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The fatigue life of notched magnesium sheet metals with emphasis on the effect of bands of twinned grains

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ABSTRACT

Notched AM50 sheet metal specimens with four different stress concentration factors are tested under quasi-static and cyclic uniaxial loading, and the results are analyzed and compared with those of unnotched specimens. Special attention is given to the formation of bands of twinned grains and the inhomogeneous local strain field in the vicinity of notches, which is measured by an in situ optical strain measurement technique. It is shown that the notch sensitivity is reduced, if bands of twinned grains occur. In the range between 500 and 1000 load cycles to fracture, the endurable load is only slightly reduced by the presence of a notch for completely reversed fatigue tests. In contrast, specimens are notch sensitive under loading conditions, where no twin formation occurs.

1. Introduction

Magnesium alloys exhibit a hexagonal close packed crystal structure with the major deformation mechanisms at ambient temperature being basal $\langle a\rangle$ slip and $\{10-12\}\langle 10-11\rangle$ extension twinning [1]. Further slip mechanisms of magnesium alloys are non-basal prismatic $\{10-10\}$ and pyramidal $\{10-11\}$ slip, which have a higher critical resolved shear stress compared to that of basal $\langle a\rangle$ slip [2]. Extension twins can be formed at low stresses in polycrystalline magnesium alloys for specific load directions [1]. These are a tensile stress along the c-axis or a compressive stress perpendicular to the c-axis of the lattice system [1,3,4]. Consequently, the strong basal texture of wrought magnesium sheet metals with the c-axis lying almost normal to the sheet plane [3,5,6] results in an asymmetry of the tensile and compressive yield stress for the same load direction [7,8]. In this case, twinning can be activated under tensile loading in the direction normal to the sheet metal surface or under compressive loading perpendicular to the normal direction.

The fatigue life of wrought magnesium sheet metals is strongly influenced by twinning [e.g. 3,7,9–13]. When the compressive yield stress is exceeded (perpendicular to normal direction) $\{10-12\}\langle 10-11\rangle$ twinning occurs and strain hardening is nearly absent for the first load cycle and low for all further load cycles [14,15]. Most of the twins are detwinned by reverse loading [16,17]. Thus, in case of twinning during completely reversed fatigue tests, stress-strain hysteresis areas are significantly enlarged [15] and the fatigue life is distinctly reduced [7].

Once formed, twins are not randomly distributed along the gauge section of a specimen, but are rather grouped in bands of twinned grains. These bands are often called twin bands. However, the expression "twin band" is used in different contexts. Some authors refer to a single twin within a single grain when using the expression twin band [3,4,18,19]. A chain of twins in twinned grains where the twins adjoin each other may be called a long twin band [20]. In [7,21,22], however, a twin band describes the accumulation of twinned grains within a macroscopic band that is referred to as a band of twinned grains (BTG) within the scope of this paper.

The compressive strain within a BTG is considerably larger compared to that of the area next to a BTG [23]. During three-point bending of 1 mm thick AZ31 magnesium sheet metals, localized BTGs occur within the compressive zone [21]. The observed BTGs are widest at the top surface of the specimen where the compressive bending stress is at its maximum, follow an angle of approximately 45° relative to the normal direction of the sheet metal, and are parallel to the transverse direction [21].

Owing to stress concentrations in the vicinity of notches, the yield stress can be exceeded locally by applying comparatively low external loads. Different results are published concerning the notch sensitivity according to Thum and Buchmann [24] of

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Nomenclature

BTG	band of twinned grains
c	coefficient of power function
G_σ	related stress gradient
K_t	stress concentration factor
K_f	fatigue notch factor
N	load cycle
N_b	cycles to fracture
p	power of power function
q	notch sensitivity
r^2	coefficient of determination
RD	rolling direction
$R_{\sigma,n}$	stress ratio of nominal stress controlled fatigue tests
S-N curve	stress-cycle curve
ε_y	normal strain in y-direction
$\varepsilon_{y,mean}$	mean normal strain in y-direction of an evaluated zone
$\sigma_{a,n}$	nominal stress amplitude
σ_{max}	maximum linear elastic normal stress
σ_n	nominal stress

magnesium alloys within the high cycle fatigue regime. While the notch sensitivity of cast AZ91HP, AM50HP, and AM20HP has been observed to be about 30% in the long life fatigue [25], extruded AZ80 wrought alloys [26,27] show a notch sensitivity of 100% in this cycle range.

