Influence of specimen size and sheet thickness on the material behavior of AZ31B under uniaxial tension

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Abstract. Concerning a low specific density, magnesium alloys offer a great potential to reduce the part weight. Due to the conditional formability of magnesium alloys at room temperature, forming processes are mostly realized at elevated temperatures. Within this contribution, uniaxial tensile tests for two different specimen geometries with a gauge length of 50 mm and 2 mm and a cross section of 12.5x1 mm\(^2\) and 2x1 mm\(^2\) are carried out for the magnesium alloy AZ31B at an elevated temperature of 200 °C. Since the specimen size is reduced, the influence of the sheet thickness needs to be analyzed. The analysis of the sheet thickness results in a change of the determined flow curve above a strain level of 0.1 and a much earlier failure of specimen with an initial sheet thickness of 1.5 mm. The changed material behavior can be explained by a different microstructure, e.g. the influence of the grain size. In summary, a characterization of the magnesium alloy AZ31B at elevated temperatures can be realized with a miniaturized test setup.

1. Introduction

The realization of lightweight design is driven by the demand on reducing greenhouse gas emission. One possibility to reach this aim is the replacement of conventional materials like steel with lighter materials, as aluminum or magnesium. Another chance of reducing the part weight is the maximum utilization of the material’s performance by an exact characterization of the material behavior. Therefore, the knowledge of local mechanical properties enables an accurate validation of process- and part design to extend the process limits [1]. Especially, the variation of local material behavior of a part can be characterized for the validation of a numerical simulations [2]. For testing local material properties, a miniaturization of well-established test setups, as the uniaxial tensile test is needed.

Regarding tension and compression tests, the miniaturization of the measuring area to a measuring length of 2.0 mm permits a detection of the material behavior under uniaxial compression without an early buckling [3]. Another method to prevent the specimen from buckling is the usage of additional stabilization plates in the relevant area with side forces, which includes an influence of friction [4].

In case of magnesium alloys, the material consists of a hexagonal close-packed microstructure with a low number of slip systems, which leads to an asymmetric behavior of the beginning of plastic yielding between tension and compression testing [5]. Disregarding this material behavior during numerical process design leads to significant differences of the predicted results compared with experimental results [6]. Another challenge for the usage of magnesium alloys is the low formability at room temperature. Due to the low number of slip systems at room temperature, forming processes of magnesium alloys are realized at temperatures above 150 °C [7]. In this context, an increase of the
forming temperature from 20 °C to 200 °C improves the ductility of AZ31 around 38% [8]. Thus, experimental setups with miniaturized specimen design for compressive load but also for testing at elevated temperatures up to 200 °C are needed for the numerical process design of magnesium alloys. However, the miniaturization of the specimen size begs the risk of losing the transferability of the outcome to results of standardized test methods.

For this reason, the investigation of the influence of miniaturized specimen size for the characterization result under uniaxial tension of the magnesium alloy AZ31B at an elevated temperature of 200 °C is superior aim of this research work. Therefore, the test results are compared to results of a test setup with a standardized specimen geometry. Concerning a small specimen size, the influence of sheet thickness can be important and needs to be investigated. Therefore, AZ31B magnesium alloy sheets with an initial sheet thickness of 1.0 mm and 1.5 mm are investigated.

2. Material, experimental setups and specimen geometry

2.1. Material

In this research work, the wrought magnesium alloy AZ31B with initial sheet thicknesses \( t_0 \) of 1.0 mm and 1.5 mm is investigated. The main alloying elements are aluminum (3%) and zinc (1%), which increase the tensile ductility compared to pure magnesium. The chemical composition of AZ31B according to ASTM B90/B90M is shown in Table 1.

|          | Al [wt\%] | Zn [wt\%] | Mn [wt\%] | Si [wt\%] | Cu [wt\%] | Fe [wt\%] | Ni [wt\%] |
|----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| AZ31B    | 2.5 - 3.5 | 0.6 - 1.4 | > 0.2     | > 0.1     | > 0.05    | > 0.05    | > 0.005   |

The grain size of both investigated magnesium sheets is measured by EBSD (Merlin Gemini II, Carl Zeiss AG) and averaged for approximately 500 grains. In case of the sheet thickness 1.0 mm, the average grain size is detected to 5.3 µm. For a sheet thickness of 1.5 mm, the average grain size is almost twice as large with 10.8 µm.

2.2. Specimen geometry

Tensile test specimens are cut out via laser cutting (Tru Laser Cell 7020, Trumpf GmbH + Co. KG). Due to an observed influence of strain hardening, which falsifies the obtained yield stress (see figure 1), no further milling operation is done in the measuring area of the examined specimen.

