DETERMINATION OF THE CRITICAL VALUE OF NORMALIZED COCKROFT - LATHAM CRITERION FOR THE AZ31 MAGNESIUM ALLOY BASED ON TENSILE TEST

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Abstract

Limit values of the normalized Cockroft - Latham criterion for different range of temperature and strain rates may be determined by using the comparative method for the uniaxial tensile test of notched specimens. Uniaxial tension of notched specimens was performed on a multi-function metallurgical process simulator, Gleeble 3800. In order to determine the actual values of the normalized Cockroft - Latham criterion, theoretical studies of the notched specimen tension test were also conducted. The hot tensile deformation and the fracture behaviors of the AZ31 magnesium alloy were studied with the temperature range of 350 - 450°C and strain rates 0.1, 1.0 and 10.0 s^{-1}.

Keywords: Magnesium alloy, fracture, normalized Cockroft - Latham criterion, FE modeling

1. INTRODUCTION

Metal forming processes of magnesium alloys have a specific character and their proper realization in industrial practice is often very difficult [1,2]. The main limitation concerning their application is low plasticity of these alloys, leading to fracture appearance. In the case of magnesium alloys this phenomenon is more often present than during forming of other nonferrous metals or steel. It is needed to work out a method of cracks appearance foreseeing at the stage of theoretical analysis of the designed process, which is based on forming process simulation with the application of appropriate cracking model. For the known limiting conditions, it is possible to forecast probable cracks areas and modify parameters of the process to eliminating this phenomenon. There are a number of criteria associated with ductile fracture, void nucleation and growth play a key role leading to necking [3,4]. Among these fracture criteria, the normalized Cockcroft-Latham fracture criterion is widely used in engineering analysis [5]. The normalized Cockcroft-Latham criterion assumes that the maximum principal stress is the most relevant in the initiation of fracture. The criterion is defined in terms of traction plastic work associated with the principal stress along the path of the equivalent plastic strain, as shown in following equation:

$$C = C_0 + \int_0^{\bar{\varepsilon}} \frac{\sigma_1}{\sigma_i} d\bar{\varepsilon} \tag{1}$$

where:

C_0 - initial value of the normalized Cockroft - Latham criterion

$\bar{\varepsilon}$ - equivalent strain

σ_1 - 1st main stress (MPa)

σ_i - equivalent stress (MPa)

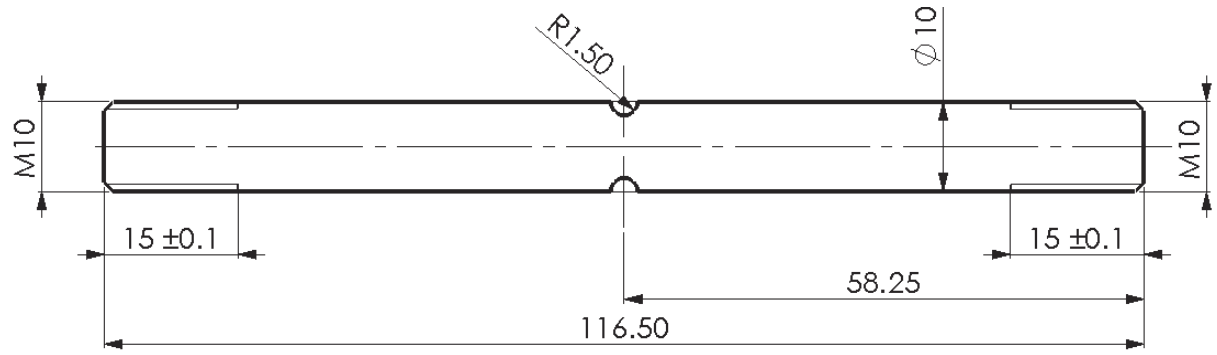
To determine the limiting values of normalized Cockroft - Latham criterion the comparative method was used [6,7]. Research have been done to determining limiting values of normalized Cockroft-Latham criterion during the deformation at elevated temperatures 350÷450°C of the AZ31 magnesium alloy, which chemical composition is shown in **Table 1**.

