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Fabrication of Strong and Ductile AZ31 Magnesium Alloy Using High Strain Rate Multiple Forging in a Wide Temperature Range

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Abstract: High strain rate multiple forging (HSRMF) was successfully carried out on AZ31 magnesium alloy at a temperature range of 250–400 °C, and the microstructure, texture and mechanical properties were examined. Full recrystallized structure developed at a relatively lower strain due to the twining induced dynamic recrystallization (TDRX) mechanism, which is also responsible for the feasibility of HSRMF deformation at relative low temperature. The average grain sizes of the alloys high strain rate multiple forged (HSRMFed) to the accumulated strain of $\sum\Delta\varepsilon = 1.32$ increased from 7.07 to 9.99 μm as the temperature ranged from 250 to 400 °C, i.e., the grain sizes of the HSRMFed alloy were less sensitive to temperature. The weakened basal texture characteristic of titled or double peak achieved was ascribed to the alteration of forging direction. The HSRMFed alloys demonstrated both excellent strength (UTS > 300 MPa) and good ductility (δ > 20%), which resulted from the combined effects of grain refinement and weakened basal texture. Therefore, HSRMF was an efficient technique to produce strong and ductile wrought AZ31 alloy.

Keywords: AZ31 alloy; high strain rate multiple forging; mechanical property; microstructure; texture

1. Introduction

Magnesium alloys have great potential for energy-saving and emission reduction in airplanes and automobiles due to the combination of light weight with good machinability, excellent damping capacity and favorable recycling capability [1–3]. However, the relative low strength and ductility limits their widespread application [4,5]. Recently, significant efforts have been devoted to developing stronger magnesium alloy with better ductility, and the particular interest is to develop a cost-effective processing technique that can meet industrial requirements. There are reports on the achievement of a good combination of high strength and ductility produced by severe plastic deformation (SPD) [6], such as accumulative roll bonding (ARB), high-pressure torsion (HPT), equal channel angular pressing (ECAP), cyclic extrusion compression (CEC), severe rolling (SR) and multiple forging (MF). MF is cost-effective and is one of the most versatile techniques to produce large bulk materials, and has been used for the refinement of microstructures in magnesium alloys at low strain rate forging [7–10]. Compared with low strain rate MF, high strain rate multiple forging (HSRMF) is more desirable for the fabrication of wrought products due to its high product efficiency, and HSRMF of magnesium alloys has been reported in recent years. For example, Chen et al. adopted small strain impact multi-directional forging to produce AZ61 [11–13] and Mg–Gd–Y–Zr [14] alloy, and the microstructure, texture and mechanical properties of the forged alloys have been investigated. In our previous

research, multiple forging was successfully carried out on ZK60 [15,16] and AZ31 [17] magnesium alloys by using an industrial air pneumatic hammer machine, and excellent balance of strength and ductility were achieved in those alloys owing to grain refinement. This research mainly focused on microstructure, texture and property evolution during HSRMF, but the influence of process parameters such as forging temperature and pass strain on HSRMF were still unknown. In this work, the effect of forging temperature on microstructure and texture of HSRMFed AZ31 magnesium alloy and its resultant mechanical properties were systematically investigated.

2. Experimental Procedures

The material studied in the present study was a commercial AZ31 magnesium alloy with the chemical composition of Mg–3%A1–1%Zn–0.3%Mn. The as-cast billets were homogenized at 400 °C for 12 h followed by water quenching. Rectangular samples were machined from the homogenized ingot for HSRMF. The height, width and length for the sample were 40, 35 and 35 mm respectively. The samples were heated in a muffle furnace at 250, 300, 350 or 400 °C for 5 min before forging, and multiple forging was carried out along three orthogonal directions in turn on an air hammer; the strain rate was about 100/s. A schematic drawing of the multiple direction forging (MDF) process is shown in Figure 1. In the first pass, the initial forging direction was normal to the face A; in the following pass, the forging direction was normal to the face B, and then the forging direction was normal to face C in the third pass. A pass strain of $\Delta\varepsilon = 0.22$ was employed, and HSRMF was carried out to an accumulated strain of $\sum\Delta\varepsilon = 1.32$, i.e., 6 passes of forging. Microstructure analysis was carried out at the central part of the specimens perpendicular to the forging direction (FD) by using optical microscopy (OM) (AX10, Zeiss, Hengyang, China) and electron back-scatter diffraction (EBSD). EBSD observation was conducted on a scanning electron microscope (EVO18, Zeiss, Hengyang, China) at 20 kV, and the orientation imaging microscopy was measured at a step size of 1.5 mm. Texture analysis was performed using the Schultz reflection method by X-ray diffraction. Dog-bone shaped tensile specimens with gauge lengths of 10 mm were machined form the forged alloys with an accumulated strain of $\sum\Delta\varepsilon = 1.32$, and tensile test was conducted under a constant tensile rate of 0.5 mm/min with the tensile direction parallel to (rolling direction) RD at room temperature.

