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Characterization of material behavior under pure shear condition

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ABSTRACT: In the last decades the design of sheet metal manufacturing processes and products has been mainly influenced by modern tools, e.g. the large field of numerical simulations based on the finite element (FE-) method. Since the modeling of the material behavior is essential for the quality of the calculated results both the determination of characteristic material data and the transformation of these into material models are of high relevance for the whole process-chain. New materials, e.g. light weight sheet metals often show anisotropic and sometimes also some special forming behavior like the twinning effect of magnesium alloys. Furthermore, car body components become more and more complex concerning the geometry and that leads to a mixture of different stress conditions during forming, e.g. deep drawing, stretching and shearing. As a consequence of these reasons also the material models have to be enhanced and therefore especially the yield locus diagram and the real stress-strain curve must include the relevant material characteristics and data. Nevertheless, the forming behavior of sheet metal under pure shearing condition is not sufficient described. In 1984 Miyauchi proposed a new kind of shear test that is characterized by a symmetrical loading of the specimen and homogenous areas of shearing. In this paper a new tool and a new specimen's geometry are introduced with which shear tests have been done in the style of Miyauchi for different materials. The forming behavior is analyzed using an optical strain measurement system, in order to obtain detailed information on the onset of plastification as well as the homogeneity of the plastification itself. It can be shown that the two shear zones are constant and homogenous during the forming process. Basing on the experimental investigations the real stress-strain curves and the yield loci under pure shear conditions are obtained.

Key words: Material characterization, Anisotropy, Yield Loci, Yielding, Shear Test

1 INTRODUCTION

Nowadays, the finite element analysis (FEA) is of essential meaning for the design of sheet metal forming processes and components. The quality of the numerical results strongly depends on the reliability of the model assumptions that have to be done in order to calculate the forming procedure. Therefore, the modeling of the material behavior is of great importance for the whole simulation. Since the most technical relevant materials, e.g. lightweight materials show anisotropic yielding behavior the current stress state have to be considered describing the forming of sheet metals.

Lots of investigations have been done all over the world to detect both the onset of yielding and the work hardening of different materials for uniaxial tensile and compressive loading and also for biaxial tensile loading. In 1984 Miyauchi introduced a new experimental setup for the determination of planar shear for sheet metals [1]. By defining a symmetrical, slitted specimen geometry, which is in principle illustrated in figure 1, two areas of simple shear are generated in the sheet. Although some problems concerning the system technology occurred that influenced the experimental results, the shape of the specimen has been applied by several research institutes [2, 3, 4]. The main challenges are on the one hand the clamping of the specimen, since buckling has to be avoided, and on the other hand the homogeneity of the sheared parts of the specimen. In order to calculate the shear stress τ_S and the shear strain γ basing on experimental data, the area of shearing must be limited to the slitted zones of the specimen. The shear stress and the shear strain are calculated with

$$\tau_S = \frac{F}{2 \cdot l \cdot t} \text{ and } \gamma = \frac{u}{2 \cdot w}, \qquad (1)$$

where F is the forming force, l is the length of the sheared area, t is the sheet thickness, u represents the displacement of the drawn part of the specimen and w is the width of the sheared area. As it becomes clear from equation 1 the calculation of the shear stress is based on the assumption that the specimen is sheared by the measured force F, whereas it is split similarly on both shear zones.

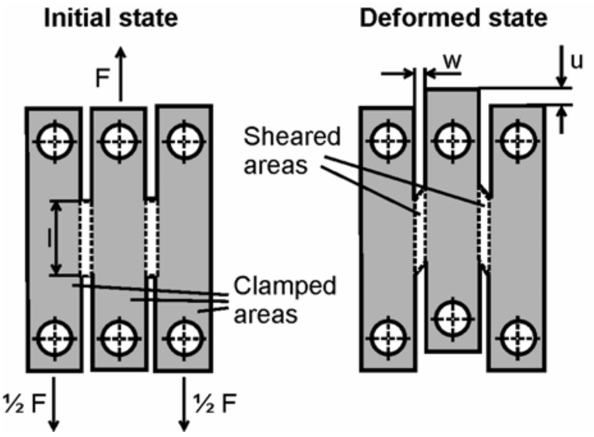

Fig. 1. Specimen for simple shear test [1]

In comparison to other tests, e.g. uniaxial tensile test and the biaxial tensile test, also with the shear test the true stress-strain curve and the yield locus can be obtained. As Miyauchi has already shown with his work, some basic differences occur concerning the yielding behavior under tensile stress conditions (TSC) and shear tensile stress conditions (SSC):

- The stress level under SSC is significantly lower than for TSC.
- The yield point obtained from the shear test is not that sharp as for the tensile test.
- The work hardening behavior expressed by the n-value varies for TSC and SSC.