Table 1 Chemical composition of magnesium alloy AZ31

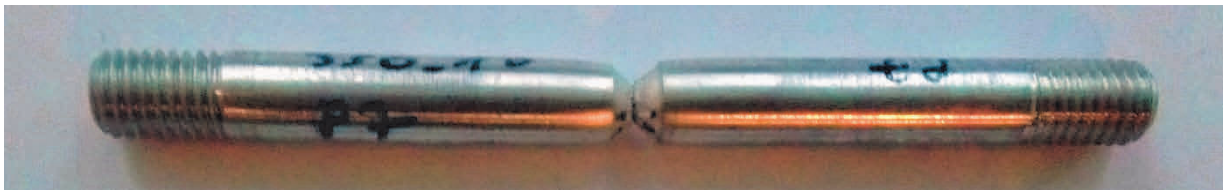
	Mg	Al	Zn	Mn	Si	Cu
AZ31	residual	2.5	1.0	0.12 - 0.14	0.08	0.03

2. UNIAXIAL TENSION TEST OF NOTCHED SPECIMENS

The limiting values of the normalized Cockroft - Latham criterion could be determined in a basic tests such as: uniaxial tension, uniaxal compresion of the shape specimens, bending or torsion. In this work to determine dependecy of the limiting values analyzed criterion to temperature and strain rate uniaxial tension of notched speciments was used. In **Figure 1** a shape and dimensions of the specimens used in uniaxial tension tests were shown.



a)



b)

Figure 1 Shape and dimensions of notched specimen used to determination of the limit values of normalized Cockroft - Latham criterion (a), an example of specimen from AZ31 alloy after the tensile test (b)

Uniaxial tension of notched specimens was performed on a multi-function metallurgical process simulator, Gleeble 3800 at the Czestochowa University of Technology. The specimens were deformed at a constant strain rate until their breaking. During the tensile tests, a constant temperature was maintained by continuously heating up the specimens. The test were performed for three temperatures: 350°C, 400°C and 450°C, and correspondent three strain rates: 0.1, 1.0 and 10.0 s^{-1}. The initial length of each specimen was equal to 116 mm. The specimens were heated to the assumed temperature with 10°C/s speed. During the tensile test, the jaws of the simulator were moved at variable velocity (to ensure a constant strain rate), which resulted in the maximum deformation of the specimen in the notch area. At the moment of reaching the limiting fracture criterion value, micro-cracks started to form in the specimen, then the plastic fracture propagation proceeded until complete breaking of the specimen. After the test each of specimen was cooled and measured to determine the length after breaking - L_k. Based on this measurements critical elongation - ΔL in which total rupture of specimen occurs has been calculated. Results of measurements of the final lengths and calculated critical elongation are presented in **Table 2**.

Table 2 Dimensions of specimens after the tensile tests

No. of spec.	Temperature (°C)	Strain rate (s^{-1})	L_k (mm)	ΔL (mm)
1	350	0.1	119.93	3.32
2	350	1.0	119.73	3.21
3	350	10.0	119.78	3.14
4	400	0.1	120.21	3.75
5	400	1.0	120.76	4.23
6	400	10.0	121.14	4.62
7	450	0.1	120.45	3.81
8	450	1.0	120.95	4.42
9	450	10.0	121.38	4.87

In the **Figure 2** dependence of the critical elongations estimated for the AZ31 magnesium alloy to the strain rate and temperature has been presented. As it can be noticed increasing the test temperature to 400°C and higher causes significant rise of the critical elongation. This correspond to the fact that, when temperature is increased, the critical shear stress of non-basal plane slip system is reduced because of the increase of the amplitude of the atomic vibration, and then some potential non-basal plane slip systems, such as the prismatic and pyramidal plane, are promoted by the thermal activation [8,9]. As we can observe for the temperature 350°C increasing the strain rate in tension tests causes a small drop of critical elongations values. This could be effect of the change of the dominant fracture mechanism [9]. Also the nucleation and growth of recrystallized grains during dynamic recrystalisation of the magnesium alloys are sensitive to strain rate [8,9]. The exact explanation of the causes of such a phenomenon requires further analysis. Reverse dependence can be observed for the temperature 400°C and 450°C, where increasing strain rate causes growth of the critical elongations values.