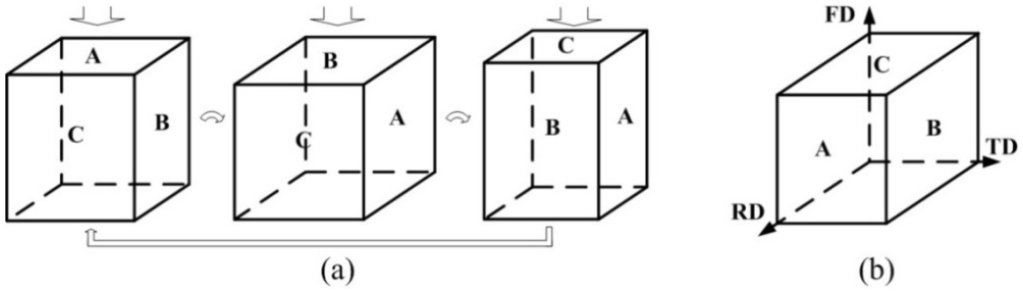


Figure 1. Schematic drawings of (**a**) the high strain rate multiple forging (HSRMF) process; (**b**) axis definition of the alloys as $\sum\Delta\varepsilon = 1.32$.

3. Results and Discussion

3.1. Microstructure

Microstructure evolution of AZ31 alloy HSRMFed at 350 °C is shown in Figure 2. As can be seen in Figure 2a, twins were extensively developed at the core of initial grain and divided the coarse grains into fine twin platelets; furthermore, dynamic recrystallization (DRX) developed at twins as $\sum\Delta\varepsilon = 0.22$. The twin density and DRX fraction increased as the accumulated strain increased. Finer twin platelets and more DRX grains were detected as $\sum\Delta\varepsilon = 0.44$ and $\sum\Delta\varepsilon = 0.88$, as shown in Figure 2b,c, respectively. With further increases of accumulated strain, a full recrystallized structure with an average grain size less than 10 μm was obtained as $\sum\Delta\varepsilon = 1.32$, as shown in Figure 2d. The initial grain could be

extensively refined by HSRMF deformation, even at elevated temperature, ascribing to twinning induced dynamic recrystallization (TDRX), which has been reported in high strain rate deformation such as rolling [3,4] and forging [11–17]. In TDRX, the twin boundaries act as barriers for dislocation motions and consequently provide the driving force for DRX.

