Mean stress sensitivity of the fatigue strength after equal-channel angular pressing of the aluminum alloys 6082 and 6060

L Winter*, K Hockauf and T Lampke

Materials and Surface Engineering Group, Institute of Materials Science and Engineering, Chemnitz University of Technology, D-09125, Germany

*e-mail: lisa.winter@mb.tu-chemnitz.de

Abstract. The present study is focused on the influence of equal-channel angular pressing (ECAP) on the mean stress sensitivity of the fatigue strength. Systematic work has been done comparing the two precipitation-hardening aluminum alloys 6082 and 6060 in peak-aged and ECAP-processed condition, respectively. The fatigue strength was determined at alternating compression-tension and tension stresses with load ratios of $R = -1$, 0 and 0.1. Both aluminum alloys in peak-aged condition exhibit a strong dependence of the fatigue strength on the load ratio; i.e. and therefore on the applied mean stress. An increase in load ratio, which implies an increase in mean stress, results in a decrease of the fatigue strength amplitude. In contrast, ECAP-processing neutralizes the mean stress sensitivity of the fatigue strength for both aluminum alloys. The fatigue strength for the ECAP-processed conditions is not influenced by the load ratio: the fatigue strength amplitudes at tension mean stresses ($R = 0$ and 0.1) are just as high as for zero mean stress at alternating compression-tension stresses ($R = -1$). The neutralization of the mean stress sensitivity of two aluminum alloys due to ECAP-processing is shown for the first time in this study.

1. Introduction

High-strength aluminum alloys are of major importance for lightweight structural applications and to meet the requirements, a further severe plastic deformation (SPD) can be beneficial. As one SPD-method for bulk material in industrial scale [1], equal-channel angular pressing (ECAP) leads to improved mechanical properties and in particular a major tensile strength and an enhanced high-cycle fatigue strength [2–6]. Outstanding mechanical properties are enabled by the introduced strain hardening and the refined microstructure with grain sizes in sub-micrometer range [7–9].

In-service fatigue loadings often exhibit changing mean stresses over operation time. Therefore, the mean stress sensitivity of materials for mechanical components is of particular interest. For most metals and their alloys, the high cycle fatigue behavior usually depends on the load ratio $R$ and therefore the mean stress [10]. An increase in mean stress results in a reduction of the fatigue strength.
HAIGH or SMITH diagrams illustrate the influence of the mean stress. The mean stress sensitivity $M$ can be calculated according to Schütz [11] as:

$$M = \frac{\sigma_{ad}(R=-1)}{\sigma_{ad}(R=0)} - 1$$  \hspace{1cm} (1)

$M$ is calculated from the fatigue strength amplitudes under alternating compression-tension ($R = -1$, zero mean stress) and under tension loading ($R = 0$, zero minimum stress) and ranges from 0 (fatigue strength is not sensitive to mean stress) to 1 (major influence of mean stress on fatigue strength).

Aluminum alloys exhibit a significant dependence of the fatigue strength on the load ratio and therefore on the applied mean stress [12–16]. The mean stress sensitivity, calculated according to equation 1, is listed with $M \approx 0.2$, depended on the alloy composition [10,17]. To the best of our knowledge, the mean stress sensitivity of the fatigue strength of ECAP-processed aluminum alloys has not been investigated, yet.

Therefore, the focus of the present study is the effect of ECAP-processing on the mean stress sensitivity of the fatigue strength. As bulk material, the aluminum alloys 6082 and 6060 were chosen, due to their wide usage in structural applications and their good workability and suitability for ECAP-processing.

2. Experimental and materials

For this study, the precipitation-hardening aluminum alloys 6082 and 6060 were used. For both alloys ECAP-processing was performed at room temperature in a friction-optimized ECAP tool with an internal angle of 90° and a cross-section of 15×15mm², equipped with movable walls and a bottom slider.

The mechanical properties were determined by quasi-static tensile tests at room temperature at a strain rate of $10^{-3}$s⁻¹ in a Zwick Roell servohydraulic testing machine (Zwick Roell, Germany). For each alloy and each condition, three samples were tested.

The fatigue testing was performed with axial fatigue specimens in a RUMUL Testronic resonant testing machine (Russberger Prüfmaschinen AG, Switzerland) under alternating compression-tension and tension-tension loading with load ratios of $R = -1$, $R = 0$ and $R = 0.1$. The fatigue tests were carried out until the endurance limit of $N_E = 10^7$ cycles for the 6082 and $N_E = 5 \times 10^7$ cycles for the 6060 aluminum alloy was reached or until a crack occurred, which was detected by a drop in the resonant frequency of 2 Hz or more.