![Figure 1](image.png)

Figure 1. Influence of milling on the beginning of plastic yielding YS of AZ31B at 200 °C test temperature

Additionally, the results without the influence of strain hardening are rather comparable to literature values [9]. In order to qualify a miniaturized specimen geometry (Type B) for uniaxial tensile tests, a standardized specimen geometry (Type A) according to DIN 50125 is chosen as reference (see figure 2).
The referencing geometry Type A consists of a measuring length of 50.0 mm and a width of 12.5 mm in the measuring area. Since buckling occurs during compression of large specimen [10], a specimen geometry according to Staud et al. [11] is used for a miniaturization of the measuring area. The miniaturized specimen (Type B) includes a measuring length and width of 2.0 mm. In contrast to specimen A with a length to width ratio of 4.0, the miniaturized specimen B contains of a length to width ratio of 1.0.

2.3. Experimental setup

For the experimental observations, two different testing machines are used. In case of the reference tests with standardized specimen geometry, a Gleeble 3500 (DSI) testing machine is used with a 98 kN load cell and an optical DIC system (Aramis, GOM mbH) with a two-dimension camera including a resolution of 4 megapixels (see figure 3). The temperature in the relevant area of the specimen is measured via thermal couple type K. Miniaturized tensile tests are realized with a built-in device (see figure 4) developed by Schaub et al. [3].

The test device in figure 4 is mounted in a universal testing machine Z100 (Zwick AG) with a 100 kN load cell, while the measuring zone is heated via conductive heating. Concerning the good thermal conductivity of magnesium, the electrical linkage is modified to reduce the electrical resistance of the system. The temperature is measured by pyrometer and controlled by an external device. Local strains are measured by an optical DIC system with a two-dimensional CCD camera with a resolution of 4 megapixels. The specimen is mounted between stabilizer plates to prevent an early buckling of the measuring zone. Therefore, a hydraulic clamping system is used with a maximum clamping pressure of 40 MPa. All tests are performed at an elevated temperature of 200 °C and a nominal strain rate of 0.01 1/s. Tests with three trails (n = 3) are carried out for each configuration and the relevant values
and curves are averaged. For the determination of average strains, an evaluation area for each specimen geometry is chosen at an average equivalent strain of 0.2 according to von Mises (see figure 5 and 6).

Figure 5. Strain distribution of the reference specimen (Type A) and evaluation area in the center of the specimen according to an inhomogeneous strain distribution

Figure 6. Strain distribution and evaluation area of miniaturized specimen (Type B)

Since an inhomogeneous strain distribution exists in the reference specimen due to the parabolic temperature propagation in a specimen with large length, an evaluation area in the center of the specimen is chosen with a maximum deviation of the strain around 5 %. In contrast to this, the evaluation area of the miniaturized specimen is selected to 50 % of the initial length due to an almost homogeneous strain distribution (see figure 6).

3. Experimental results

3.1. Flow curve

The flow curves of the reference tests (l = 50.0 mm) and the miniaturized tensile tests (l = 2.0 mm) are presented in figure 7 for a sheet thickness of 1.0 mm and at an elevated temperature of 200 °C. Due to the small evaluation area around the maximum column, flow curves beyond the tensile strength investigated. The test specimens are extracted in 0 ° to the rolling direction (RD) of the sheet.

Figure 7. Comparison of flow curves of AZ31B at an elevated temperature of 200 °C

The flow curves are almost congruent regarding the determined standard deviation (sd). Moreover, plastic strain values until 0.41 are measured in case of miniaturized tensile tests, while maximum plastic strains of 0.45 are observed for reference tests. In addition, a similar hardening behavior of AZ31B at an elevated temperature of 200 °C is noticed, while the selected area around the maximum column of the strain level allows the detection of flow curves until higher strains.

3.2. Mechanical properties

In order to qualify the miniaturized tensile test for the determination of mechanical properties, the beginning of plastic yielding YS at a plastic strain of 0.002 and the tensile strength TS for the reference geometry (l = 50.0 mm) and the miniaturized specimen (l = 2.0 mm) are compared in
To investigate the influence of anisotropy, the mechanical properties are obtained for tests in 0°, 45° and 90° to the rolling direction (RD).