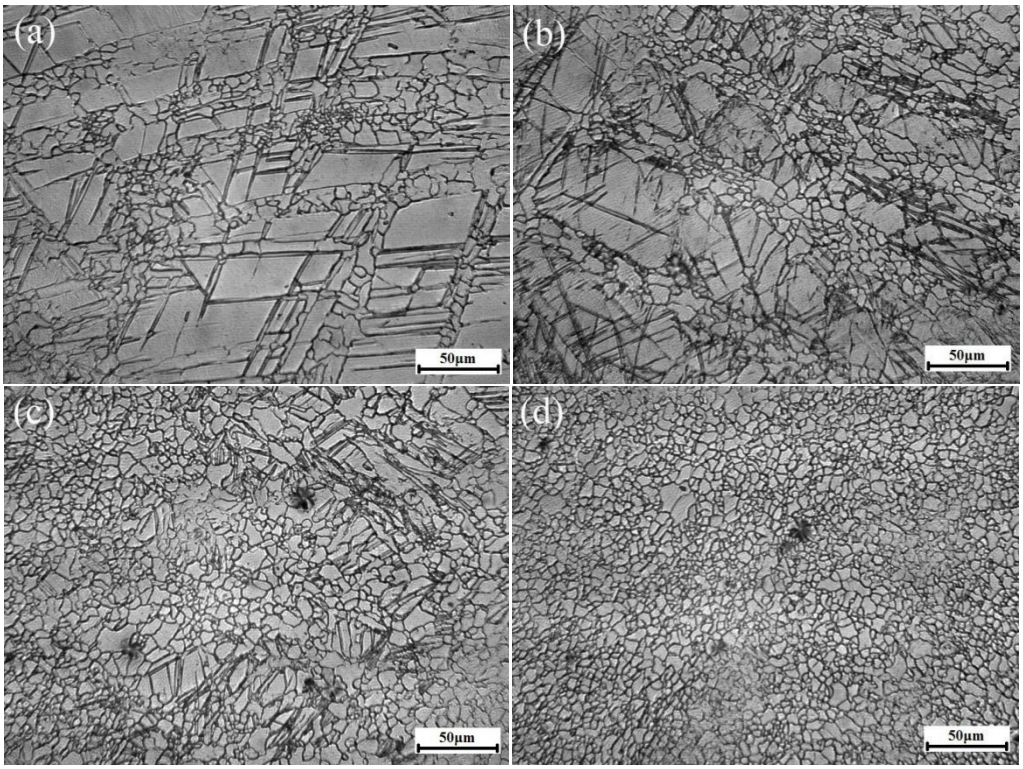


Figure 2. Microstructure of AZ31 alloys HSRMFed at 350 °C to different accumulated strains (**a**) 0.22, (**b**) 0.44, (**c**) 0.88, (**d**) 1.32.

The inverse pole figures (IPF) of AZ31 alloys HSRMFed at different temperatures as $\sum\Delta\varepsilon = 1.32$ are shown in Figure 3. As seen in Figure 3, fully recrystallized structures with different grain sizes (circle equivalent diameter) were detected at all the forging temperatures, and the average grain sizes were 7.07, 8.21, 9.33 and 9.99 μm at 250, 300, 350 and 400 °C, respectively. Nearly a quarter of the grains were smaller than 5 μm, while only a small amount (<2%) of the grains were larger than 15 μm in the alloy HSRMFed at 250 °C. The fraction of small DRX grains (<10 μm) decreased with forging temperature, ranging from 75% at 300 °C to 60% at 350 °C and 50% at 400 °C, while the frequency of the large DRX grains (>15 μm) increased with forging temperature, ranging from 2% at 300 °C to 8% at 350 °C and 13% at 400 °C.

It was evident that the fully recrystallized structures with average grain size smaller than 10 μm were obtained in the HSRMFed alloy at a low accumulated strain, which was much higher in [18–21]. The equivalent strains required to obtain a full recrystallized structure were 4.5, 2.4 and 3.4 for WE43 [18], AZ80 [20] and AZ61 [21] alloys, respectively; however, the equivalent strain was only 1.32 in the present research. Li et al. [22] also reported the same finding in rapid forging of AZ31 magnesium alloy. The relative lower strain may be ascribed to the specific deformation mechanisms during HSRMF that include the formation of high density deformation twins and subsequently TDRX. It was reported that twins frequently form with effective interface velocity, which are appreciable fractions of the velocity of sound, implying that a twin can form rapidly [23]. On the other hand, the twins, including $\{10\bar{1}2\}$ twin and $\{10\bar{1}1\}$–$\{10\bar{1}2\}$ double twin together with stacking faults formed at high strain rate deformation, facilitates the formation of low-angle grain boundaries that can subsequently transit into high-angle grain boundaries and form DRX grains at twins at low strain [22,23].

