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ANALYSIS OF SHEAR HAT TEST IN DIGITAL ENVIRONMENT

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Determination of flow curves of metals, which are indispensable for numerical simulations of forming processes, is often limited to tensile or compression tests. However in some cases the shear stress-strain behaviour of materials needs to be determined as well. In the paper digital analyses of shear-hat test at room temperature were performed for various steels, AlMg3 aluminium alloy and AZ80 magnesium alloy. Comparative analyses of process parameters and specimen geometry as a function of tool displacement were performed for better understanding of the testing procedure.

Key words: metal forming, flow curve, shear, shear-hat test, FEM simulation

Analiza smičnih naprezanja kod shear-hat ispitne metode u digitalnom okruženju. Određivanje krivulja tečenja kod metala, koje su neophodne za numeričke simulacije, često je limitirano na vlačno ili tlačno ispitivanje. Ipak u nekim slučajevima potrebno je odrediti stanje smičnih naprezanja i deformacija materijala. U članku je prikazana digitalna analiza posmičnih naprezanja „shear-hat" ispitivanja koja su za različite čelike, aluminijsku slitinu AlMg3 i magnezijsku slitinu AZ80 izvršena pri sobnoj temperaturi. Izvršene su i usporedne analize promatranih parametara u procesu te je ispitan utjecaj geometrije ispitivane epruvete kao funkcije alatnih pomaka kako bi se bolje upoznala ispitna procedura.

Ključne riječi: oblikovanje metala, krivulja tečenja, smično naprezanje, shear-hat test, MKE simulacija

INTRODUCTION

In numerical simulations of forming processes material properties are mostly described by flow curves obtained through tensile or compression tests. However, in some cases like high velocity impact loading, forging, loading of tubes [1] etc. shear stresses need to be well determined as well. For this case various tests were developed ranging from torsion test, double-shear test, the Iosipescu shear and the V-notched rail shear test methods (both ASTM standards) to analyse sheet metals and torsion test and shear-hat test to analyse the bulk metals.

The shear-hat test is based on upsetting of hat-shaped specimens in order to obtain a pure shear deformation zone. Two different types of specimens are used in order to define the shear loading conditions of the analysed material. Type A [2 - 4] has an outer-top diameter larger than the inner diameter, while type B [5, 6] has an opposite relation of observed diameters (Figure 1). A compression force applied to the top of the specimen induces shear stress in a truncated-cone at type A or solely a ring shaped deformation zone considering the type B specimen. Piers et. all [4] studied the influence of specimen's inner and outer radii and their relationship. It was found out that the best results can be achieved when the inner radius is slightly smaller than the outer one (type A) in order to have also some normal pressure in the shearing region. The pure shear zone is more homogeneous through this normal pressure in its middle area. On the other hand, longitudinal stresses appear with type B specimens which have a negative impact on the formation of the shear zone.

Since the shearing process begins with a concentration of stresses in the edges of the specimen [2], rounded corners decrease stress concentration and postpone strain localization. Radii of corners have an important role in the testing and also affect the value of applied force, as larger radii induced higher forces in order to overcome the shearing stresses [4]. Therefore, the radii on the surface of the shearing zone should be as small as possible and mainly limited by the machining process used. While at quasi-static loading of the specimen the strain hardening of the material appears additionally to this phenomenon also thermal softening appears at dynamic loaded shear zone with high strain rate [2].

As a majority of papers dealing with a shear strain analysis are focused on the impact loading there are insufficient data available for quasi-static conditions appearing at conventional forming. Furthermore, none of the presented research works analyses the real cross-section of the shearing zone, upsetting of the upper specimen area and time-dependant shape of the area surrounding the shear zone. Due to the fact that the real shear zone cannot be directly observed during the ex-