An earlier beginning of plastic yielding is detected for miniaturized specimen extracted in 0° and 45° to the rolling direction, while no significant difference is observed for tests in 90° to RD. With a yield stress of 99.4 MPa ± 1.16 MPa in case of the reference tests and a yield stress of 96.4 MPa ± 0.63 MPa for miniaturized tests a deviation smaller than 3.1 % is determined. Contrariwise, the comparison of tensile strength TS leads to an opposite behavior in case of tests in 0° to RD. With a tensile strength TS of 139.8 MPa ± 5.4 MPa for the referencing tests in 0° to RD (l = 50.0 mm) and a tensile strength of 143.6 MPa ± 1.92 MPa in case of miniaturized tensile tests (l = 2.0 mm) in 0° to RD, a deviation smaller than 2.7 % exists. Regarding the standard deviation, no significant influence of the specimen size on the beginning of plastic yielding and the tensile strength exists. In addition, no dependency on anisotropy is detected for the yield stress and tensile strength at an elevated temperature of 200 °C. This means, that the results of mechanical properties of both specimen geometries are comparable and no influence of miniaturization is recognizable.

3.3. Strain path and Lankford coefficient r

Since the reduced specimen size leads to a change of the length to width ratio from 4.0 in case of the reference geometry to 1.0 for the miniaturized specimen geometry, the evolution of the major and minor strain is observed (see figure 10). Therefore, the strain path for both specimen geometries is presented. Moreover, the average standard deviation (sd) for both test setups is listed.
Furthermore, the influence of the aspect ratio on the anisotropic behavior is determined regarding the Lankford coefficient $r$ (see figure 11). Relating to the evolution of the strain path in figure 10, a similar behavior for the miniaturized specimen geometry ($l = 2.0 \text{ mm}$) compared to the reference geometry ($l = 50.0 \text{ mm}$) is observed, while uniaxial tensile tests with miniaturized specimen lead to lower reachable strains. Additionally, higher Lankford coefficients $r$ are observed for the miniaturized tensile tests (see figure 11). Considering the standard deviation, no significant difference exists, while miniaturized specimen in 45 ° to RD indicate a slightly higher anisotropic behavior than the reference tests. With a Lankford coefficient of $1.46 \pm 0.04$ in 0° to RD, the results of the miniaturized specimen are comparable to Fukuda et al. [9] with a Lankford coefficient of 1.52 at an elevated temperature of 200 °C. Although, no significant differences of the miniaturization of the specimen on the evolution of the strain path (see figure 10) and the Lankford coefficients (see figure 11) are observable.

3.4. Influence of sheet thickness

Since the miniaturized specimen width is 2.0 mm, the influence of the sheet thickness on the material behavior of AZ31B at an elevated temperature of 200 °C is analyzed. Therefore, the determined flow curves of test specimen with an initial sheet thickness of 1.0 mm are compared to the results of miniaturized tests with an initial sheet thickness of 1.5 mm (see figure 12). Additionally, the influence of sheet thickness on the yield stress $Y_S$ at a plastic strain of 0.002 is observed (see figure 13).

![Figure 12](image12.png)  
**Figure 12.** Flow curves of AZ31B for miniaturized tensile specimen with an initial sheet thickness of 1.0 mm and 1.5 mm at an elevated temperature of 200 °C

![Figure 13](image13.png)  
**Figure 13.** Beginning of plastic yielding at a plastic strain of 0.002 for specimen with an initial sheet thickness of 1.0 mm and 1.5 mm at an elevated temperature of 200 °C

The resulting flow curves are almost congruent to a plastic strain of 0.1, while stresses for tests with a sheet thickness of 1.5 mm are slightly smaller. At a plastic strain level higher than 0.1, a relevant difference of the hardening behavior occurs with a smaller stress level for miniaturized tensile tests at a sheet thickness of 1.5 mm. Moreover, a significant earlier failure due to cracking is observed in case of the thicker sheet metal. Accordingly, an earlier beginning of plastic yielding is obtained for a sheet thickness of 1.5 mm (see figure 13).

4. Discussion

The influence of a miniaturization of the specimen size on the mechanical behavior of AZ31B under uniaxial tension at an elevated temperature of 200 °C is observed within this research work. The resulting flow curves (see figure 7) show no significant difference of stress gain between a standardized specimen geometry (reference geometry) and the investigated miniaturized specimen, while miniaturized tensile tests result in a lower reachable plastic strain. In this context, the flow curves are determined for an area around the maximum column of the strain distribution, where the
selected area influences the maximum reachable strain due to the region of averaging the strain values. A direct relationship of the maximum reachable strain level and the miniaturization of the specimen size cannot be observed.

The mechanical properties, the beginning of plastic yielding (see figure 8) and the tensile strength (see figure 9) clarify an assimilable material behavior in case of miniaturized specimen compared to the results of the reference geometry with a measuring length of 50.0 mm. Additionally, the results of both test setups illustrate that no significant influence of the anisotropy on the yield stress and the tensile strength exists at an elevated temperature of 200 °C. Fukuda et al. [9] explained the material behavior at elevated temperature above 473 K (= 200 °C) by the activation of additional slip systems at elevated temperatures and dynamic recovery, which reduces the texture induced anisotropic behavior of the initial sheet metal.

