Effects of ageing on low-cycle fatigue (LCF) properties of AZ80 magnesium alloy wheel hub

Jun Wang¹,², Fulai Yang¹, Jin Ma¹, Tingyan Zhang¹, Hui Cao¹, Xin Che¹, Liye Geng¹, Zhimin Zhang¹, Qiang Wang¹ and Yongbiao Yang¹

¹ College of Materials Science and Engineering, North University of China, Taiyuan 030051, People’s Republic of China
² Technology Center, ShanXi Taigang Stainless Steel Co., Ltd, Taiyuan 030003, People’s Republic of China
³ Shanxi Diesel Engine Industries Co., Ltd, Datong 037036, People’s Republic of China
⁴ State Key Laboratory of Advanced Stainless Steel Materials, Taiyuan Iron and steel (Group) Co., Ltd, Taiyuan 030003, People’s Republic of China

E-mail: yangyongbiao@nuc.edu.cn

Keywords: AZ80 magnesium alloy, wheel hub, expanding-reducing extrusion (ERE), low-cycle fatigue (LCF), basal texture, ageing

Abstract
A hollow billet Expanding-Reducing Extrusion (ERE) wheel hub forming process was carried out with AZ80 magnesium alloy. The effects of ageing on Low-cycle fatigue (LCF) properties were investigated, and the microstructure was characterized with scanning electronic microscopy (SEM). The LCF testing results exhibited that the stress amplitude increased with increasing ageing time, while the plastic strain decreased with increasing ageing time. Cyclic softening followed by hardening was observed for 0 h and 16 h aged samples; however, there was no obvious cyclic softening or hardening for 36 h aged sample. The tension-compression asymmetry were not obvious due to the low strain, precipitation and the non typical basal texture. Fracture observations indicated that the fatigue cracks were initiated on the surface, and the crack propagation area decreased with increasing ageing time. Thus, it can be concluded that ageing has strong effects on the fatigue life for the studied magnesium alloy.

1. Introduction
Light weight has become a matter of significant concern in an era of increasingly worsening resource and energy. Magnesium alloy, as one of the lightest non-ferrous metals with the widest industrial applications in structural materials, has a lot of excellent properties: high specific strength, high specific stiffness, high specific modulus, and high electromagnetic interference (EMI) shielding, which makes it a better choice in automobile, space, and electronics industries [1–4]. Thus, Mg-alloy can serve as an excellent Wheel hub-making material. Wheel hubs bearing loads might crack [5–7] and fail leading to catastrophic car incidents; therefore, as an important vehicle part, the wheel hub must have sufficient strength, stiffness, toughness and fatigue strength [8–10].

Early works on fatigue properties of AZ80 magnesium alloy have been carried out extensively, including cast, rolled and extruded AZ80 magnesium alloy, which revealed that deformation is capable of increasing the low cycle fatigue life of the AZ80 magnesium alloy [11–13]. Moreover, Texture played an important role in influencing the fatigue life: the fatigue life is closely related with the orientation of the loading force with respect to the c axis of the magnesium alloy with basal texture [14–16]. Our team has investigated the low cycle fatigue behaviour of the wheel hub, and found that deformation can improve the LCF life of the wheel hub, and that the fatigue life of the rim was higher that of the spoke due to the refined grains and weakened basal texture [17]. Rong zhu investigated the solution treated and peaked aged magnesium alloy and found that ageing decreased the asymmetrical behaviour of the extruded AZ80 magnesium alloy caused by twinning behaviour at as train amplitude of 0.4% [18]. However, the solution and ageing processes, which were termed as T6, might not be suitable for the manufacturing of workpiece with large size due to the fact that cracks might be induced owing to the thermal stress, which tend to increase with the scale of the workpiece.
The aim of the present paper is to investigate the effects of direct ageing after hot deformation, which were termed as T5, on the low cycle fatigue properties of the extruded AZ80 wheel hub using Expanding-Reducing Extrusion (ERE), and examined in detail the microstructure and fracture so as to provide a basis for developing Mg-alloy wheel hub with optimized low cycle fatigue properties.

2. Experiment

2.1. Experimental materials and forming process

The chemical compositions of the as received casting AZ80 magnesium alloy with a diameter of 300 mm are listed in table 1. The wheel hubs were prepared by expansion-reducing extrusion (ERE) as follows: machining, upsetting, punching and backward extruding as shown in figure 1 and table 2 respectively.

