Twinning-induced recrystallization behaviour in AZ61 magnesium alloy during high-speed rolling.

Jagannath Mohapatra, Pitara Sabara

College of Engineering Bhubaneswar, Biju Pattnaik University of Technology, Odisha, India

Abstract

This study examines the microstructural and textural changes that occur in an AZ31 Mg alloy during high-speed rolling (HSR) and how these changes relate to the rolling temperature. HSR is carried out at temperatures of 300, 350, and 400 degrees Celsius at a rolling speed of 470 m/min with an 80% reduction in a single pass. All high-speed rolled (HSRed) materials exhibit shear band formation; however, as rolling temperature rises, the density and intensity of the shear bands decrease significantly due to an increase in deformation homogeneity. Because of the encouraged twinning-induced recrystallization behavior, the area fraction of dynamically recrystallized (DRXed) grains gradually increases with increasing rolling temperature. The reduced area fraction of coarse unDRXed grains causes the average grain size of the HSRed materials to decrease with increasing rolling temperature from 300°C to 350°C; on the other hand, the increased DRXed grain size causes the average grain size to increase at 400◦C. Because of the intense shear deformation that occurs at lower temperatures, the basal texture of the HSRed materials tilts toward the rolling direction as the rolling temperature decreases. Due to a rise in the area fraction of the unDRXed region, which has a notably strong texture, the texture intensity also increases with decreasing rolling temperature.

1. Introduction

Recently, magnesium alloys have garnered significant interest in the transportation sector due to their superior specific strengths and lower densities when compared to rival metal materials like steel and aluminum alloys. Magnesium alloys have primarily been utilized as casting materials for steering wheels and instrument panels in automobiles. But as new, highly productive processes like twin-roll casting (TRC) and horizontal continuous casting (HCC) for the production of magnesium plates are developed, the use of rolled magnesium sheets—which have far superior mechanical properties than cast magnesium alloys—is growing quickly. Although magnesium plates are produced using the TRC or HCC process, they must undergo multiple passes and intermediate annealing treatments in between to ensure the formation of thin magnesium sheets suitable for use as automotive components due to their limited rollability of 10% to 30% in a single hot rolling pass [1, 2]. The time and energy required for this multi-pass hot rolling and heat treatment process raises the price of the finished goods.

It has recently been reported that when rolling is done at high speeds of >200 m/min, the amount of rolling reduction that can be applied to magnesium alloys in a single pass without fracture increases significantly [3-5]. According to Su et al. [4], an AZ31 alloy sheet fractured into multiple pieces at a rolling reduction of 37% when it was rolled at a conventional low rolling speed of 15 m/min and a rolling temperature of 100 °C. On the other hand, the sheet could be rolled to a significant reduction of 72% in a single pass without breaking when the rolling speed was increased to 1000 m/min. The production of homogeneous deformation throughout the material [8], suppression of the formation of macroscopic shear bands [7], and encouragement of twinning and dynamic recrystallization (DRX) [6] are known to be the primary causes of this exceptional rollability that can be achieved through high-speed rolling (HSR). Furthermore, it has been documented that enhancing the rollability of magnesium alloys through HSR may involve the activation of extra {c + a} slip systems [5,9]. Numerous investigations into the mechanisms of DRX that occur during the HSR of cast and wrought magnesium alloys have been carried out. It has been reported that twinning-induced DRX (TDRX) is essential for accommodating large plastic deformations and for altering the material's microstructure [10,11].

It is anticipated that the rolling temperature in the HSR process will have a significant impact on the DRX behavior during rolling and on the resulting microstructure of the material after rolling, since strain, strain rate, and temperature are the primary process parameters under hot deformation conditions. Numerous investigations have been carried out to examine the changes in rolling reduction and rolling speed, which correlate to the process parameters of strain and strain rate, respectively, and the microstructural and textural evolutions of high-speed-rolled (HSRed)Mg alloys [4,10,11]. On the other hand, there hasn't been much in-depth investigation into how rolling temperature affects microstructural variations in magnesium alloy HSR [3]. Thus, the impact of rolling temperature on the microstructural properties of HS Red Mg sheets is examined in this study by rolling at three different temperatures—300, 350, and 400 degrees Celsius—to a high reduction of 80% at a fast pace of 470 meters per minute. A systematic analysis is conducted on the changes in the DRX fraction, texture, grain structure, and deformation homogeneity of the HSRed materials with rolling temperature.

2. Materials and methods

An alloy known as Mg-3.6Al-1.0Zn-0.3Mn (wt%) (AZ31) was hot-rolled and used as the starting material for this study. The alloy underwent a 24-hour homogenization treatment at 400°C. The homogenized alloy was then used to machine three rolling samples, each measuring 60 mm by 50 mm by 10 mm (length by width by thickness), which correspond to the rolling direction (RD), transverse direction (TD), and normal direction (ND), in that order. Prior to rolling, each sample was preheated for 10 minutes to 300, 350, and 400 degrees Celsius. The samples were then rolled at a very high speed of 470 meters per minute to achieve an 80% reduction without the rolls being heated. The sheets that were rolled at temperatures of 300°C, 350°C, and 400°C are referred to as HSR300, HSR350, and HSR400 samples, in that order. Using previously published equations [11], the average strain and strain rate were computed; the results were 1.61 and 181 s^{-1}, respectively. The HSRed samples' microstructural variations with rolling temperature were examined using optical microscopy (OM), electron backscatter diffraction (EBSD), and X-ray diffraction (XRD) equipment. This included an analysis of their localized deformation, DRX behavior, grain structure, and crystallographic orientation. The mid-thickness in the central region of the HSRed samples was measured using EBSD. You can find a detailed method of measuring and analyzing EBSD elsewhere [12].

