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Determining the Normalized Cockroft-Latham Criterion for Titanium Alloy Ti6Al4V in Tensile Testing At Room Temperature

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Abstract -The paper presents a method for determining the boundary value of the normalized Cockroft-Latham (C-L) damage criterion for titanium alloy Ti6Al4V. This criterion is used to predict material cracking in metal forming processes. This method consists in subjecting specimens with necking to tensile tests until their failure. The tests are conducted at room temperature with a velocity of 100 mm/min. The experiments are modelled numerically using finite element method simulation software. Based on the comparison of the experimental and numerical results, the boundary value of the C-L criterion is determined. This value is essential for developing a model that enables analysis of ductile fracture occurrence in numerical simulations.

Keywords**:** ductile fracture, Cockroft-Latham criterion, titanium alloy Ti6Al4V

1. Introduction

Fracture results from the separation of a material under the action of stress and it is considered an undesired phenomenon in metal forming processes (Anderson, 2005; Freund, 2008). For this reason, there are numerous studies which present the results of predicting material ductile fracture initiation (Cao, 2015; Yanshan and Hoon, 2013; Quan et al., 2013; Ohata, 2014). Both numerical calculations and experimental tests conducted to investigate this problem facilitate the design of processes for producing parts by metal forming technologies. In order to investigate this phenomenon, simulation programs based on different fracture models, e.g. the Cockroft-Latham model (Cockroft and Latham, 1968), which is analyzed in this paper, or the Oyanne, Freudenthal and McClintock models, are used. The normalized Cockroft-Latham criterion is expressed with the following formula:

$$\int_0^{\varepsilon_f} \frac{\sigma_{\max}}{\sigma_H} d\varepsilon_{pl} = C, \tag{1}$$

Where:
σ_{max} - the maximum principal stresses,
σ_H - the stress according to the Huber – Misses hypothesis,
ε_f - the limit fracture strain,
ε_{pl} - the plastic strain,
C - the material constant in the fracture criterion.

To apply this criterion, we must know the integral's boundary value at which cracking occurs. This value is fundamental for predicting the moment of material cohesion loss using commercial software for analysis of metal forming processes. For this reason, it seemed justified to develop a research method for determining the boundary value of titanium alloy TiAl4V which is widely used in the production of machine parts.

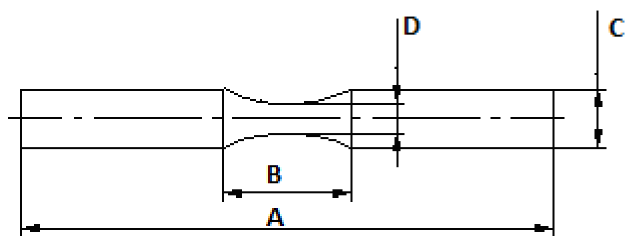
2. Research Method and Results

The tests were conducted on two-phase titanium alloy Ti6Al4V whose chemical composition is listed in Table 1. Titanium alloys are more and more often used in the machine, automotive, aviation and aerospace industries as well as in medicine. The popularity of titanium results from its relatively low absolute weight (4500 kg/m^3), relatively good strength and plastic properties, good resistance to corrosion, high melting point (1649°C) which makes this metal fire-resistant, as well as its high contents in the crust of the earth. The main titanium alloy additions include Al, Sn, Mo, V, Mn, Fe, Cr. These elements dissolve in titanium, thus increasing titanium strength and affecting, at the same time, the temperature of allotropic change.

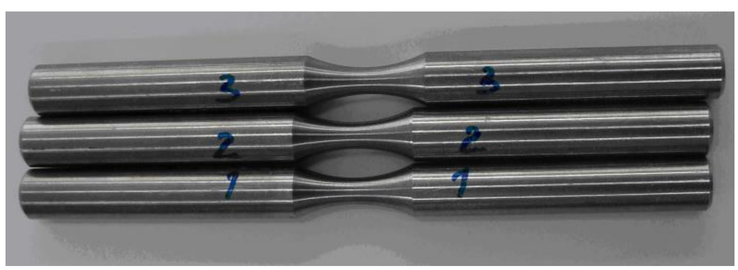
Table. 1. Chemical composition of Ti6Al4V alloy in accordance with ISO 5832/3 (mass %)

Al	V	Fe	O	C	N	H	Ti
5.5	3.5	<0.3	<0.2	<0.08	<0.05	<0.0015	the rest

The specimens used in the experimental tests are shown in Fig. 1. The rolled specimens had a necking made in their central part to excite fracture in the predicted region. The dimensions of the specimens used in the experimental tests are listed in Table 2.