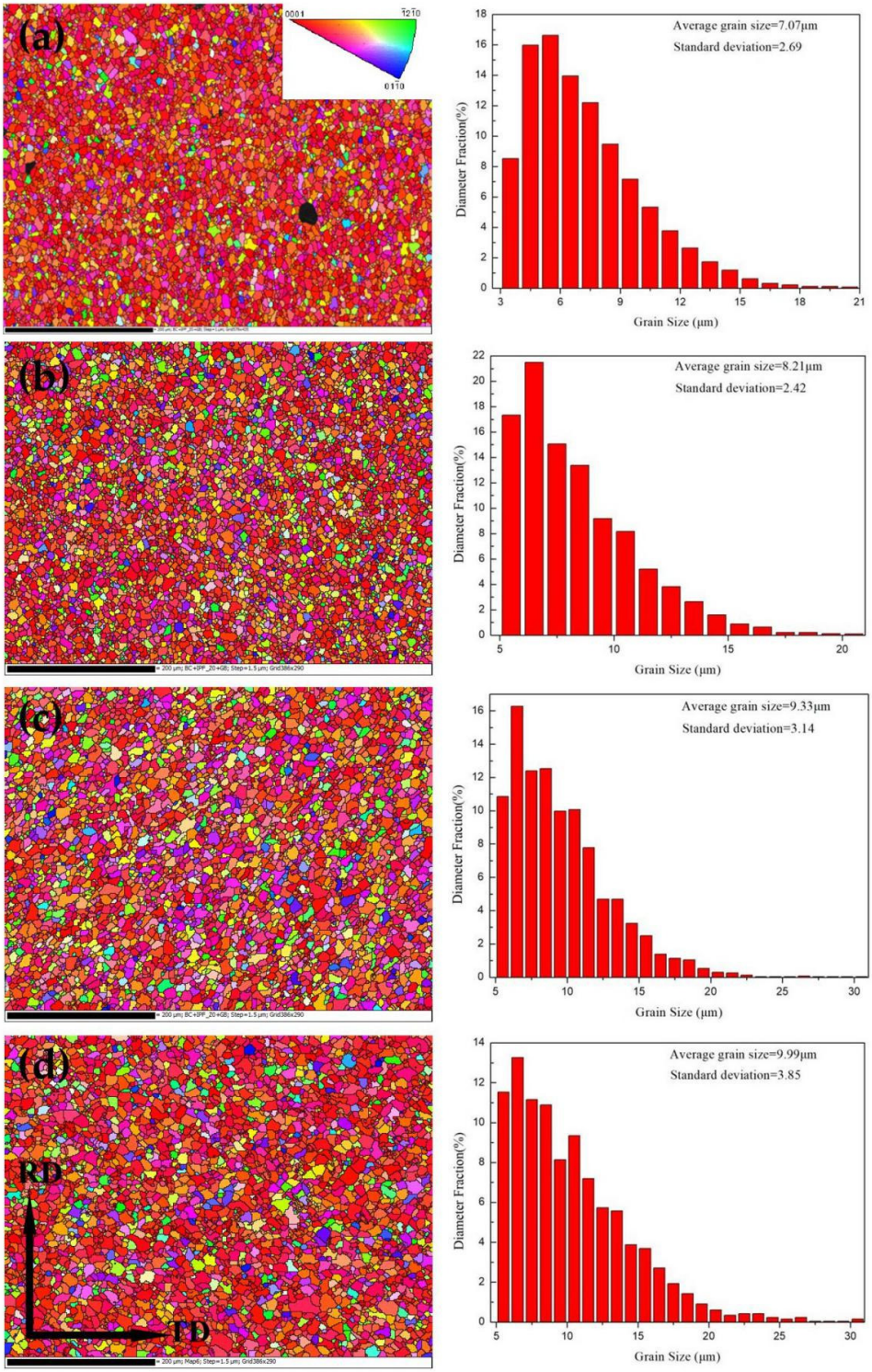


Figure 3. Inverse pole figures and grain size distribution of AZ31 alloys HSRMFed at different temperatures as $\sum\Delta\varepsilon = 1.32$: (**a**) 250 °C, (**b**) 300 °C, (**c**) 350 °C, (**d**) 400 °C.