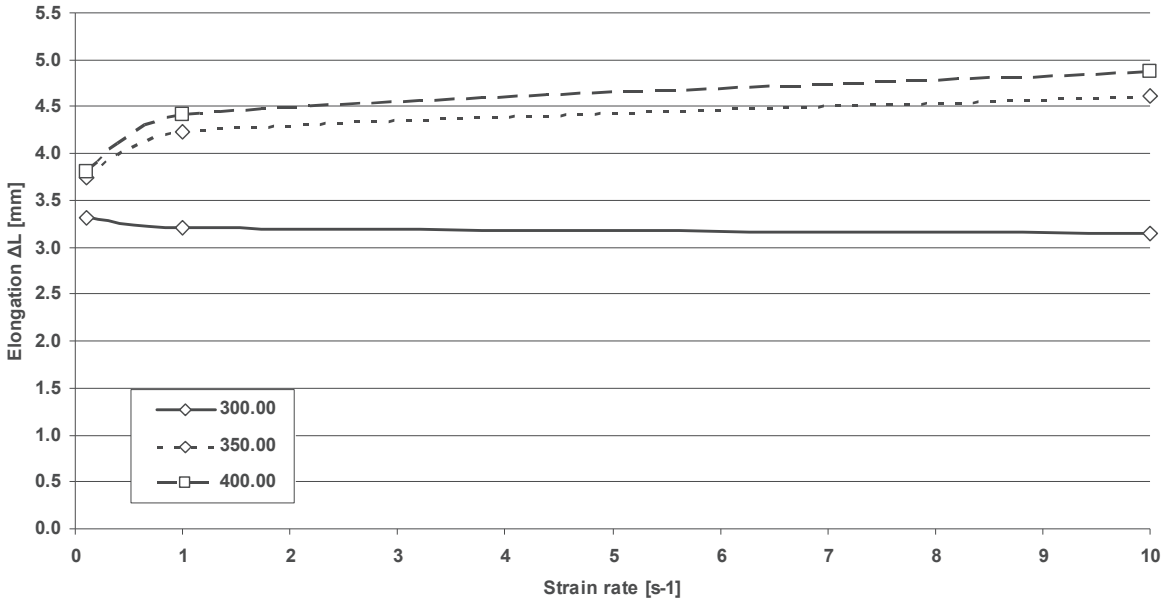


Figure 2 Dependence of the critical elongations estimated for the AZ31 magnesium alloy to the strain rate and temperature

3. DETERMINATION LIMITING VALUES OF THE NORMALIZED COCKROFT - LATHAM CRITERION BY USING COMPARATIVE METHOD

In order to determine the actual values of the normalized Cockroft - Latham criterion, theoretical studies of the notched specimen tension test were conducted. The theoretical studies were carried out for the same parameters to those used in the laboratory tests. For the numerical modeling the computer program Forge 2011® based on finite element method was used. In calculations, material model destined for own research in plastometer compression test and described in the work [10] was applied. As the notched specimen tension process is an axially symmetrical process, the numerical studies were conducted only for a section making up the ¼ of the actual specimen volume by introducing two planes of symmetry. To preserve the geometrical specimen shape in the notch region during deformation, the length of mesh sides were locally densified. To establish the limiting values of the normalized Cockroft-Latham criterion, the obtained theoretical study results were compared with the results of the experimental tests at the moment of specimen breaking (**Table 2**). For the analysis, the assumption was made that the critical elongations (the ones for which specimen breaking occurs) obtained in the laboratory tests correspond to the moment of specimen breaking in the theoretical studies. **Figure 3** presents the distribution of the normalized Cockroft-Latham criterion estimated in the theoretical studies at the rupture moment - reaching the critical elongation obtained in the laboratory test.

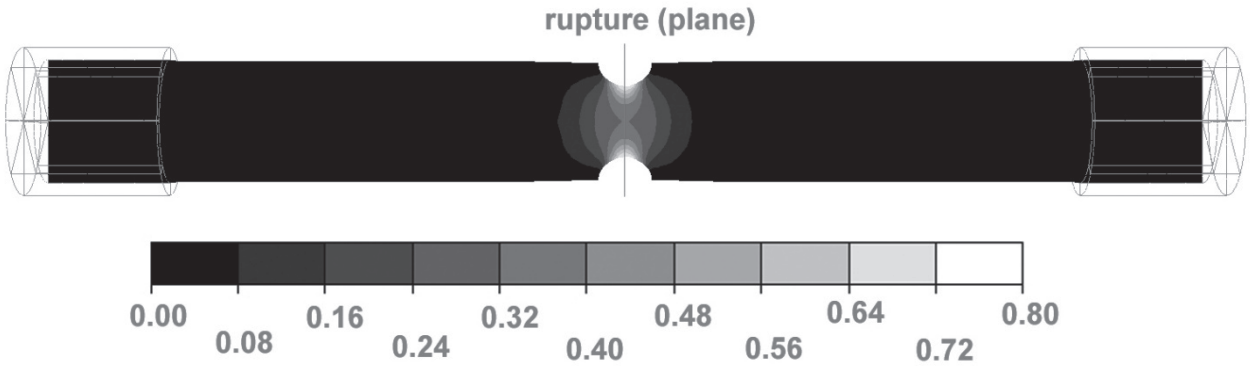


Figure 3 An example of distribution of the normalized Cockroft-Latham criterion at the fracture moment - reaching the critical elongation obtained in the laboratory test (T = 400 °C and strain rate = 1 s^{-1})

The obtained results (**Figure 3**) do not allow determining definitely the limiting normalized Cockroft-Latham criterion value, for which the specimen breaking occurred. In order to determine the limiting value, the normalized Cockroft-Latham criterion values were calculated as an average over the cross-section. The determined limiting values of the normalized Cockroft-Latham criterion for the analyzed conditions are given in **Table 3**.