To enable a broad use of wrought magnesium alloys, a detailed knowledge of the influence of notches on the fatigue life is necessary [25,28–30], especially for designing structural components. There are a number of studies that examine the fatigue performance of wrought magnesium alloys within the low cycle fatigue regime where twinning plays a prominent role [e.g. 3,7,19,22,31–33]. Nevertheless, there is no investigation on the low cycle fatigue behavior of notched magnesium sheet metals and there are a limited number of studies, which consider the influence of different stress concentration factors on the fatigue behavior of magnesium alloys. In addition, the influence of BTGs at notches on the fatigue life has not been examined to date as well. Hence, the present study is dedicated to these subjects. The magnesium alloy AM50 is used for all investigations within this study and is a commercially available alloy [34] that is applied in automotive industry [35].

2. Material and experimental procedure

2.1. Alloy and its manufacturing

The investigation of the quasi-static and cyclic mechanical behavior of notched and unnotched specimens was performed using 1.2 mm thick twin roll cast AM50 magnesium alloy sheet metals provided by the Magnesium Flachprodukte GmbH, Freiberg. The sheet metals were ground on both sides after twin roll cast processing. The effective sheet width is 650 mm, and the manufacturing process is described in detail in [36]. The chemical composition of the material was measured via atomic emission spectroscopy [7] and fulfills the tolerances that are given in ASTM: B951–11.

2.2. Specimens and their preparation

Fig. 1 shows the geometries of the specimens used for mechanical testing. Results of the fatigue tests of unnotched AM50 standard dog bone specimens (Fig. 1a, described in [37]) are taken from [7]. Four different notch shapes were used for mechanical tests on notched specimens (Fig. 1b and c). The used coordinate system is shown in Fig. 1b. This coordinate system is used for all specimens and is indicated in most figures. Note that the origin of the coordinate system is shifted most times when the origin defined in Fig. 1 is not part of the figure, but the directions remain the same. The loading direction of all specimens is parallel to the rolling direction (RD) of the sheet metals (y-direction). The stress concentration factor K_t describes the ratio of the linear elastic normal stress in load direction at the notch root in the middle of the sheet metal (maximum linear elastic normal stress σ_{max}) and the nominal stress σ_n ($K_t = \sigma_{max}/\sigma_n$). The nominal stress σ_n is calculated by dividing the applied force by the nominal cross section which is the cross section of the specimen at the notch root normal to the y-direction. To calculate the related stress gradient G_σ the stress gradient at the notch root $(d\sigma/dx)|_{\sigma max}$ is divided by σ_{max} ($G_\sigma = (d\sigma/dx)|_{\sigma max}/\sigma_{max}$). The stress concentration factors K_t and the related stress gradients G_σ are determined by linear elastic finite element analyses. Therefore, one eighth of each specimen shape is modeled using all three symmetry planes by suppressing the displacements normal to the symmetry planes. The mesh consists of 20 node hexahedrons and exhibits an element size of 0.05–0.1 mm at the notch root. The load is applied at the top surface of the specimens at the grip section. To calculate K_t and G_σ, the maximum linear elastic normal stress in load direction σ_{max} is taken from the node at the notch root where two symmetry planes meet up. Coming from this node the neighboring node in x-direction is taken to determine the stress gradient at the notch root $(d\sigma/dx)|_{\sigma max}$. Table 1 lists the corresponding stress concentration factors K_t and related stress gradients G_σ.

All lateral surfaces of the specimens were machined via milling. The upper and lower surfaces of the specimens are kept in the as-received condition. The milling process was adapted to achieve a surface roughness that approximately matches the original sheet metal surface roughness of $R_a = 0.6–1.2\ \mu m$.

Samples for microstructural investigations were ground with a grit size of P600 and P4000 by use of a Bühler MetaServ 250 grinding and polishing system. In a second step, the samples were mechanically polished with a colloidal silica suspension (SiO_2 with 0.04 µm particle size) on a Struers RotoPol-11 and finally etched with a four percent picric acid solution. The optical microscope Leitz Laborlux 12 ME was used for image acquisition.

2.3. Experimental setup

Due to the occurrence of compressive loads during mechanical testing, appropriate buckling guides are necessary [38]. The used buckling guide for unnotched specimens is the same as shown in [6]. A similar but geometrically adopted buckling guide is used for notched specimens (Fig. 2). To minimize friction between the buckling guides and the specimens, a 0.2 mm thick self-adhesive PTFE-foil was mounted on the contact areas. During all tests, the temperature was between 18 °C and 22 °C. The specimen temperature was checked during mechanical testing to ensure that no specimen warming occurs.

All quasi-static and cyclic tests were conducted on a servo hydraulic test rig with a 25 kN cylinder, a 5 lpm Moog valve, an Instron Labtronic 8800 controller, and a 25 kN Instron PM-L load cell. The nominal stress σ_n was the controlling parameter of all mechanical tests. A nominal stress rate of 1 MPa/s was used for