In manufacturing industries, the thermoforming of magnesium alloys generally occurs in a narrow temperature range of 300–400 °C because of the poor formability at low temperature and grain growth at high temperature. However, in this investigation, AZ31 alloy was successfully fabricated at 250 °C. Meanwhile, the average grain sizes of the HSRMFed alloys grew from 7.07 to 9.99 μm as the forging temperature increased from 250 to 400 °C with standard deviations in the range of 2.42–3.85 μm, indicating that the grain sizes of the HSRMFed alloy were less sensitive to temperature. The same

results have been reported by Zhu et.al in ZK60 [3] and AZ31 [4] alloys fabricated by high strain rate rolling. The broadening of the process temperature region and the less pronounced influence of temperature on grain size may be caused by the specific deformation mechanisms during HSRMF. Since the time for dislocation slip is limited, twining plays a more important role during high strain rate deformation. The initiation of twinning and the subsequent TDRX can compete against cracking by dissipating the deformation energy and releasing the stress concentration [3], and consequently resulted in the decrease of process temperature. Moreover, twinning is not thermally activated but, rather, occurs at places of high stress concentration [24,25]. In other words, twining can develop extensively during high strain rate deformation even at high temperature, and the strain energy or driving force stored by twin boundaries does not decrease significantly with temperature. As a result, the influence of temperature on grain size was less pronounced in the present research.

3.2. Texture

The (0002) pole figures of the AZ31 alloy HSRMFed at different temperatures as $\sum\Delta\varepsilon = 1.32$ are shown in Figures 4 and 5. Both of the pole figures detected by EBSD and XRD showed similar results, i.e., the basal poles split from the center of the pole figure and the intensity decreased as the temperature increased. As can be seen from Figure 4a,b and Figure 5a,b, the texture of the alloys HSRMFed at 250 and 300 °C showed a characteristic of hot-rolled magnesium alloy, i.e., a pronounced basal texture with a circle-shaped distribution of {0002} orientation. However, the basal poles split 10–30° from the center of the pole figure, implying that the c-axis of the hexagonal cell inclined at about 10° at 250 °C to 30° at 300 °C from the forging direction (FD). The basal texture of the alloys HSRMFed at 350 and 400 °C showed the characteristic of a double peak. In the double peak texture, as shown in Figure 4c,d, the pole figures were asymmetric, and both of the maximum intensities rotated to the rolling direction (RD). However, in the double texture examined by XRD, nearly axisymmetric pole figures were obtained, and each maximum intensity rotated to RD away from the center of the pole figure.

Due to the limited number of soft slip systems in hexagonal crystal (HCP) structures, strong textures always exists in wrought magnesium alloy after plastic deformation, and many efforts have been done on texture weakening. Both titled texture [26] and double peak texture [27–30] were typical textures with better formability, which recently received great attention in tailing texture of magnesium alloy. Shear deformation is common in special processes such as equal channel angular pressing (ECAP), differential speed rolling (DSR) and friction stir processing (FSP) and is one of the effective methods to achieve tilted-basal texture; the inclinations were reported to be 5–55° [26]. Double textures are usually achieved in Mg–Al alloys fabricated by special rolling techniques such as large strain rolling [23], high-temperature rolling [28] and variable-plane rolling [29]. The formation mechanism has been reported by Agnew et al. [30], who found that enhanced activity of a non-basal <c + a> slip can be ascribed to the double peak texture. The pyramidal slip usually operates at temperatures over 225 °C and plays a more deciding role in deformation of magnesium with increasing temperature. Therefore, it was reasonable to expect that as temperatures increased above 300 °C, the increasing activity of the pyramidal slip would result in double peak textures in HSRMFed alloy in the present study.

It is worth noting that titled or double peak textures can be achieved in AZ31 alloy HSRMFed at a wide temperature range, i.e., HSRBF is an efficient technique for wrought magnesium alloy with weaker texture. The weaker texture in this study could be related to the following reasons [13,31]. Firstly, the activation of the slip occurred in different slip planes for a pass, rather than being restricted to a single plane. Secondly, the activation of different strain paths was caused by the alteration of forging directions. Thirdly, the DRX discussed above was also subjected to reorientation during HSRMF.