Concerning the evolution of the strain path (see figure 10), no significant difference of major and minor strain development is observed for miniaturized specimen. However, a fractional lower strain level can be achieved with miniaturized specimen, which is caused by the size of the selected evaluation area.

Otherwise, the determined Lankford coefficients (see figure 11) are slightly higher in case of miniaturized specimen with a length to width ratio of 1.0 compared to the reference geometry with an aspect ratio of 4.0. Regarding the estimated standard deviation, this influence is not significant. Comparing the Lankford coefficient in 0 ° to RD with results from literature [9], a smaller deviation in case of miniaturized specimen is identified compared to the results of the reference geometry. Additionally, no steady increase of the Lankford coefficient with higher angle to the rolling direction is ascertained for miniaturized tensile tests as well as for the reference tests with larger specimen. Only a trend is observed in case of the reference tests, which is not significant regarding the standard deviation. As already mentioned for the stress values, no significant anisotropic behavior is examined for the Lankford coefficient, which can be explained by the activation of additional slip systems and dynamic recrystallization, where a predominant forming direction is attenuated.

Finally, the influence of sheet thickness is analyzed. Since the specimen width of the miniaturized geometry is 2.0 mm, an increase of the sheet thickness from 1.0 mm to 1.5 mm leads to a significant difference in the development of the hardening behavior above a strain level of 0.1 (see figure 12) and a decrease of the obtained yield stress at a plastic strain of 0.002 (see figure 13). Additionally, a much earlier failure due to cracking is detected in case of a sheet thickness of 1.5 mm. Regarding the determined grain size, which is twice as large in case of a sheet thickness of 1.5 mm, the higher reachable strains and the higher beginning of plastic yielding for a thickness of 1.0 mm are explainable by a better dislocation motion due to smaller grains. A similar influence of the grain size on the elongation behavior at 200 °C is presented by Mabuchi et al. [12]. Zhu et al. explained the increase of the yield stress by the effect of twinning, where the critical resolved shear stress (CRSS) increases significantly with a decrease of grain size [13]. Thus, additional observations on the microstructure are needed to analyze the material behavior for different sheet thicknesses.

Hence, the discrepancy in the mechanical properties and the material behavior can be explained by the differences of the grain size, while no direct influence of the width to thickness ratio is detected for the investigated sheet thicknesses. This can be seen in case of small strains less than 0.1, where the flow behavior is almost congruent, but with a smaller beginning of plastic yielding for AZ31B magnesium alloy sheets with a thickness of 1.5 mm.

5. Conclusion

Uniaxial tensile tests are carried out for the wrought magnesium alloy AZ31B at an elevated temperature of 200 °C and two different test setups to analyze the influence of specimen miniaturization on the resulting mechanical behavior. Moreover, the influence of sheet thickness on the characterization results is investigated. Although, the results confirm no significant difference between the standardized specimen and the miniaturized specimen geometry, while a lower strain level can be detected in case of the small-sized specimen.

Additionally, no influence of anisotropy on the yield stress and tensile strength is observed for both test setups, which can be explained by the activation of additional slip systems and dynamic
recrystallization at an elevated temperature of 200 °C. The analysis of the sheet thickness results in a change of the determined flow curve above a strain level of 0.1 and a much earlier failure of specimen with an initial sheet thickness of 1.5 mm compared to sheets with a thickness of 1.0 mm. The changed material behavior can be explained by a different microstructure, e.g. the influence of the grain size, which is almost twice as high for a sheet thickness of 1.5 mm compared to the sheets with a thickness of 1.0 mm.

In summary, a characterization of the magnesium alloy AZ31B at elevated temperatures can be realized with a miniaturized test setup. Especially for the determination of mechanical properties under compressive loading due to an asymmetric material behavior of magnesium between tension and compression, a miniaturization of the measuring area is needed to prevent an early buckling of the specimen. Therefore, a transferability of the results of small-sized specimen to results with standardized specimen is required regarding the identification of complex yield criteria.

Acknowledgments
The authors are grateful to the German Research Foundation (DFG) for funding the research project “Contribution to an efficient FE-based design of magnesium sheet metal parts” (ME 2043/40-1). Supplementary, a special thank belongs to Mr. Luigi De Marinis for the input during his bachelor of science thesis “Contribution to a mechanical and microstructural investigation of the magnesium alloy AZ31 under uniaxial tension at elevated temperature”.

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