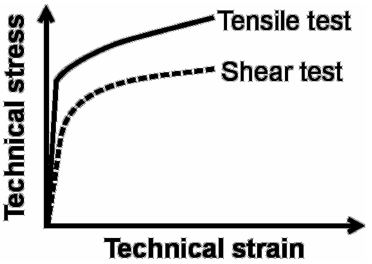

Fig. 2. Scheme of stress-strain curves under TSC and SSC

These phenomena are explained by the different slip systems that are activated in the tensile test and in the shear test [1] and they can be seen from figure 2. In addition also Berg et al. and An et al. observed these influences of the stress-strain curves for various stress states [2, 4].

2 EXPERIMENTAL INVESTIGATIONS

2.1 *Experimental setup*

According to the recommendations made by Miyauchi concerning the realization of the experimental investigations a new setup has been developed at the Chair of Manufacturing Technology (LFT). As it is shown in figure 3 a universal testing device with a special tool is used to fix the main parts of the specimen by clamping. The bar in the middle is drawn vertically, so that simple shearing occurs in the parts in between the clamped areas. The optical strain measurement system Aramis, GOM company is applied in order to detect the deformation characteristics of the shear test specimen by a CCD-camera. Especially the homogeneity of shearing, which is mainly influenced by the layout of the specimen, as well as the variation of the sheared areas, i.e. the sheet thickness t, the width w and the length l can be observed with this device.

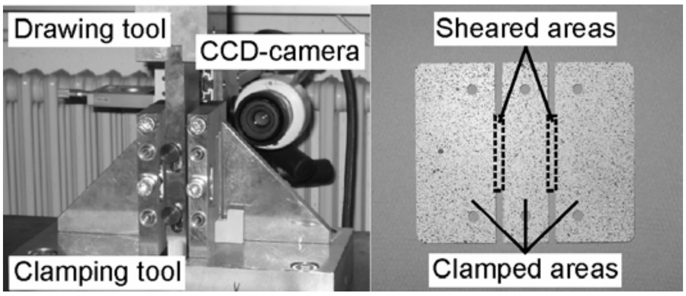

Fig. 3. LFT-setup (left) and specimen (right) for shear test

2.2 *Specimen geometry and evaluation of the test*

The specimen geometry, which has been developed to be tested with the LFT-setup, shows generally a similar shape as that of Miyauchi. Furthermore, the illustration in figure 3 shows the stochastical black-and-white distribution that is applied on the specimen surface to realize the pattern recognition. In order to enhance the shearing conditions the sheet thickness is reduced in the sheared areas before material testing by milling.

For the evaluation of the experimental tests the current data of the geometrical values t, l, u and w are determined with the optical measurement system.

Therefore, the calculation of the real stress-strain curve is based on the mean values of the measured data for five single points of each sheared area and the forming force. The onset of yielding is defined at the equivalent strain of 0.2%.

In this work two lightweight materials are investigated, namely the aluminum wrought alloy AA6016 and the magnesium alloy AZ31. Since reference data concerning real stress-strain curves and yield loci for various stress conditions have been already obtained before, the evaluation of the material behavior under shear stress conditions can be done.

3 EXPERIMENTAL RESULTS

3.1 Real stress-strain curves

In order to detect the influence of the testing method, i.e. the resulting stress condition in the sheet the experimental results that are obtained out of the shear test are compared to those of the uniaxial tensile test. The results are given as real stress-strain curves for the different stress state and the orientation of the specimen in rolling direction RD or transverse direction TD.

3.1.a AA6016

Evaluating the experimental results for the aluminum wrought alloy AA6016 the influence of the stress state on its forming behavior becomes clear (figure 4).

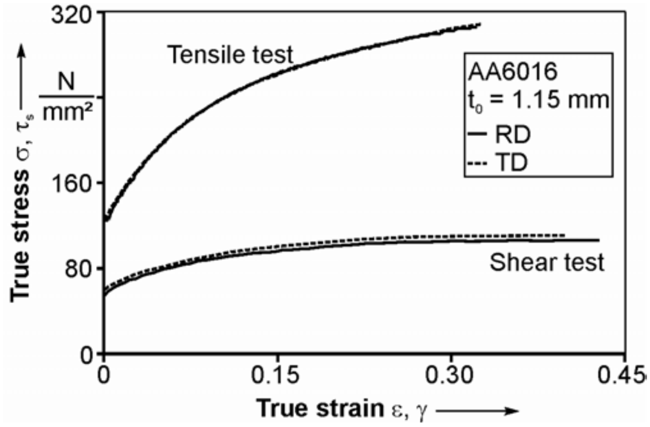

Fig. 4. True stress-strain curves of AA6016

As already detected by Miyauchi for steel sheets [1] the shear stress condition leads to a significant reduction of the yield strain σ_Y also for AA6016. The value is diminished of more than 50% concerning the values of the tensile test. Furthermore, the maximum stress σ_{max} is reduced to approximately 35% of the value of uniaxial tension, since also the work hardening parameter n is decreased under shear stress condition. As a consequence of that the distance between the yield stresses under the different stress conditions grows with increasing strain level. In addition figure 4 illustrates the enhanced maximum strains under shear stress condition that are also expressed by the percentage plastic elongation without necking A_g. Finally, no significant influence of the material orientation concerning its orthotropic axes is detected. This holds for both, the tensile test and the shear test. The summary of the material data is given in table 1.