3. Results and discussions

3.1. Deformation Homogeneity during HSR

The optical micrograph and XRD pole figure of the original material are displayed in Fig. 1. With an average grain size of 38.2 μm and an intense basal texture with a maximum intensity of 9.1, this material has an equiaxed grain structure; most grains' basal poles are almost parallel to the ND. The optical micrographs of the ND–RD plane of the HSRed samples are displayed in Fig. 2(a)–(c). All of the HSRed samples show shear bands connected to an abrupt loss of deformation homogeneity; however, the shear bands' density and intensity decrease as rolling temperature rises. This finding suggests that the localized deformation produced during high-speed rolling (HSR) is suppressed and the applied strain is uniformly applied across the material as the rolling temperature rises. The shear bands that are formed when AZ31alloy samples are hot-rolled at a standard rolling speed of 14.8 m/min are inclined at about ±30 to the RD [13]. However, the shear bands of the HSRed samples in this study are inclined at about ±20°to the RD (Fig. 2(a)–(c)); this is because the high rolling speed of 470 m/min causes intense shear deformation. The optical micrographs of the HSRed samples taken at the mid-thickness on the TD-RD plane are displayed in Fig. 2(d)–(f). A bimodal grain structure made up of coarse unDRXed grains and fine dynamically recrystallized (DRXed) grains is seen in the HSR300 sample. Figure 2(d) of the sample shows the formation of multiple deformation twins in the unDRXed grains and the fine-DRXed grains at the twins. Consequently, during HSR, deformation twinning breaks up the relatively large grains of the initial material (38.2 m), and the formation of fine DRXed grains at the twins refines the microstructure. There are unDRXed grains in the HSR350 sample as well, but they are smaller in size and quantity than the unDRXed grains in the HSR300 sample. On the other hand, the DRXed grains in the HSR350 sample have a larger size than the grains in the HSR300 sample (Fig. 2(e)).

Consequently, it is evident that the microstructural homogeneity and size difference between the DRXed and

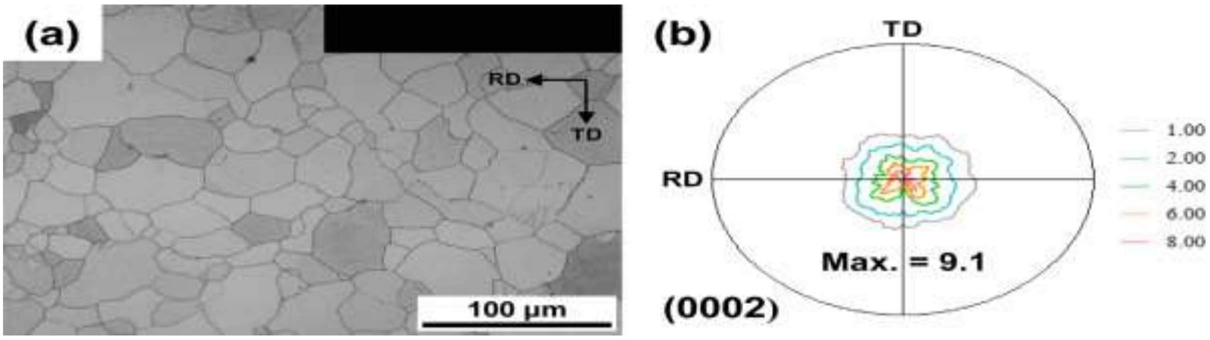


Fig. 1 – (a) Optical micrograph and (b) (0 0 0 2) X-ray diffraction pole figure of initial material. d_{avg} denotes the average grainsize.

unDRXed grains decrease as the rolling temperature rises from 300 to 350 degrees Celsius. The HSR400 sample shows a nearly fully DRXed grain structure with few unDRXed grains (Fig. 2(f)), where shear band formation is not apparent. But compared to the HSR300 and HSR350 samples, the DRXed grains in this sample are substantially larger. Through EBSD analysis, the microstructural characteristics of the HSRed samples and the variations among these characteristics are more clearly identified.