The billets were heated at 390 °C for 12 h before upsetting, at 385 °C for 4 h prior to punching, and at 360 °C for 4 h ahead of backward extruding. The obtained wheel hub was cooled at ambient temperature for about an hour, then the specimens were cut from the bottom of the wheel, as shown in figure 2. Aging was conducted at
175 °C for 16 h and 36 h, respectively. An RX3-40-6 heat treatment furnace was used for heat treatment, and a 12.5 MN oil press and a 30 MN oil press were used for extrusion.

2.2. Mechanical tests and microstructure characterization

A short specimen (\(L = 5\Phi; \Phi = 5\) mm) was used as the tensile test properties. The surface of the specimens were grounded using 1000-grit sandpaper in order to avoid stress concentration. Tensile test and hardness test were conducted using an Instron 3382 universal testing machine and a THBP-62.5 Brinell tester, respectively. Tensile strain rate for the experiment was set at \(1.0 \times 10^{-3} \text{ s}^{-1}\). For low-cycle fatigue testing, the specimens were machined to standard samples according to GB/T15248-2008. The surface was grounded using a SiC paper of mesh #5000. The low-cycle fatigue performance test was conducted with an Instron8801 servo hydraulic universal testing machine. A sinusoidal waveform was adopted with a strain ratio \((R)\) of \(-1\) and a cycle frequency \((f)\) of 0.3 Hz. The total strain amplitude was set at 0.4%. When the load dropped by 20% in the test, the test will be terminated automatically.

The specimens were sectioned vertically to the cylindrical axis of the specimens, polished for microstructure and texture analyses. A Hitachi SU5000 scanning electronic microscope (SEM) was employed with an electron backscatter diffraction (EBSD) system using a step size of 0.1 μm.

3. Results and discussions

3.1. Initial microstructure

Figure 3 shows the inverse pole figure for the sample at the bottom of the AZ80 alloy wheel hub, which exhibited dynamic recrystallized (DRXed) grains with average grain size of \(\sim 28\) μm. Moreover, it can be seen that the the sample displayed a strong basal texture after extrusion. However, the \(C\) axis of the HCP unit cells were 60° away from the extrusion direction (radial direction of the bottom), which is different from that of typical basal texture formed by conventional rolling plate or extruded bar. Typically, the \(C\) axis of the HCP unit cells is vertical to the rolling direction for the plate, and the extrusion direction of the extruded bar. The formation of the specific basal texture might be contributed to the specific stress state and the specific deformation process, which was quite different from that of the conventional rolling and extruding for the manufacturing of plate and bar for the AZ80 magnesium alloy, giving rise to its specific fatigue mechanical properties, as we will discuss later.

The SEM images of the samples, which were aged for 0 h, 16 h, and 36 h, are represented in figure 4 in order to observe the ageing effects on microstructure evolution. It can be seen that extensive granular \(\beta\)-Mg\(_{17}\)Al\(_{12}\) phase could be found both inside the grains and on the grain boundaries, and that the \(\beta\)-Mg\(_{17}\)Al\(_{12}\) was distributed mainly along the grain boundaries figure 4(a). The mechanism of the formation of \(\beta\)-Mg\(_{17}\)Al\(_{12}\) along the grain boundaries was discontinuously precipitation, while that of the \(\beta\)-Mg\(_{17}\)Al\(_{12}\) formed inside the grain was continuous precipitation.

The formation of the \(\beta\) phase should mainly be contributed to dynamic precipitation, particularly the formation of the granular shaped discontinuous precipitation, which decorated the grain boundary. Grain boundaries are places with high energy where precipitate phase transformation occurred easily compared with grain interior. Therefore, it was not difficult to understand why the predominant precipitation \(\beta\) phase was
decorating the grain boundaries, especially at areas with dynamical recrystallization where there was more grain boundaries due to the refined grain size. When the ageing time was 16 h, as shown in figure 4(b), the initiation and growth of the lamellar shape $\beta$ phase was observed. The lamellar shape $\beta$ phase, which was also formed by discontinuous precipitation, invaded more area percentage of the sample with ageing time extending to 36 h (figure 4(c)). It can be seen that the area percentage of the $\beta$ phase increased with increasing ageing time, which should exert strong influence on the LCF properties of the investigated alloy.

3.2. Hardness and tensile performance

Figure 5 illustrates the effects of ageing on the hardness and tensile mechanical performance. It can be seen that the hardness of the aged alloy increased with ageing time from 71HBS to 85HBS, and that both the yield stress (YS) and ultimate tensile stress (UTS) increased with the aging time extending from 0 to 36 h. However, the elongation of the aged alloy decreased from 12% to 5% with prolonged ageing time.
This result was consistent with the microstructure observation, as we had discussed, because the area percentage of the second phase increased with prolonged ageing time, which resulted in second phase hardening, leading to increased hardness, YS, and UTS. With increasing hardness and strength, the elongation of the studied alloy were reduced, which is very common for various kinds of alloy. This was also termed as trade off effects.