a)



b)

Fig. 1. Specimens used in tests: a) figure, b) photography

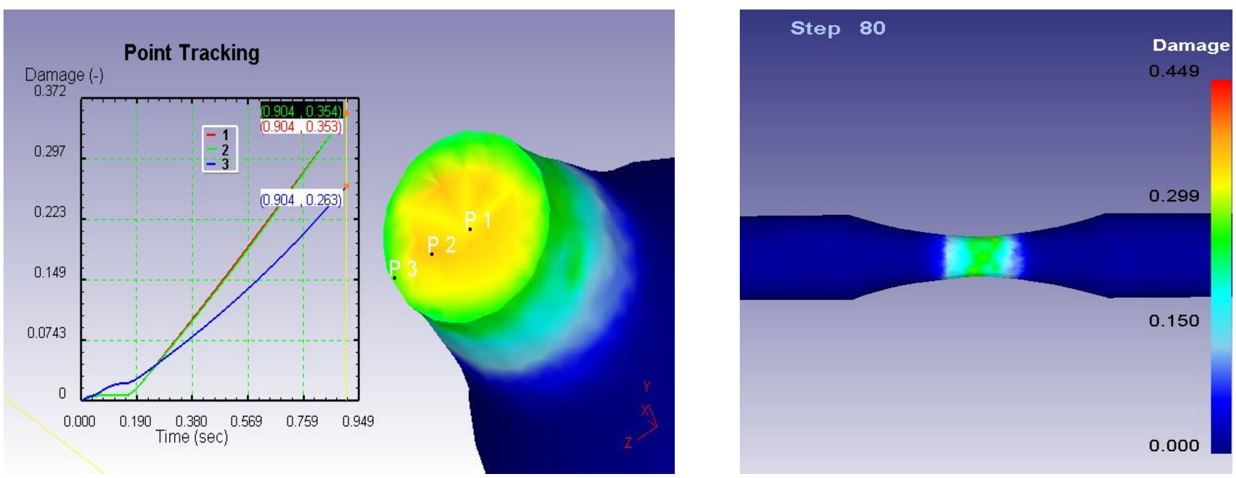
Table. 2. Dimensions of the specimens used in tests

Specimen number	A [mm]	B [mm]	C [mm]	D [mm]	Elongation [mm]
1	130	21.9	10	5	1.5
2	129.9	21.7	10	5	1.6
3	130	21.9	10	5	1.5

The specimens were subjected to tensile testing until ductile fracture (Fig. 2) at room temperature, with the velocity of 100 mm/min. Following the fracture, the specimens were examined and measured in order to estimate their elongation.

Fig. 2. Titanium alloy Ti6Al4V specimen after tensile testing

The experimental test results were analyzed using numerical simulations. The simulations were performed using the FEM-based DEFORM 3D program, in which the Cockroft-Latham damage model, determined by the integral expressed with the formula (1), was implemented. The material model was obtained from the material database of the program used. The integral was calculated at characteristic points in the specimen cross sections (Fig. 3). The points underwent displacement during the tensile testing of the specimens. The values of the C-L integral at fracture for all the specimens are listed in Table 3. Based on the calculations made, it was observed that at specimen fracture the maximum value occurred in the central area of the cross section (points P1 and P2 in Fig. 3). The highest value at fracture equal to 0.354 was taken to be the limit value determining fracture under experimental conditions, i.e. in tensile testing at room temperature, with the tensile velocity of 100 mm/min.



a) b)

Fig. 3. Distribution of the Cockroft- Latham damage criterion: a) in the cross section with position of characteristic measuring points, b) on the surface of the specimen

Table. 3. Values of the C-L integral at fracture for specimen number 1

Specimen / Point	Specimen number 1
Point 1	0,353
Point 2	0,354
Point 3	0,263

3. Conclusion

The results demonstrate that the applied method is a successful way of determining the boundary value of the C-L damage criterion. As expected, the shape and dimensions of the workpiece led to controlled cracking in the region of the necking's centre. The numerical results reveal that the distribution of the investigated damage criterion is not uniform in the section where the cracking occurs. Its higher values are located in the central layers of the material, while the lower ones can be observed in the outside layers of the section. It is found that the boundary value of the normalized Cockroft-Latham criterion for titanium alloy Ti6Al4V formed at room temperature is 0.354.

Acknowledgements

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