SIZE EFFECTS ON FLOW STRESS AND FAILURE OF Ti-6-22-22S AND Al7075 OVER A WIDE RANGE OF STRAIN RATES

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ABSTRACT
The effect of specimen size and strain rate on the failure behaviour of Ti-6-22-22S and Al7075 T6 under compressive loading was investigated at room temperature. It was found that larger specimen dimensions and higher strain rates lead to smaller plastic deformability before failure. Possible explanations for the measured mechanical behaviour are due to the increased influence of friction effects by scaling specimen geometry or due to the intensified effect of residual stresses caused by manufacturing processes.

1 INTRODUCTION

When manufacturing technologies like cutting and forming are applied to small dimensions, scaling effects may occur. These effects appear as a not directly predicable change of component or process behaviour even when scaling was done in correct similarity relations. The observed changes in material properties are a consequence of strong effects that size introduces on material behaviour, e.g. flow stress and failure. There are already publications about the influence of grain size, specimen dimension or friction effects on the flow stress behaviour of metals under quasistatic and moderate loading rates (e.g. Geiger et al. [1]-[3]). However, less is known about the influence of specimen dimensions on failure behaviour of metals under compressive or tensile loading. Furthermore, the mechanical behaviour at high strain rates sometimes differs considerably from that measured at quasistatic or intermediate strain rates. Because many manufacturing processes occur at higher strain rates the knowledge of material behaviour at different scaling and time levels is essential.

This paper addresses size effects and the influence of strain rate on the flow stress and failure behaviour under compressive loading.

2 MATERIALS AND METHODS

Within this study two materials were tested. First the titanium alloy Ti-6Al-2Sn-2Zr-2Cr-2Mo-Si (Ti-6-22-22S) with (α+β)-microstructure was investigated. The chemical composition is presented in Table 1. The β-transition temperature of the alloy is 960 °C. The final bimodal microstructure contains globular α-phase between the lamella arrangement of α- and β-phase.

The aluminium alloy Al7075 T6 was solution heat treated and artificially aged [4]. Its chemical composition is shown in Table 1, too.

Table 1: Chemical composition of Ti-6-22-22S and Al7075 (wt%).

Titanium alloy Ti-6-22-22S									
Al	Sn	Zr	Mo	Cr	Si	Fe	O	N	C
5.75	1.96	1.99	2.15	2.10	0.13	0.04	0.082	0.006	0.009

Aluminium alloy Al7075								
Zn	Mg	Cu	Fe	Si	Mn	Ti	Cr	Zr
5.1-6.1	2.1-2.9	1.2-2.0	0.50	0.40	0.30	0.20	0.18-0.28	0.05

Cylindrical compression specimen with different diameters between 1 and 9 mm and a length to diameter ratio of 1 were made of these materials. To manufacture the small specimens (Ø 1 and 2 mm) at first bars of about 50 mm in length were electro discharge machined (EDM) out of a block of the material, followed by external cylindrical grinding. Bars with larger diameter were cutted, turned and finally ground. Then the specimens were cut from the bars and the endface was ground to the initial length.

To investigate the material behaviour under different loading rates and as a function of the specimen dimensions, compression tests were performed in special designed test set-ups. Especially for tests of small sample sizes special requirements for flatness and parallelism of the top and the bottom of the specimen and die platens, and surface finish have to be fulfilled (e.g. Krüger et al.[5]). All tests at quasistatic strain rate were performed in a special designed alignment fixture, which ensures a carefully aligned loading train. The applied force was measured with a calibrated load cell. The measurement of the axial displacement was realized either by a laser-optical device or by inductive sensors. For dynamic tests at strain rates of about 200 s^{-1} the design of a drop weight test, which was already successfully applied for the investigation of larger cross sections (e.g. Meyer and Krüger [6]), was used. The applied force was calculated by the elastic deformation of the punch and by means of calibrated strain gauges and Hooke´s law. The axial deformation was measured by an incremental gauge with a resolution of 2 µm. For the investigation of the materials behaviour at high loading rates (> 2000 s^{-1}) tests in a Split Hopkinson Pressure Bar (SHPB) adjusted to small specimen dimensions were performed. The stress-time and strain-time response was calculated from the sound velocity in the input and output bar (Gray [7]).

3 EXPERIMENTAL RESULTS

3.1 Flow stress behaviour of Ti-6-22-22S and Al7075

Figure 1 shows the flow stress behaviour of Ti-6-22-22S as a function of specimen dimensions and strain rate.

