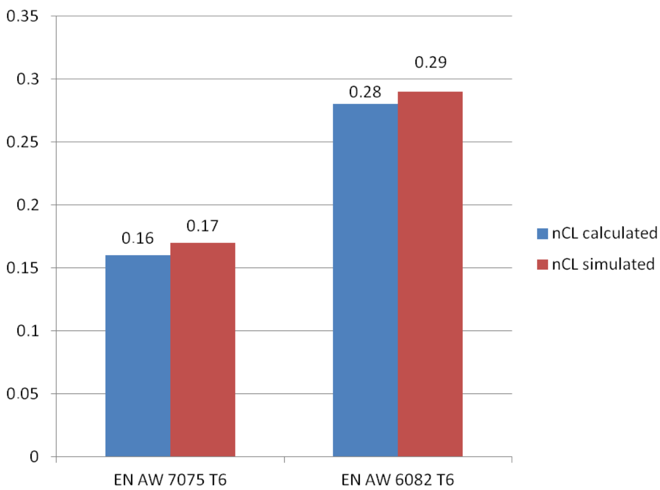

Fig. 4 Critical nCL values given from physical experiments and numerical simulations

Further, the nCL criterion for EN AW 6082 T6 was determined of 0.28-0.29 what is similar to [23] where a critical value of the nCL criterion was established at 0.3. Besides, authors [24] 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 from 0.3 to 0.5. Similar results were obtained in the experimental study [1]. According to the [1], calculated nCL value for material processed by ECAR (equal channel angular rolling) was helpful to predicting 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 predicting the material workability during metalworking processes, what was also confirmed by [19, 25].

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4 Discussion

As a result of deformation, dislocations accumulate and pile up at second phase particles and grain as well as subgrain boundaries. An increasing dislocation density results in work hardening. By contrast, elevated temperatures make the dislocations move freely and annihilate each other. As a result, the material softens. The competition between the hardening and softening mechanisms yields a dynamic equilibrium, and therefore a steady state flow stress with a constant dislocation density is observed in the material [26]. For materials with low stacking fault energy, which is related to the atomic bonding in the material, climb and cross slip of the dislocations are hindered. Hence, dislocations build up faster during deformation and the critical dislocation density for the initiation of recrystallization can be attained [26]. By contrast, for materials with high stacking fault energy, such as aluminium, dislocations are very mobile and can recovered more easily. Therefore, dynamic recovery is more likely to happen than conventional dynamic recrystallization in aluminium. The microstructure evolution during extrusion process is affected by local changes in strain, temperature and strain-rate. Especially for aluminium alloys differences in grain size, grain shape, texture and precipitation behavior have to be considered since these are the controlling factors determining the local strength, the fatigue properties and the corrosion behavior of the final work piece. For high strength applications of aluminium alloys, generally small grain sizes are desired [26], which can be achieved via recovery or recrystallization. Due to the high stacking fault energy of aluminium alloys, dislocations formed during plastic deformation have a high tendency to annihilate such that the recovery process is favored instead of the classical recrystallization mechanism, which requires a substantial increase in dislocation density.

For 7075 aluminium alloy, the precipitation hardening phase is $MgZn_2$, provided the ageing temperature is below 200 °C. 7075, with more than 1% Cu also precipitates $CuMgAl_2$. The hardening precipitates are up to 0.01 µm in size [27].

For 7000 series alloy, their strength is derived from the precipitation of coherent $MgZn_2$ phase in the grain interiors and noncoherent $MgZn_2$ along the grain boundaries [28]. However, for 7075-T6 with many precipitates, the strain hardening may be depend considerably on these precipitates in Al matrix. Strain hardening results from the obstruction of these precipitates for dislocations gliding and intersecting. Less precipitates in 7075-T6 lead to its lower hardening behavior [29].

5 Conclusion

According to this study, following conclusions can be made:

- in terms of determination of the nCL criteria, physical and numerical simulations showed a high common similarity.
- experimental compression tests together with mathematical calculations could be used as a suitable tool to calculate the critical nCL values.
- EN AW 6082 is a material with higher workability than EN AW 7075 what was also confirmed by calculated and simulated nCL data:
    - EN AW 6082 T6: nCL calculated: 0,28; nCL simulated: 0,29
    - EN AW 7075 T6: nCL calculated: 0,16; nCL simulated: 0,17

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