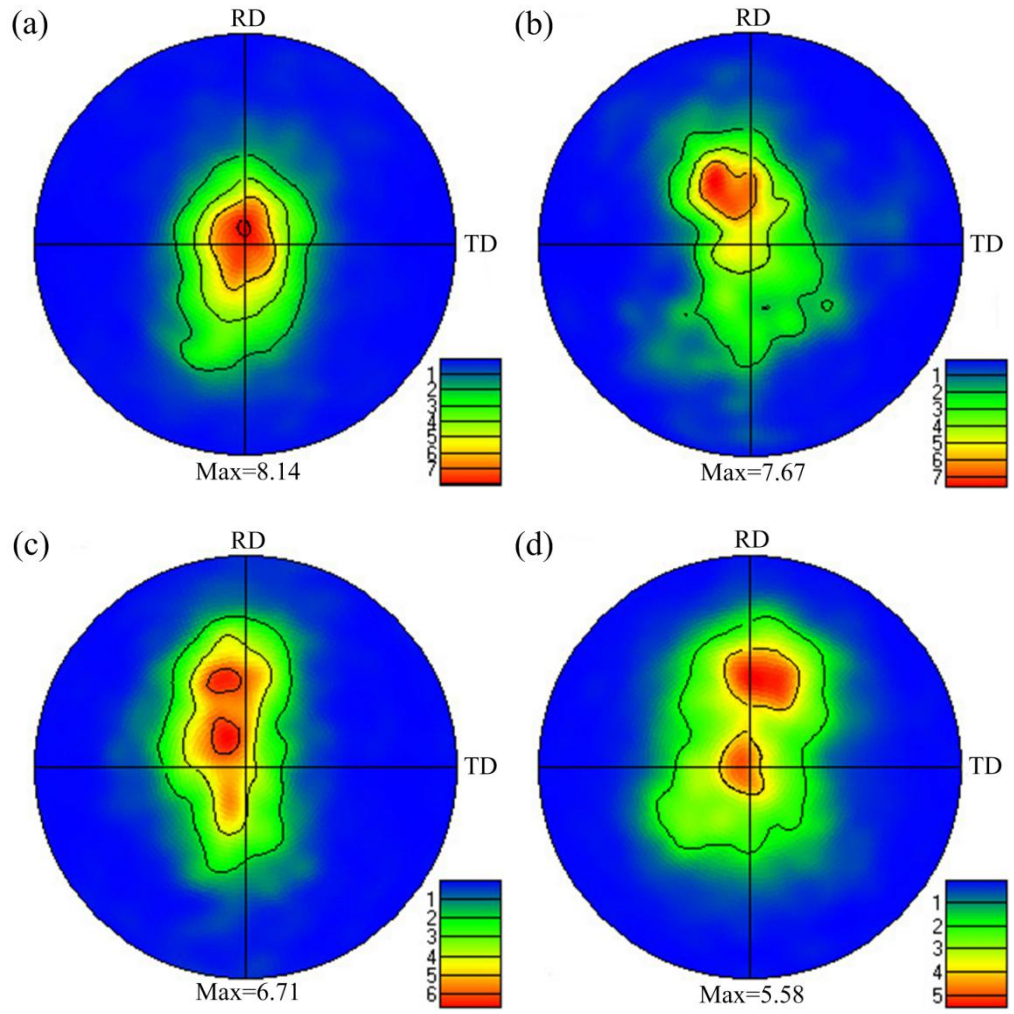


Figure 4. Pole figure detected by electron back-scatter diffraction (EBSD) in AZ31 alloys HSRMFed at different temperatures as $\sum\Delta\varepsilon = 1.32$: (**a**) 250 °C, (**b**) 300 °C, (**c**) 350 °C, (**d**) 400 °C.