Table1. Experimentally determined material data of AA6016

	Tensile test		Shear test	
	RD	TD	RD	TD
σ_Y (in N/mm^2)	125	124	56	60
σ_{max} (in N/mm^2)	305	309	106	111
A_g	0.39	0.40	0.48	0.46
n	0.30	0.26	0.18	0.19

3.1.b AZ31

The evaluation of the experimental investigations done with the magnesium wrought alloy AZ31 confirms in principle the results of AA6016, i.e. the significant reduction of the yield stress σ_Y for shear loading and also the marginal impact of the material orientation on the real stress-strain curves (figure 5).

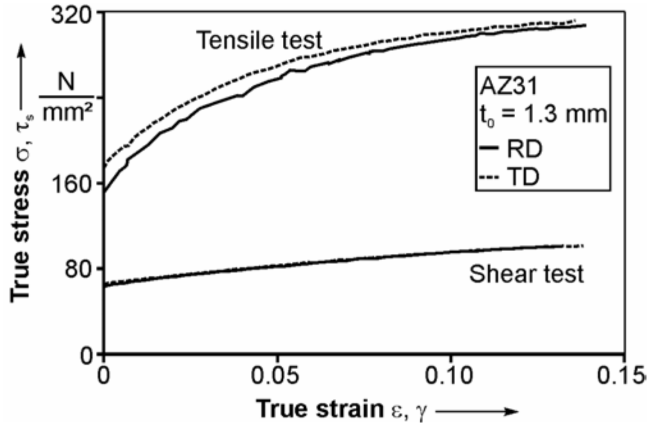

Fig. 5. True stress-strain curves of AZ31

Table2. Experimentally determined material data of AZ31

	Tensile test		Shear test	
	RD	TD	RD	TD
σ_Y (in N/mm^2)	156	179	65	65
σ_{max} (in N/mm^2)	313	321	103	101
A_g	0.16	0.18	0.15	0.15
n	0.21	0.16	0.21	0.19

But obviously some discrepancies occur between the characteristic forming behavior of both materials.

Firstly, the maximum strains of AZ31 reach about only 32% of those of AA6016. Secondly, both the work hardening parameters and the maximum strains are not influenced by the stress state in case of AZ31, which is confirmed by the material data given in table 2. Nevertheless, the real stress-strain curves obtained from tensile test and shear test show different runs. Under uniaxial tensile stress the typical work hardening behavior expressed by degressive graphs can be registered, whereas an approximately linear work hardening characteristic is observed for the results in the shear test.

3.2 *Yield loci*

In order to estimate the anisotropic forming behavior for the onset of yielding, yield loci are obtained from the shear tests for AA6016 and AZ31. These are compared in a yield locus diagram with yield loci determined under uniaxial and biaxial tensile stress conditions [5, 6]. Obviously the anisotropic forming behavior of both materials, the aluminum alloy AA6016 and the magnesium alloy AZ31 is shown explicitly by the different yield loci in figure 6.

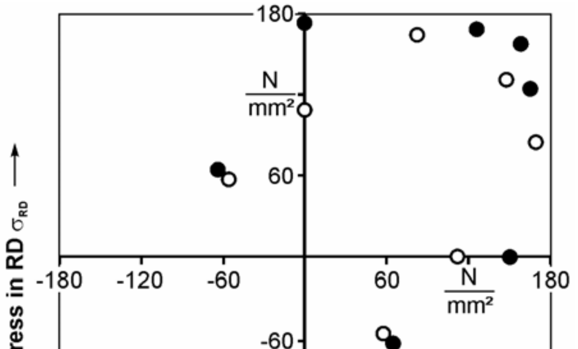

Fig. 6. Experimentally determined yield loci of AA6016 and AZ31 under various stress conditions

Furthermore, a significant difference between the characteristic material data is observed. Whereas the yield loci under biaxial tensile stress conditions and under shear stress conditions are nearly in the same range for both materials, especially the yield stresses for uniaxial loading show significant discrepancies. Concerning the overall forming behavior for various plane stress conditions for AA6016 an elliptical yield locus diagram can be suggested as it results from the formulations, e.g. by Barlat [7]. In the case of the magnesium alloy AZ31 the strength differential effect becomes clear, since the level of yield stresses depends on the direction of loading. Therefore, the yield criterion, which was proposed by Cazacu and Barlat [8] seems to be a good approximation for these data.

4 CONCLUSIONS

In this paper a novel setup for the characterization of sheet metal under shear stress conditions is introduced and the results are given for the aluminum alloy AA6016 and the magnesium alloy AZ31. As predicted by Miyauchi the stress-dependence of the material behavior is clearly shown within these investigations.

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