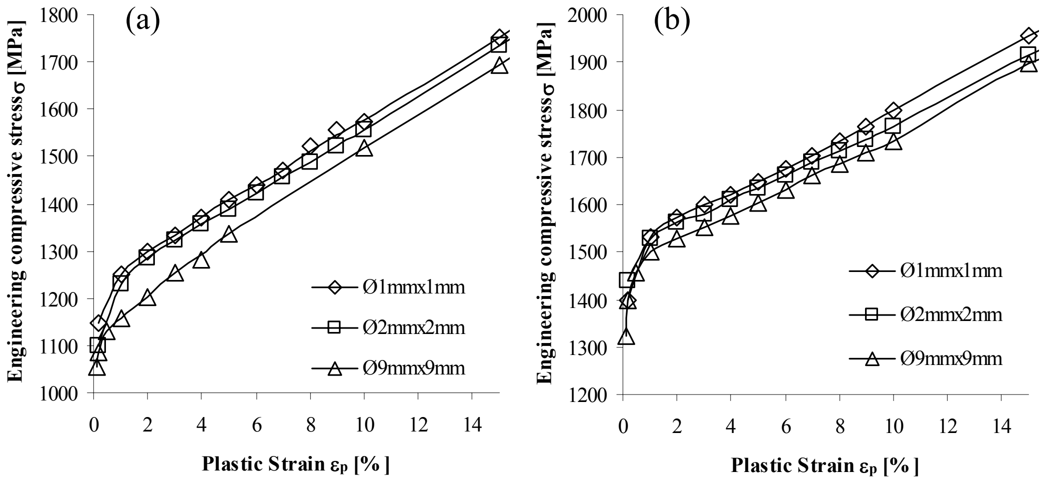


Figure 1: Flow stress behaviour of Ti-6-22-22S as a function of specimen dimensions at different strain rates: (a) 10^{-3} s^{-1} and (b) 200 s^{-1}.

Under quasistatic conditions (Figure 1a) flow stress of smaller specimen with 1 mm in length and diameter is about 80 MPa higher than that measured by larger specimen. Even at higher deformations this difference in flow stress was found. A similar behaviour was detected at strain rates of about 200 s^{-1}, whereas the difference between flow stress of smaller and larger specimens decreases to 50 MPa.
For the aluminium alloy Al7075 a similar behaviour was found (Figure 2).

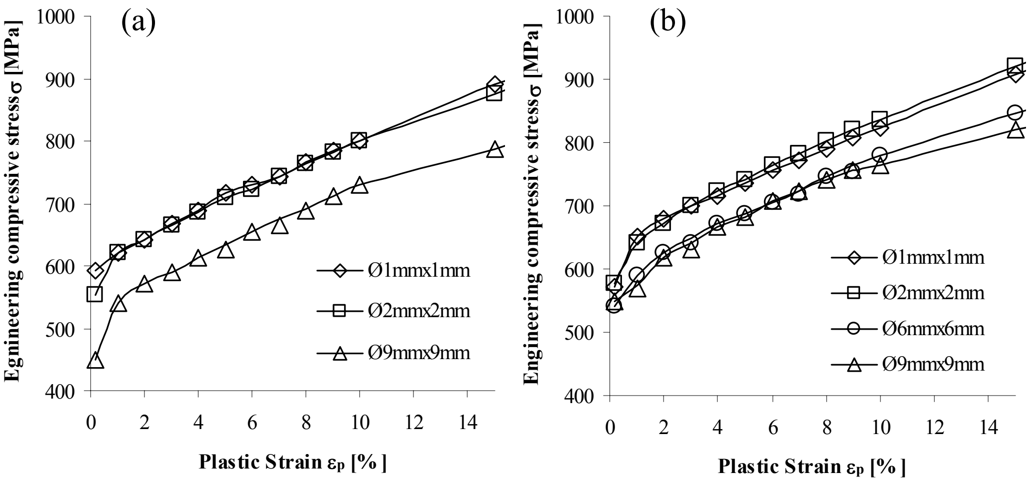
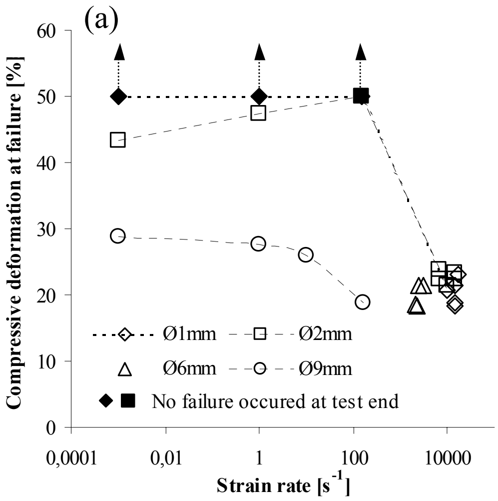


Figure 2: Flow stress behaviour of Al7075 as a function of specimen dimensions at different strain rates: (a) 10^{-3} s^{-1} and (b) 200 s^{-1}.