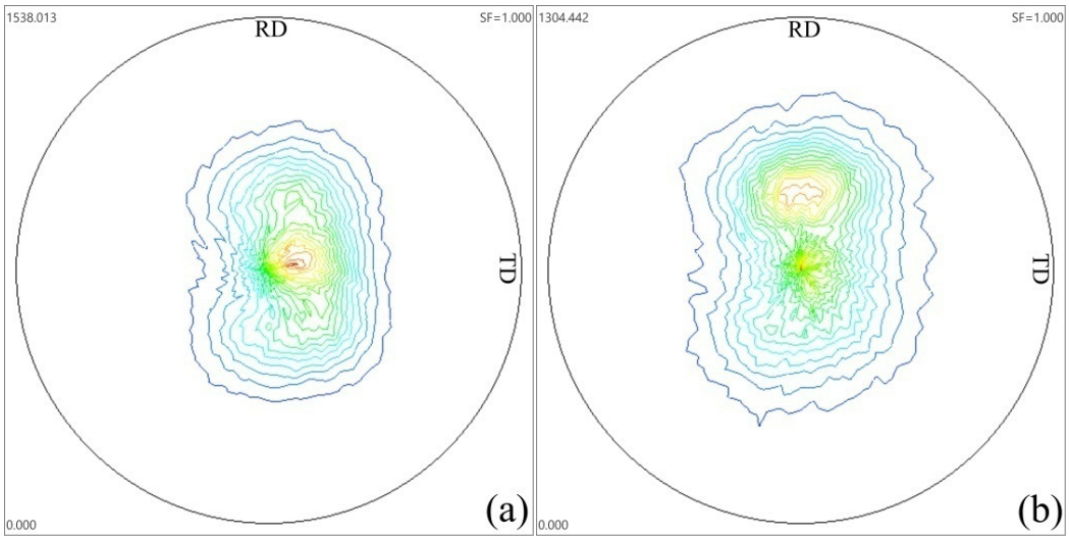


Figure 5. *Cont*.

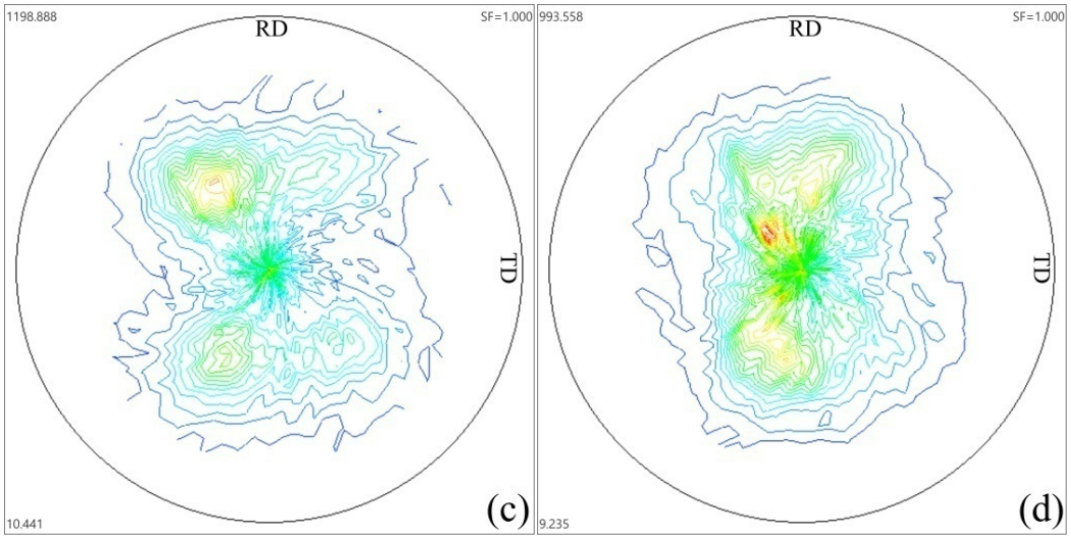


Figure 5. Pole figure detected by XRD in AZ31 alloys HSRMFed at different temperatures as $\sum\Delta\varepsilon = 1.32$: (**a**) 250 °C, (**b**) 300 °C, (**c**) 350 °C, (**d**) 400 °C.