2.1. Aluminum alloy 6082
The chemical composition of the aluminum alloy 6082 (AlSiMgMn) is given in table 1. For this alloy a peak-aged and an ECAP-processed condition were compared, hereafter referred to as condition “6082 T6” and “6082 E1”. To achieve peak strength, the material was solid-solution treated at 530 °C for 1 h, quenched in water and subsequently aged at 170 °C for 65 h. To produce the condition “6082 E1” the material was solid-solution treated at 530 °C for 1 h, quenched in water and immediately afterwards ECAP-processed at room temperature with a processing speed of 50 mm/min for one pass and peak-aged at 170 °C for 40 min. The mechanical properties for the peak-aged and the ECAP-processed 6082 aluminum alloy are given in table 2.

**Table 1.** Chemical composition of the aluminum alloy 6082 (AlSi1MgMn).

| Element | Si | Mg | Mn | Fe | Cu | Zn | Al |
|---------|----|----|----|----|----|----|----|
| wt.-%   | 1.00 | 0.90 | 0.76 | 0.21 | 0.05 | 0.02 | balance |
Table 2. Mechanical properties determined by tensile testing of the aluminum alloy 6082 in peak-aged condition (T6) and after one ECAP-pass (E1). The standard deviation is given in absolute values.

| Condition | Yield strength in MPa | Ultimate tensile strength in MPa | Uniform elongation in % | Elongation to failure in % |
|-----------|-----------------------|----------------------------------|-------------------------|--------------------------|
| 6082 T6   | 297 ± 1               | 307 ± 4                          | 5.2 ± 0.8               | 23.7 ± 0.9               |
| 6082 E1   | 332 ± 12              | 345 ± 12                         | 5.4 ± 0.4               | 18.9 ± 0.5               |

2.2. Aluminum alloy 6060

The chemical composition of the aluminum alloy 6060 (AlMgSi0.5) is given in table 3. For the aluminum alloy 6082, a peak-aged and an ECAP-processed condition were compared, as well, hereafter referred to as condition “6060 T6” and “6060 E2”. The peak-aged condition was solid-solution treated at 525 °C for 1 h, quenched in water and subsequently aged at 170 °C for 16 h. ECAP-processing was performed on the peak-aged condition at room temperature with 25 mm/min processing speed for two passes. The mechanical properties for this alloy in peak-aged and ECAP-processed condition are given in table 4.

Table 3. Chemical composition of the aluminum alloy 6060 (AlMgSi0.5).

| Element | Mg | Si | Fe | Mn | Zn | Cu | Al |
|---------|----|----|----|----|----|----|----|
| wt.-%   | 0.52 | 0.43 | 0.16 | < 0.01 | < 0.01 | < 0.01 | balance |

Table 4. Mechanical properties determined by tensile testing of the aluminum alloy 6060 in peak-aged condition (T6) and after two ECAP-passes (E2). The standard deviation is given in absolute values.

| Condition | Yield strength in MPa | Ultimate tensile strength in MPa | Uniform elongation in % | Elongation to failure in % |
|-----------|-----------------------|----------------------------------|-------------------------|--------------------------|
| 6060 T6   | 187 ± 2               | 214 ± 2                          | 6.6 ± 0.2               | 24.3 ± 0.8               |
| 6060 E2   | 301 ± 4               | 305 ± 3                          | 1.0 ± 0.1               | 16.9 ± 0.5               |

3. Results and discussion

The load-ratio dependent high-cycle fatigue behavior in peak-aged and in ECAP-processed condition are given in figure 1 (for Al 6082) and in figure 2 (for Al 6060). The fatigue strength at the three tested load ratios are listed in table 5 (for Al 6082) and table 6 (for Al 6060).

In general, the aluminum alloy 6082 exhibits a higher fatigue strength, if compared to the alloy 6060 due to its higher tensile strength (see figures 1a) and 2a). The peak-aged condition of both tested aluminum alloys shows a significant influence of the applied load ratio R on the fatigue strength amplitude. At alternating tension-compression stresses (R = -1), the fatigue strength amplitude is the highest for the respective alloys. With an increasing load ratio to R = 0 and R = 0.1, and therefore an increasing mean stress, the fatigue strength amplitude decreases significantly for both alloys. This effect is confirmed by the literature [12–15].

ECAP-processing results in a higher fatigue strength for both tested alloys due to the enhanced tensile strength as a consequence of the severe plastic deformation [2–5] (see figures 1b) and 2b). Moreover, the fatigue strength of both ECAP-processed alloys is not influenced by the load ratio. For the respective alloy, the fatigue strength amplitudes of the ECAP-processed condition at alternating compression-tension stresses (R = -1) are just as high as for tension and tension-tension stresses (R = 0 and R = 0.1).
Figure 1. Fatigue strength depending on the load ratio of the aluminum alloy 6082 in a) peak-aged condition and b) after 1 ECAP-pass. ECAP-processing leads to an enhanced fatigue strength and a diminished influence of the applied load ratio on the fatigue strength amplitudes.