Under quasistatic loading conditions (Figure 2a) the flow stress of smaller specimens is significantly higher (about 80 MPa) than for larger specimens. At higher strain rates of about 200 s^{-1} the difference of flow stress diminishes to 55 MPa (Figure 2b). At even higher loading rates (>10^3 s^{-1}) no significant distinction in flow stress behaviour for different specimen geometries was found.

3.2 Failure behaviour of Ti-6-22-22S and Al7075

Apart from the influence of specimen geometry on flow stress behaviour, size effects on failure behaviour were found, too. Figure 3a shows the compressive deformation at failure of Ti-6-22-22S as a function of strain rate and specimen dimensions. The larger specimens of the titanium alloy even tend to fail at quasistatic conditions, whereas smaller specimen (Ø 1 mm) were deformed to 50 % plastic strain without fracture. Similar behaviour was found at intermediate strain rates. The smallest specimen didn't show failure at plastic strains of 50 %, whereas larger specimen tend to fail. Only when strain rate is increased to more than 10^3 s^{-1} even small samples tend to fail. Figure 3a illustrates the influence of strain rate on failure behaviour of Ti-6-22-22S, too. The higher the loading rates, the more the material tend to fail at smaller plastic deformation.
Furthermore, Figure 3a shows, that over a wide range of strain rates (up to 200 s^{-1}) the specimens with a diameter of 2 mm tend to sustain more plastic deformation with increasing strain rates before fracture. At very high loading rates (> 10^3 s^{-1}) the fracture initiation starts at lower compressive deformation. A possible explanation for the measured behaviour may be the temperature increase in the material during deformation at moderate strain rates (e.g. at 1 s^{-1}). As long as there are no adiabatic conditions the temperature rise may lead to an increase of deformability of the titanium alloy. At high strain rates (> 10^3 s^{-1}) adiabatic conditions predominate and failure occurs.



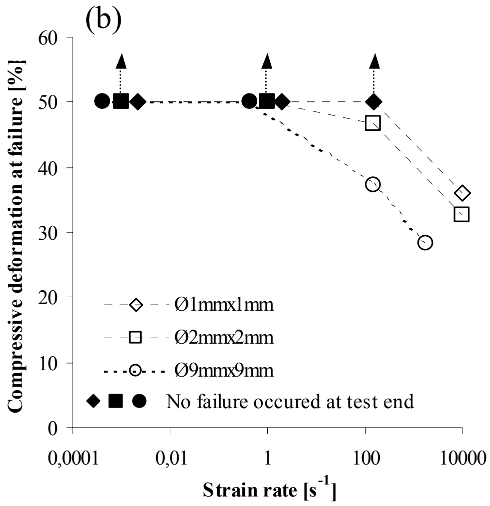


Figure 3: Deformability behaviour of (a) Ti-6-22-22S and (b) Al7075 under compressive loading as a function of strain rate and specimen geometry.

The failure behaviour of Al7075 differs considerably from those of the titanium alloy (Figure 3b), especially under quasistatic conditions and low strain rates. Under quasistatic loading conditions (10^{-3} s^{-1}) and intermediate strain rates (e.g. 1 s^{-1}) no failure was detected in specimens with small and large dimensions. At higher strain rates of about 200 s^{-1} the smallest specimen (Ø 1 mm) were still deformed to plastic strains of 50 % without failure. At even higher loading rates (> 2000 s^{-1}) all specimens tested within this study failed. According to the behaviour of the titanium alloy (Figure 3a) at this loading rate level, both, strain rate and specimen geometry have an influence on failure behaviour of Al7075. Higher strain rates and larger specimen sizes lead to a reduction in deformability and earlier failure.