Table 3 Limiting values of normalized Cockroft-Latham criterion determined in uniaxial tension test

Strain rate (s^{-1}) / Temperature (°C)	0.1	1.0	10.0
350	0.35	0.33	0.23
400	0.43	0.6	0.67
450	0.45	0.65	0.77

Figure 4 shows the dependence of the determined limiting normalized Cockroft - Latham criterion values to the strain rate and temperature. As it can be noticed comparing data presented in **Figure 4** are similar to data presented in **Figure 2**. For the temperature 350°C along with the increase strain rate critical value of the normalized Cockroft - Latham criterion decreases. Increasing temperature to 400°C and higher causes the

trend to reverse. As it was mentioned at a temperature 400°C for magnesium alloys are activated additional mechanism of deformation [9]. As it can be observed further increase temperature causes increases the plasticity range for the AZ31 magnesium alloy. Estimated values of normalized Cockroft - Latham criterion allow to defining zones in a deformed material for which fracture may occur. It should also be noted that due to the anisotropy of magnesium alloys [8], the determined critical values of normalized Cockroft - Latham criterion will be valid for processes in which the state of stress coincides with that which occurs in the tensile test. That is, when tensile stress is the dominant one.

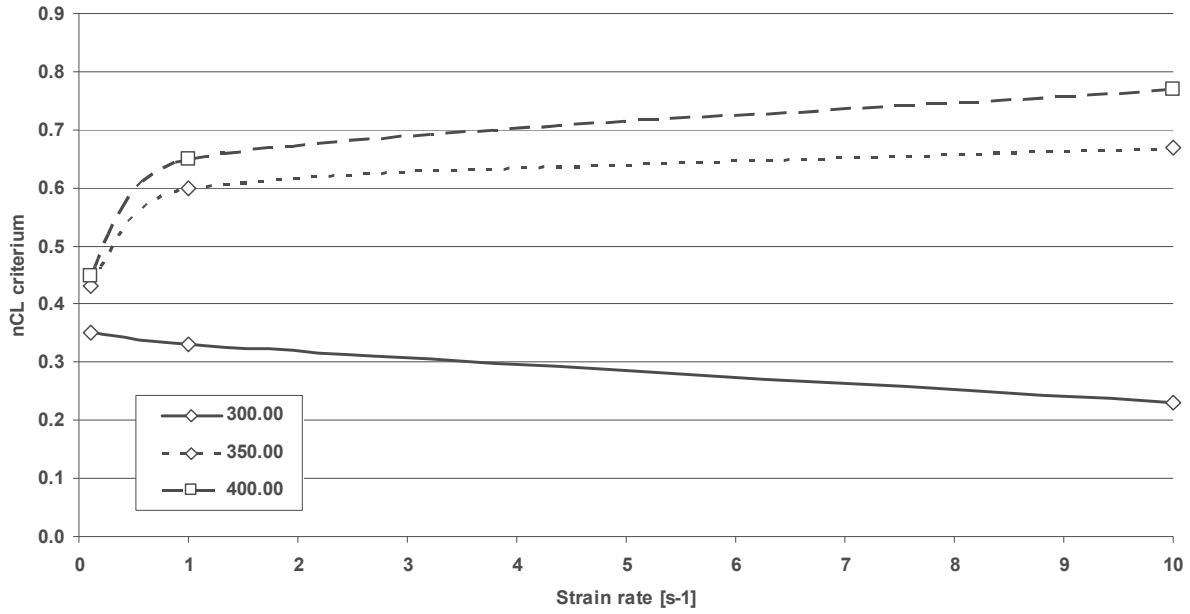


Figure 4 Dependence of the normalized Cockroft - Latham criterion for AZ31 magnesium alloy to the strain rate and temperature

4. CONCLUSIONS

The comparative method allows to determine the limiting values of normalized Cockroft - Latham criterion, for which the fracture of the material during hot plastic working process appear. For the temperature 350°C along with the increase strain rate critical value of the normalized Cockroft - Latham criterion decreases. Increasing temperature to 400°C and higher, causes an increase of the critical values of the normalized Cockroft - Latham criterion. In this temperature additional mechanism of deformation for magnesium alloys are activated (additional slip planes) which causes a significant increase in the deformability of the tested alloy. For the temperatures above 400°C it can be noticed that with increasing strain rate increases critical values of analyzed criterion. Estimated values of normalized Cockroft - Latham criterion allows to defining zones in a deformed material for which fracture may occur.

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