Figure 2. Fatigue strength depending on the load ratio of the aluminum alloy 6060 in a) peak-aged condition and b) after 2 ECAP-passes. ECAP-processing leads to an enhanced fatigue strength and a diminished influence of the applied load ratio on the fatigue strength amplitudes.

Table 5. Fatigue strength of the aluminum alloy 6082 in peak-aged condition and after one ECAP-pass at $N_E = 10^7$ cycles at the tested load ratios.

| Condition  | Load ratio $R$ | Maximum stress $\sigma_0$ in MPa | Stress amplitude $\sigma_a$ in MPa | Mean stress $\sigma_m$ in MPa |
|------------|----------------|-------------------------------|---------------------------------|---------------------|
| 6082 T6    | -1             | 120                           | 120                             | 0                   |
|            | 0              | 180                           | 90                              | 90                  |
|            | 0.1            | 200                           | 90                              | 110                 |
| 6082 E1    | -1             | 135                           | 135                             | 0                   |
|            | 0              | 290                           | 145                             | 145                 |
|            | 0.1            | 310                           | 139.5                           | 170.5               |
Table 6. Fatigue strength of the aluminum alloy 6060 in peak-aged condition and after two ECAP-passes at \( N = 5 \cdot 10^7 \) cycles at the tested load ratios.

| Condition | Load ratio R | Maximum stress \( \sigma_o \) in MPa | Stress amplitude \( \sigma_a \) in MPa | Mean stress \( \sigma_m \) in MPa |
|-----------|--------------|--------------------------------------|--------------------------------------|---------------------------------|
| 6060 T6   | -1           | 85                                   | 85                                   | 0                               |
|           | 0            | 130                                  | 65                                   | 65                              |
|           | 0.1          | 140                                  | 63                                   | 77                              |
| 6060 E2   | -1           | 110                                  | 110                                  | 0                               |
|           | 0            | 220                                  | 110                                  | 110                             |
|           | 0.1          | 240                                  | 108                                  | 132                             |

The mean stress sensitivity of the fatigue strength for the aluminum alloys 6082 and 6060 is represented in the form of a HAIGH diagram in figure 3. The slope of the secant of the data points for the fatigue strength indicates the mean stress sensitivity \( M \), which was calculated according to equation 1.

The secant of the fatigue strength shows a considerable slope for the peak-aged condition of the tested alloys. The fatigue strength amplitude decreases with an increased load ratio \( R \) and therefore an increased mean stress. For both aluminum alloys, the calculated mean stress sensitivity is approx. \( M = 0.2 \), which is in good accordance with the literature [10,17].

In contrast, for the ECAP-processed conditions, the mean stress sensitivity is diminished to \( M = 0 \), which shows in a horizontal course of the secant in the Haigh diagram. After ECAP-processing, the fatigue strength amplitudes of the aluminum alloys 6082 and 6060 are not influenced by the applied load ratio and therefore are independent from the mean stress. This neutralization of the mean stress influence of the fatigue strength after ECAP-processing is shown for the first time here. However, this effect contradicts with the accepted theory, that an increase in strength results in an increase in mean stress sensitivity [10].

Figure 3. Haigh diagram representing the fatigue strength amplitudes depending on the load ratio for the a) 6082 aluminum alloy and for the b) 6060 aluminum alloy, both in peak-aged condition and after ECAP-processing. The slope of the secant indicates the mean stress sensitivity \( M \), which is calculated according to Schütz [11]. For both aluminum alloys, ECAP-processing leads to a neutralized influence of the applied load ratio and therefore to a diminished mean stress influence on the fatigue strength.
Summary and conclusions

The influence of equal-channel angular pressing (ECAP) on the mean stress sensitivity of the fatigue strength was investigated. For the aluminum alloys 6082 and 6060 in peak-aged as well as in ECAP-processed condition, the fatigue strength at three different load ratios was compared. Conclusions can be drawn as follows:

1. Equal-channel angular pressing generally results in a significant enhancement in fatigue strength. This enhanced high cycle fatigue behavior is a consequence of the grain refinement and the increased tensile strength of the ECAP-processed material.

2. The fatigue strength of both aluminum alloys, 6082 and 6060, in unprocessed, peak-aged condition, is dependent on the applied mean stress. With an increase in load ratio and therefore an increase in mean stress, the fatigue strength is reduced. The mean stress sensitivity is approx. \( M = 0.2 \) for both alloys.

3. ECAP-processing results in a neutralized influence of the mean stress on the fatigue strength. Both ECAP-processed aluminum alloys exhibit a mean stress sensitivity of \( M = 0 \). This contradicts the accepted theory, that an increase in strength results in an increase in mean stress sensitivity. The influence of ECAP on the mean stress sensitivity of the fatigue strength of aluminum alloys is investigated for the first time in this study and further research is required to clarify this point.

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