3.3. LCF behavior analysis

Figure 6 presents the cyclic deformation responses of aged samples deformed with a strain amplitude of 0.4%. Obviously, the cyclic stress of the sample aged for 36 h was the highest, and the 0 h aged sample was the lowest among three samples at the initial stage of the cycling, which was related to the corresponding tensile strength of the samples aged for 36 h being the highest and the sample aged for 0 h being the lowest (figure 5). Apparently, there was obvious cyclic softening at the initial stage of cycling for 0 h aged sample, then at about 200–300 cycles cyclic hardening was observed upon further cycling, and the characteristic cyclic softening followed by cyclic hardening was remained for 16 h aged sample. Interestingly, however, there was no obvious cyclic softening or hardening for the sample aged for 36 h. As a result, with increasing number of cycles, the stresses of the sample for 0 h and 16 h aged samples increased to the extent that there were no obvious stresses differences among the three sample before fracture. The different softening and hardening behaviour for the three samples were corresponding with increasing area percentages of the precipitation phases with prolonged ageing time, which could affect the movement of dislocation and strength of the investigated alloy during cycling loading.

Furthermore, the fatigue life decreased with ageing time from 18000 to 10000 and 8000 for samples aged for 0, 16 h and 36 h respectively, indicating the strong effects caused by the precipitation phases.

Representative hysteresis curves are shown in figure 7 for the aged samples at a total strain amplitude of 0.4%. In the first cycle, the hysteresis loops of the 0 h aged sample was symmetric, meaning dislocation slip dominated the deformation in this alloy [11]. First, due to the small strain applied at the sample, the force ensued might not surpass the critical stress force required for twinning to be activated. Moreover, the presence of Mg_17Al_12 precipitates could hinder the operation of the twinning contributing to the reduced operation of twinning. It was reported that asymmetric behaviour tended to be reduced with lower strain amplitude and more precipitates [19, 20]. Furthermore, the specific texture, as we have discussed, deflected 60° away from the axis direction of the sample, which made the operation of tension twining even harder, thus basal slip should be the dominating slip system. This is because the average schmid factor (m) for the tension twining to be operated decreased from typical basal texture around 0.44 [21] to 0.38, as shown in figure 8, according to the following equation:

\[ m = \cos(\alpha) \cos(\beta); \quad \sigma = \frac{\tau}{m} \]  

where \( \alpha \) represents the angle between the applied stress direction and the slip plane normal, and \( \beta \) is the angle between the applied stress direction and the slip direction. The applied stress (\( \sigma \)) of the sample depend on the Schmid factor (SF) (m) and the CRSS (\( \tau \)); therefore, a low m leads to higher strength: hard to operate.

Due to the combined effects caused by the low strain, the granular Mg_17Al_12 precipitates and the specific texture for the 0 h aged sample, there were no obvious asymmetric behaviour for the first cycle, which was different from the asymmetric fatigue behaviour for the solution treated AZ80 alloy [18]. As a result, increasing
ageing time has little effects on the symmetric cyclic behavior of the investigated alloy, because there were more precipitates with increasing ageing time, which further prevent the twinning from operating. Therefore, increasing ageing time had little influences on the first cycle tension-compression asymmetric behaviour, irrespective of ageing time.

The mean stress as a function of cycle is given in figure 9. It can be seen that the mean stress for the 0 h aged sample was in the positive range at the initial stage of cycling, and decreased with increasing number of cycling up to 200–300 cycles, then, the mean stress was in the negative range, indicating that the mean stress was compressive. The compressive mean stress for the 0 h aged sample increased with increasing cycling continually before fracture. The mean stress for the 16 h aged sample was in the negative range at the initial stage of cycling, and increased with increasing number of cycling up to 200–300 cycles, then, the stress was in the positive range before fracture. The 36 h aged sample was in the negative range, and the mean stress did not change much with changing cycling. The mean compressive stress of the 0 h sample was the highest after about 1000 cycles. It is well known that tensile mean stress has a harmful effect on the fatigue resistance by accelerating crack initiation and propagation mechanism, while the reverse is true for compressive mean stress [5]. Hence, the increase in compressive mean stress should have beneficial effects in improving the fatigue life, thus the fatigue life for the 0 h sample was the highest for the extruded wheel hub among three samples.
Figure 10 shows a plot of plastic strain amplitude versus the number of cycles at a total strain amplitude of 0.4%. As we can see, the plastic strain amplitude increased slightly with increasing number of cycles up to about 200–300 cycles, then it decreased with increasing ageing time before fracture, and that the plastic strain for the 36 h aged sample was the lowest before fracture. The total strain amplitude can be expressed as the sum of elastic strain amplitude and plastic strain amplitude:

$$\Delta \varepsilon_t / 2 = \Delta \varepsilon_e / 2 + \Delta \varepsilon_p / 2$$  \hspace{1cm} (2)$$