3.3. Mechanical Properties

The flow curves of HSRMFed alloys are shown in Figure 6, and the tensile data is listed in Table 1 containing yield strength (YS) σ_s, ultimate tensile strength (UTS) σ_b and elongation δ. As can be seen in Figure 6 and Table 1, two important trends can be inferred. Firstly, the strength decreased with increasing temperature, as the UTS of the alloy HSRMFed at 250 °C was 332.2 MPa compared to 301.1 MPa of the alloy HSRMFed at 400 °C. Secondly, the elongation increased with temperature at low temperature (<350 °C) but decreased slightly at high temperature (>350 °C), and the highest elongation of 28.6% was achieved in the alloy HSRMFed at a temperature of 350 °C. With the combination of the microstructure and texture discussed above, the grain refinement and texture weakening may be attributed to the variation of strength and ductility. It is worth noting that owing to the grain refinement and weakened texture caused by HSRBF, the HSRMFed alloys demonstrated both excellent strength (UTS > 300 MPa) and good ductility (δ > 20%). Therefore, HSRMF was an efficient technique for producing strong and ductile wrought AZ31 alloy.

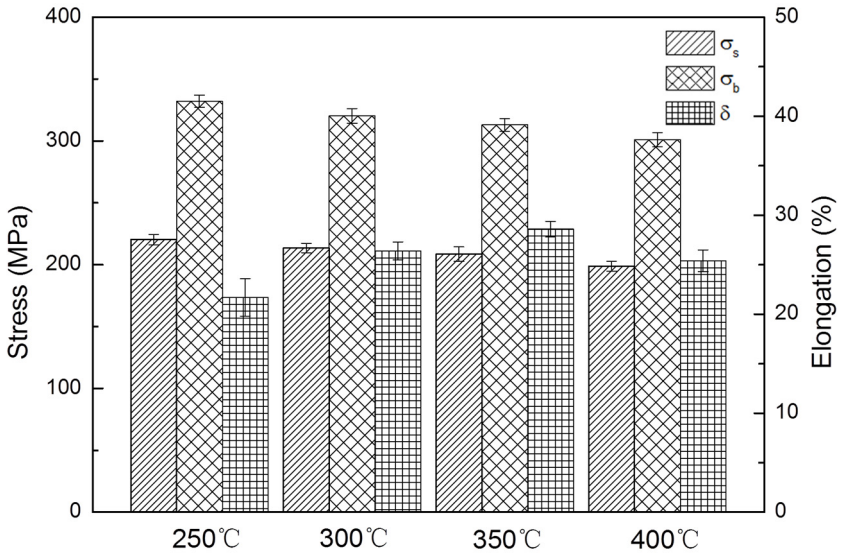


Figure 6. Curves of AZ31 alloys HSRMFed at different temperatures as $\sum\Delta\varepsilon = 1.32$.

Table 1. Properties of AZ31 alloy HSRMFed at different temperatures as $\sum\Delta\varepsilon = 1.32$.

Temperature (°C)	σ_s (MPa)	σ_b (MPa)	δ (%)
250	220.3 ± 4.1	332.2 ± 4.8	21.7 ± 1.9
300	213.5 ± 3.8	320.3 ± 5.9	26.4 ± 0.9
350	208.6 ± 5.9	312.9 ± 5.1	28.6 ± 0.8
400	198.8 ± 3.9	301.1 ± 5.8	25.4 ± 1.1

4. Conclusions

High strain rate multiple forging (HSRMF) was successfully used to fabricate AZ31 alloy in a wide temperature range of 250–400 °C. The microstructure, texture and mechanical properties of the HSRMFed alloy were examined. The main conclusions are listed as follows:

1. The initial grain can be rapidly refined during HSRMF ascribing to the twining induced dynamic recrystallization (TDRX). The average grain sizes of the HSRMFed alloys were 7.07, 8.21, 9.33 and 9.99 μm when deformed at 250, 300, 350 and 400 °C, respectively, implying that the grain sizes of the HSRMFed alloy were less sensitive to temperature.
2. The alteration of forging directions leads to the weakening of basal texture, and the basal texture is characteristic of titled texture at low temperature (<350 °C) and double peak at high temperature (≥350 °C).
3. The HSRMFed alloys demonstrate both excellent strength (UTS > 300 MPa) and good ductility (δ > 20%), resulting from the combined effects of grain refinement and weakened basal texture. Therefore, HSRMF was an efficient technique to produce strong and ductile wrought AZ31 alloy.

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