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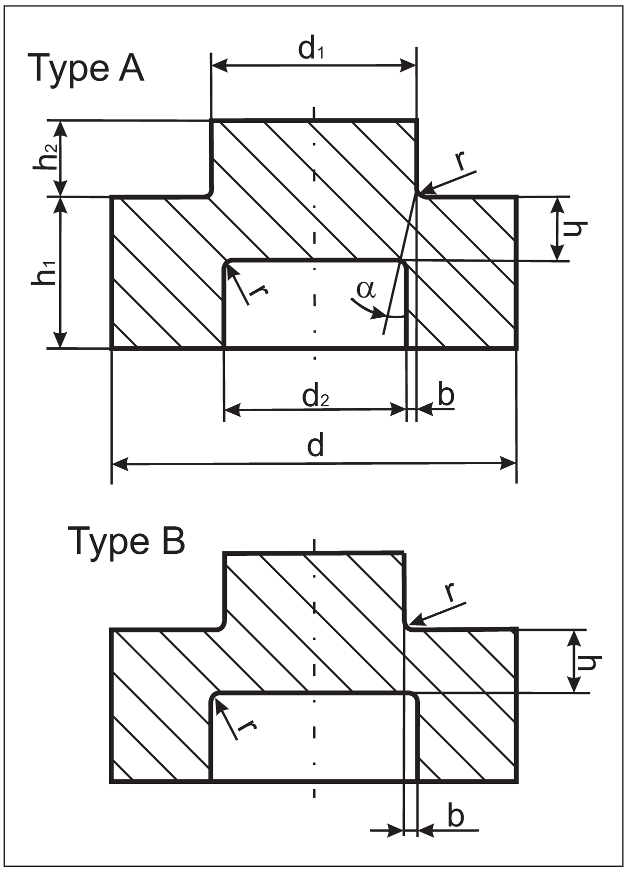

Figure 1 Types of hat-shaped specimens

periment, it is necessary to analyse the shaping of a part during the testing procedure. Moreover, a majority of testing equipment acquires displacement of the compression bar Δh which differs from the real displacement of the shear zone Δh_A due to the upsetting of the upper specimen part – Figure 2.

Therefore, the main objective of the present paper is a comparative analysis of geometry of a shear-hat specimen influenced by the variation of material properties. Being given that the aim of the presented research work was not the impact shear loading at extremely high strain rates, the thermal influence could be neglected.

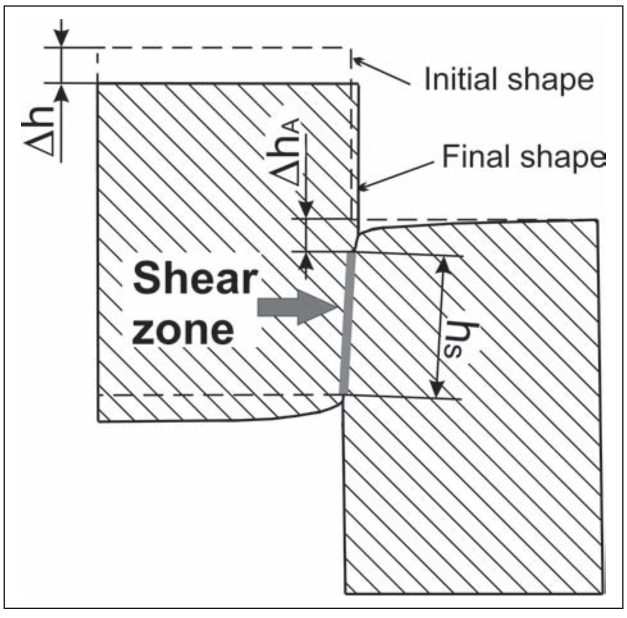

Figure 2 Contour of the deformed specimen: $\Delta h > \Delta h_A$

MATERIAL PROPERTIES

In order to analyse the influence of various materials, main industrially interesting groups [7] of metals were considered. Therefore, three flow curves for steel, one for aluminium and one for a magnesium alloy were selected. In the selection of the steel properties C15E quality served as a basis material followed by the spread of the C constant of ± 200 MPa, hardening exponent n of ± 0,04 and yield point R_p of ± 50 MPa. The variation of steel properties serves to analyse the influence of various flow curves to specimen shaping. The aluminium as the second most often used material group [8] was selected, which is softer than the analysed steels. The mechanical properties used in simulations of the shear-hat test are presented in Tables 1 and 2.

Magnesium alloy AZ80 is defined by the Swift law [5]:

$$\sigma = K\,(B + \varphi)^n \quad (1)$$

having the following constants: K=670 MPa, B=0,005 and n=0,27.

