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

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. al. [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-
Experiment, 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 $\Delta h$ which differs from the real displacement of the shear zone $\Delta h_s$ 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.

**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]:

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

having the following constants: $K=670$ MPa, $B=0.005$ and $n=0.27$.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density/ kg/m³</th>
<th>Young’s modulus/ GPa</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>7 850</td>
<td>210</td>
<td>0.3</td>
</tr>
<tr>
<td>AlMg3</td>
<td>2 700</td>
<td>70</td>
<td>0.33</td>
</tr>
<tr>
<td>AZ80</td>
<td>1 800</td>
<td>47</td>
<td>0.35</td>
</tr>
</tbody>
</table>

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

$$\sigma = C \cdot \varphi^n$$

<table>
<thead>
<tr>
<th>Material</th>
<th>$C$/MPa</th>
<th>$n$</th>
<th>$R_p$/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel 1</td>
<td>500</td>
<td>0.17</td>
<td>200</td>
</tr>
<tr>
<td>Steel 2</td>
<td>700</td>
<td>0.21</td>
<td>250</td>
</tr>
<tr>
<td>Steel 3</td>
<td>900</td>
<td>0.25</td>
<td>300</td>
</tr>
<tr>
<td>AlMg3</td>
<td>381</td>
<td>0.216</td>
<td>115</td>
</tr>
</tbody>
</table>

**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.
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 \( \Delta h_A \). Necessary to determine the shear strain according to the equation

\[
\gamma = \frac{\Delta h}{b} [4].
\]

Furthermore, the surface loaded with shear stress is inclined for angle \( \alpha \) (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 \( \alpha \) is defined with

\[
\cos \alpha = \frac{h+2r}{h_s}. \quad (5)
\]

The length of the deformed shear zone decrease from initial \( h_{S0} = 2.544 \) mm to final \( h_{S\text{fin}} = 2.28 \div 2.31 \) mm depending on the observed material – Figure 5. This 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 \( \Delta h_A \). Necessary to determine the shear strain according to the equation

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\gamma = \Delta h / b \quad [4].
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**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
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 predominate 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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**REFERENCES**


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