The first part can further be expressed in terms of Basquin equation [11]:

$$\Delta \varepsilon_e / 2 = \Delta \sigma / 2E$$  \hspace{1cm} (3)$$

Substitute equations (2) to (1) gives the following equation:

$$\Delta \varepsilon_p / 2 = \Delta \varepsilon_t / 2 - \Delta \sigma / 2E$$  \hspace{1cm} (4)$$

where E is the Young’s modulus, which is insensitive to the heat treatment. At a given total strain amplitude, a lower stress amplitude will result in a higher plastic strain amplitude, which was in consistent with the results we obtained from figures 6 and 10: high stress was correlated with low plastic strain. The high plastic stress in the 36 h aged sample may lead to severe accumulated cyclic damage, while the low stress increased the fatigue life for 0 h aged specimen.

The typical examples of fractures are shown in Figure 11 for the aged samples at a strain amplitude of 0.4%. It can be seen that three major zones with different features could be recognized. Fatigue crack initiation and stable growth occurred at lower stress amplitude.

Figure 9. Variation of mean stress of AZ80 samples with different aging time versus cycles.

Figure 10. Evolution of plastic strain amplitude for AZ80 samples with different aging time alloy samples.
propagation zone were indicated by red solid line; the outside region was the final rupture zone, as shown in figure 11(a). It was found that the 36 h aged sample had the smallest initiation and crack stable propagation areas. And the more important was that the area of the fatigue crack stable propagation zone decreased with prolonged ageing time. Furthermore, the decreased area of crack propagation zone was coincided with the decreased plastic strain with increasing ageing time, which might shortened the fatigue lifetime. Figure 11 also shows typical SEM fractures taken from the fatigue crack propagation area at approximately the same distance from the fatigue crack initiation site at a higher magnification.

The fractures for 36 h aged AZ80 sample was characterized by rough area with lamellar structure. While for the 0 and 16 h aged samples, the fracture surface was comparatively flat. The difference between the samples may be due to the reverse plastic zone size. When the reverse plastic zone size was less than the grain size, the crack tend to interact within one grain, so that a fatigue crack will propagate along a specific plane, thereby resulting in rough faceted fracture surfaces. When the plastic zone was larger than the grain size, the crack will interact with several grains during cyclic loading so that the fracture surface was flat [18].

The reverse plastic zone size ($r_p$) under plane stress condition is defined follows:

$$r_p = (1/10\pi)(\Delta k/\sigma_{ys})$$

At approximately the same distance from the fatigue crack initiation site, the stress intensity factor range, $\Delta k$, was assumed to be similar for those aged samples. The yield strength of the sample for 0, 16 and 36 h aged samples was 185 MPa and 203 MPa and 273 MPa, respectively. It was apparent that the 36 h aged AZ80 alloy, with the highest $\sigma_{ys}$, had the smallest reverse plastic zone compared with that of the 0 and 16 h aged samples, which was corresponded to the roughed fracture surface for 36 h aged AZ80 sample. Ageing has strong effects on the size and morphology of the propagation zones of the AZ80 magnesium alloy.

4. Conclusions

The effects of ageing on Low-cycle Fatigue (LCF) Properties of the Expanding-Reducing Extrusion AZ80 Magnesium Alloy Hub were discussed, and the conclusions were as following:

1. The area percentage of the $\beta$-Mg$_{17}$Al$_{12}$ phases increased with increasing ageing time, and the morphology of the $\beta$-Mg$_{17}$Al$_{12}$ phases changed from granular being the dominant shape to lamellar being the majority shape with prolonged ageing time;
2. The wheel hub material exhibited non-typical basal texture, which was one of the important reason contributing to the reduced tension-compression asymmetry. The fatigue life decreased with increasing ageing time;

3. Fracture observations indicated that the fatigue cracks were initiated on the surface, and the crack propagation area decreased with increasing ageing time, which was correlated with the increasing stresses levels and decreasing plastic strains with extending ageing time.

Acknowledgments

The authors are grateful for the research support of the National Key Research and Development Plan (2016YFB0301103), Natural science foundation of Shanxi Province (201901D111167), Shanxi Scholarship Council of China (2020-117) and the National Natural Science Foundation of China (U1764253).

ORCID iDs

Yongbiao Yang  https://orcid.org/0000-0002-5699-859X

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