Table 1 **Material properties**

Material	Density/ kg/m^3	Young's modulus/ GPa	Poisson's ratio
Steel	7 850	210	0,3
AlMg3	2 700	70	0,33
AZ80	1 800	47	0,35

The flow curves of steel and AlMg3 material are determined by Hollomon approximation:

$$\sigma = C \cdot \varphi^n \quad (2)$$

Table 2 **Flow curve constants**

Material	C / MPa	n	R_p / MPa
Steel 1	500	0,17	200
Steel 2	700	0,21	250
Steel 3	900	0,25	300
AlMg3	381	0,216	115

FEM MODEL

The FEM model for a digital analysis of a shear-hat test consists of an elasto-plastic specimen and rigid tool parts. As the specimen expresses rotational symmetry, the simulation can be simplified to a 2D problem. The tool parts are defined by analytical rigid elements. The specimen geometry is divided into three sections presented in Figure 3: shear zone (a), vicinity of the shear zone (b) and the rest of the specimen (c). It can be anticipated that severe shear strain can influence the reliability of the results, so the shape of the FEM mesh was "pre-deformed" into opposite direction being shaped as a rhomboid, which is expected to assume the shape of a rectangle during the upsetting of the shear-hat specimen – Figure 3.

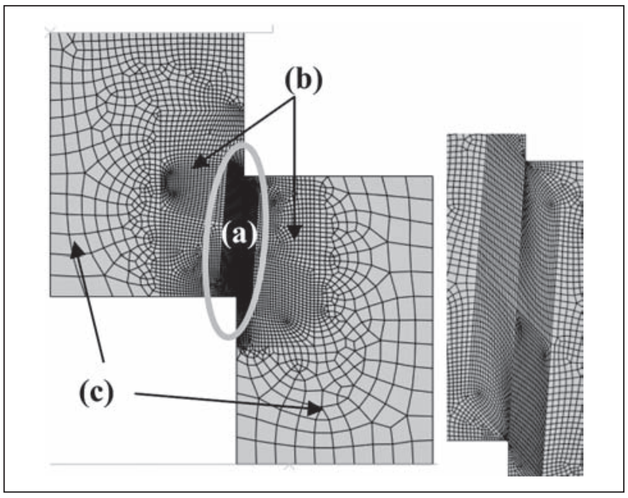

Figure 3 Mesh of the whole FEM model (left) and a detail of the shear zone (right)

Element sizes are selected according to the required accuracy of the simulation:

- in the shear zone: 30 × 50 μm
- around the shear zone: 70 × 70 μm
- general size of other specimen areas: up to 300 × 300 μm.

The presented mesh consists of 6827 nodes and 6752 elements of CAX3 and CAX4R types according to the ABAQUS terminology.

Between all adjacent objects the Coulomb friction law with the friction coefficient of μ=0,05, which is mostly used in bulk forming applications, was considered. The upsetting of the upper part of the specimen was performed with a displacement of the upper tool part for 0,85 mm with the fixed bottom tool part. The simulation was performed with an explicit solver. Since only the shaping of the deformed shear-hat specimen is analysed, the fracture criteria like ductile fracture criteria implemented by Magd and Abouridouane for AZ80 alloy in [6] were not considered in the presented work.

RESULTS AND DISCUSSION

The upsetting of the shear-hat specimen results in slight barrelling of its upper part. This phenomenon is influenced through the friction coefficient between the upper tool part and the specimen. It was established that the increase in the friction coefficient causes barrelling of the material as well. The friction coefficient on the other hand has a smaller influence on the lower (larger) part of the shear-hat specimen.

The barrelling of the upper specimen part is shown in Figure 4. The initial location of the observed edge is emphasised by a thick black line having an upper diameter of 8,1 mm. The point in the middle of the observed contour has a relatively high displacement in the radial direction, which is the most emphasized at the highest flow curve of the analysed steel.