4 DISCUSSION

The increased flow stress and deformability with reduction of specimen size may occur due to the disproportionate increase of specimen surface area related to the material volume. This may lead to a strong influence of friction on flow stress and failure behaviour with scaling specimen geometry. Figure 4 shows schematically the ratio of friction affected surface to specimen volume. It is illustrated that by scaling specimen geometry down, the ratio of friction effected surface to total surface is constant. However, the exponential increase of ratio between surface or friction affected surface to specimen volume may lead to a strong effect of friction on flow stress and failure behaviour with decreased specimen size. According to the measured differences in flow stress behaviour, e.g. in Figure 2b, the higher flow stresses if samples with small dimensions of Ø1x1 and Ø2x2 are deformed are related to the increased ratio of surface affected by friction relative to the volume.

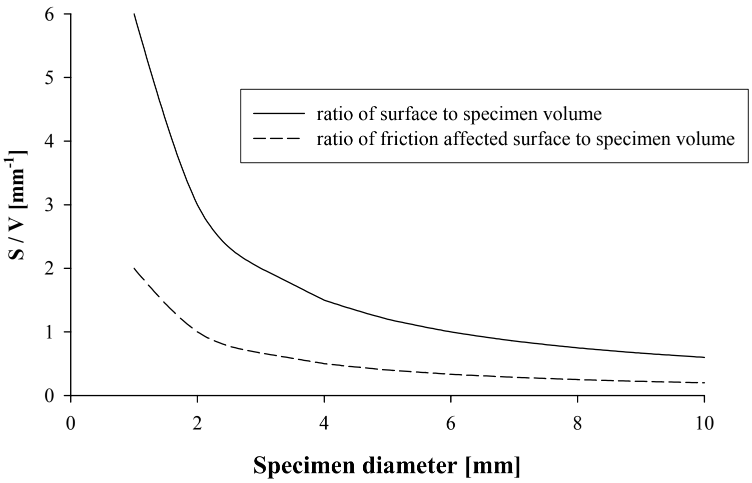


Figure 4: Modified ratios between specimen surface S and specimen volume V as a function of specimen diameter.

Furthermore, an additional influence on flow stress and failure behaviour may occur due to residual stresses resulting from specimen manufacturing. Previous investigations on size effects due to manufacturing processes and the resultant residual stresses have shown, that the manufacturing path has a strong influence on flow stress behaviour of various materials (e.g. Krüger et al. [5], Herzig [8]). Figure 5 shows schematically the increased fraction of specimen volume affected by residual stresses with decreasing specimen size for three assumed penetration depths.

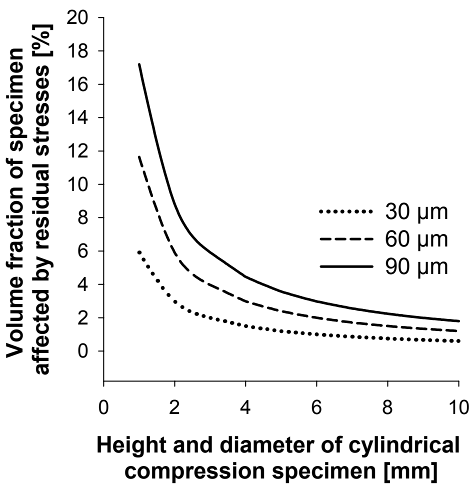


Figure 5: Estimation of specimen volume affected by residual stresses [5].

For smallest geometries in this test program of 1 mm in diameter roughly 15 % of the total volume are affected, if a depth of induced residual stresses of 60 µm is assumed. At higher dimensions this influence diminishes.

5 CONCLUSIONS

From our tests the following conclusions can be drawn. Both, specimen geometry and strain rate have an influence on flow stress and failure behaviour of Ti-6-22-22S and Al7075 under compressive loading. Both materials tested within this study show a similar hardening behaviour, whereas the flow stresses measured by small specimens differs significantly to that measured by larger specimens. This may occur due to the increased friction effect with decreased specimen size.

The titanium alloy Ti-6-22-22S tend to fail even under quasistatic conditions. A decrease of specimen size leads to a larger plastic deformability before fracture. This behaviour was found under dynamic loading conditions, too.

For the aluminium alloy Al7075 no failure occurred under quasistatic and intermediate (e.g. 1 s^{-1}) strain rates. At higher strain rates a behaviour similar to the titanium alloy was found. The larger specimen size and higher strain rates lead to less plastic deformability.

These measured behaviour is explained by the increased influence of friction and pronounced effect of residual stresses resulting from manufacturing process with decreasing specimen size. Further investigations are necessary to confirm the assumptions of the role of residual stresses and their depth profile.

ACKNOWLEDGEMENT

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