Minimum expansion due to barrelling appears with Steel 1 having the lowest flow curve from all steels. Since the displacement of the shear zone defines the shear strain, it is important to determine the exact displacement of this area. Upsetting of the top cylindrical part is directly related to a smaller displacement of Δh_A necessary to determine the shear strain according to the equation

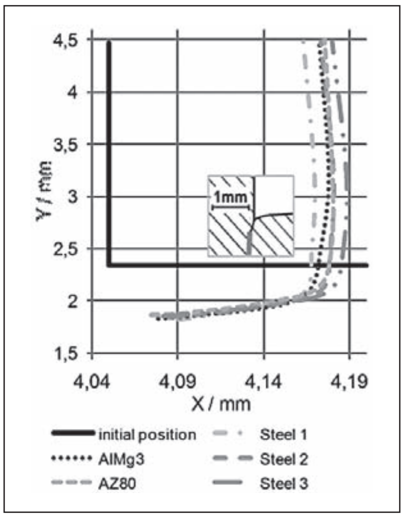

Figure 4 Outer corner and profile line of top cylindrical surface at tool displacement of 0,85 mm

$$\gamma = \Delta h_A / b \ [4]. \quad (3)$$

Furthermore, the surface loaded with shear stress is inclined for angle α (see Figure 1). Displacement difference due to the upsetting of the top specimen part can be expressed as

$$\Delta h_s \cdot \cos\alpha = \Delta h - \Delta h_A. \quad (4)$$

The cosine of inclination angle α is defined with

$$\cos\alpha = (h+2r)/h_s \quad (5)$$

The length of the deformed shear zone decrease from initial h_{S0}=2,544 mm to final h_{Sfin}=2,28÷2,31 mm depending on the observed material – Figure 5. This

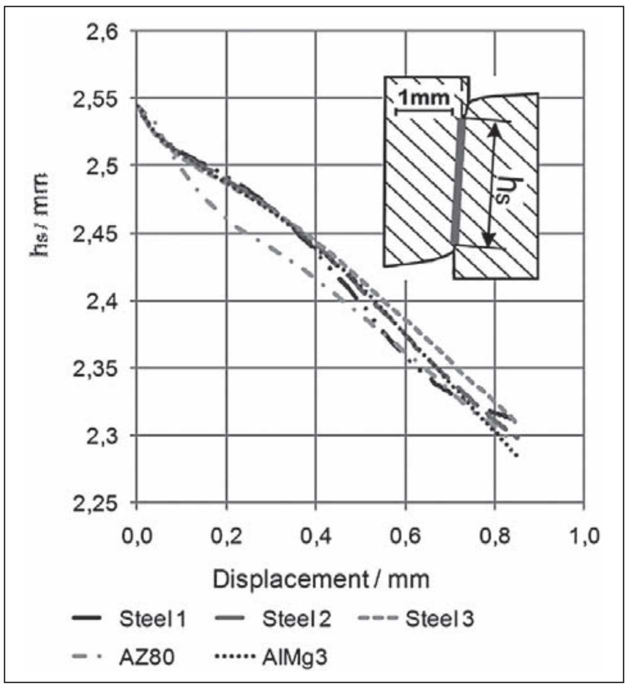

Figure 5 Shear height h_s as a function of tool displacement Δh

means a shortening of the initial length by 9,2 to 10,4 %. The shear stress can be calculated on the basis of the initial height h_{S0} or true shear area necessary to define the true stress-strain conditions:

In this case the height of the shear zone h_s and the medial diameter of the analysed shear area d_m are functions of tool displacement. As the changes of d_m lie below 1 % only, the changes of h_s need to be taken into account.

CONCLUSIONS

Flow curves for digital analyses are commonly obtained by a tensile and compression test. However, shear stresses predominante in some forming processes. Therefore, testing procedures for determination of flow curves under shear loading conditions have been developed. The paper analysed the shear-hat test and shows that good evaluation of the shear zone can influence the shear flow curve up to 10 % through variation of the shear zone during the testing procedure. Digital analyses have further shown the barreling of the upper specimen part and an increase in its diameter. This has to be considered once the real displacement of the shear zone is calculated. The analyses of other parameters defining the shear zone have shown that the variation of d_m and shearing surface change by less than 1 % according to their initial values during the shear-hat experiment.

The obtained results present a good basic knowledge of the shear zone formation which is necessary for analyses of more complex problems, which appear during testing at higher strain rates and/or elevated temperatures. In this case mixed work hardening and adiabatic softening appear, which is the target of future research work on light metals like aluminum or magnesium alloys.

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Note: The responsible for the English language is N. Henigman, Ljubljana, Slovenia.