3.2. Dynamic Recrystallization Behavior

Fig. 3 displays inverse pole figure (IPF) maps of the HSRed samples' entire region and unDRXed region. The area fraction of the unDRXed grains drops from 25.0% to 1.6% as the rolling temperature rises from 300◦C to 400◦C. The DRX fraction increases by approximately 12% in the HSRed samples for every 50◦C increase in rolling temperature. Discontinuous DRX (DDRX), which results from the nucleation and growth of new strain-free grains, is known to be the predominant recrystallization mechanism under hot deformation conditions of magnesium alloys at high temperatures of ≥300◦C [14,15]. Grain boundaries typically migrate locally, or bulge, to form the nucleus of the new grains [16]. According to the DDRX mechanism, the bulging phenomenon is promoted by an increase in grain boundary mobility, which accounts for the rise in the DRX fraction of the HSRed samples with increasing rolling temperature. Even though the deformation temperature is high (≥300◦C), the DDRX behavior is limited under hot deformation conditions with high strain rates. This is because there is not enough time for the grain boundaries to bulge. In the meantime, twinning occurs much more readily than dislocation slip under high-strain-rate deformation because a twin has a higher

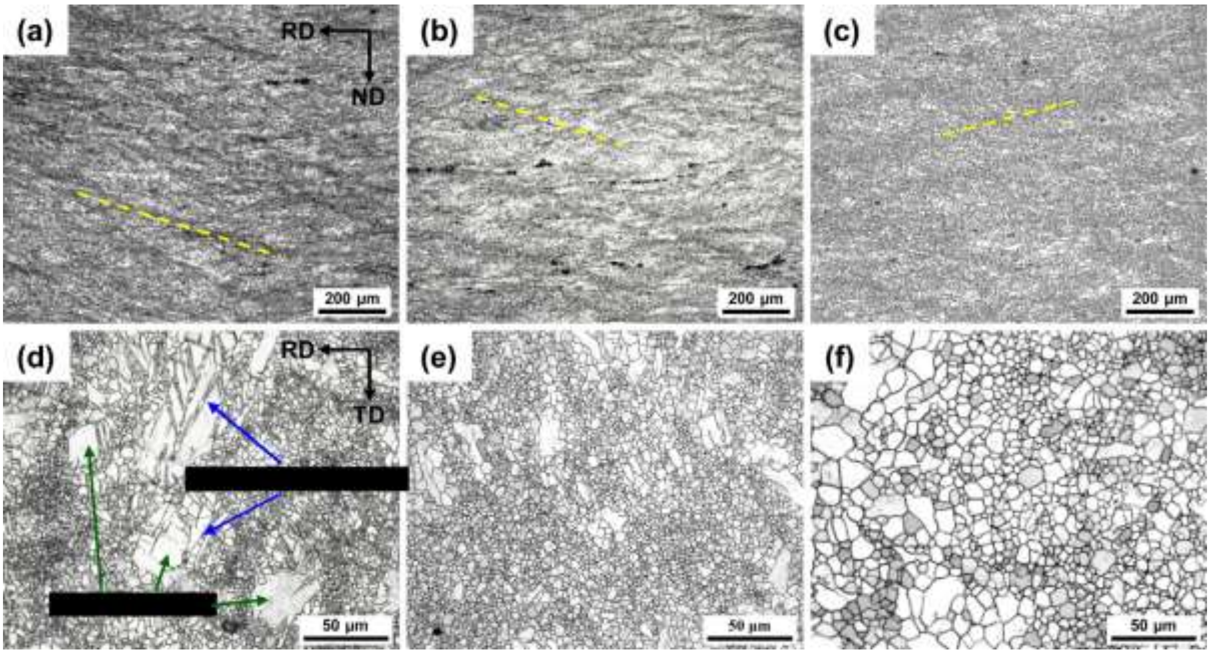


Fig. 2 – Optical micrographs obtained on (a–c) ND–RD and (d–f) TD–RD planes of (a, d) HSR300, (b, e) HSR350, and (c, f) HSR400samples. ND, RD, and TD denote normal direction, rolling direction, and transverse direction, respectively.

effective interface velocity than a slip band; consequently, not enough slip systems are activated instantly [6,17,18]. Consequently, it is evident that, independent of rolling temperature, TDRX behavior rather than DDRX behavior governs microstructural evolution during a HSR process with high strain rates.A partially DRXed grain of the HSR300 sample is displayed in Fig. 4, wherein recrystallization takes place along a twin band that was formed during HSR. Due to recrystallization occurring along the twin band, the unDRXed matrix region has a rectangular shape with high aspect ratios of ≥ 3. This can be observed in Fig. 4(b)). Furthermore, it is noted that at grain boundaries in contact with the twin band (region A in Fig. 4(c)), fine DRXed grains form. The reason for this is that twinning dislocations build up at the interface between the twin band and grain boundary, increasing the driving force for DRX [3,19]. These grains originated from the {1 0 −1 1} compression twin and the {1 0 −1 1}–{1 0 −1 2} double twin, according to the misorientation line pro-file along the DRXed grains formed at the twin band (Fig. 4(d)).This result is in line with the previously published finding that, because of the high dislocation densities of these twins, TDRX predominately occurs in {1 0 −1 1} compression twins and {1 0 −1 1}–{1 0 −1 2} double twins during the HSR process [11]. As the rolling temperature rises, the applied strain distribution throughout the material becomes more uniform, as seen in Fig. 2(a)–(c). This results in the homogenous formation of deformation twins and twinning-induced DRXed grains. As a result, when the rolling temperature rises, the

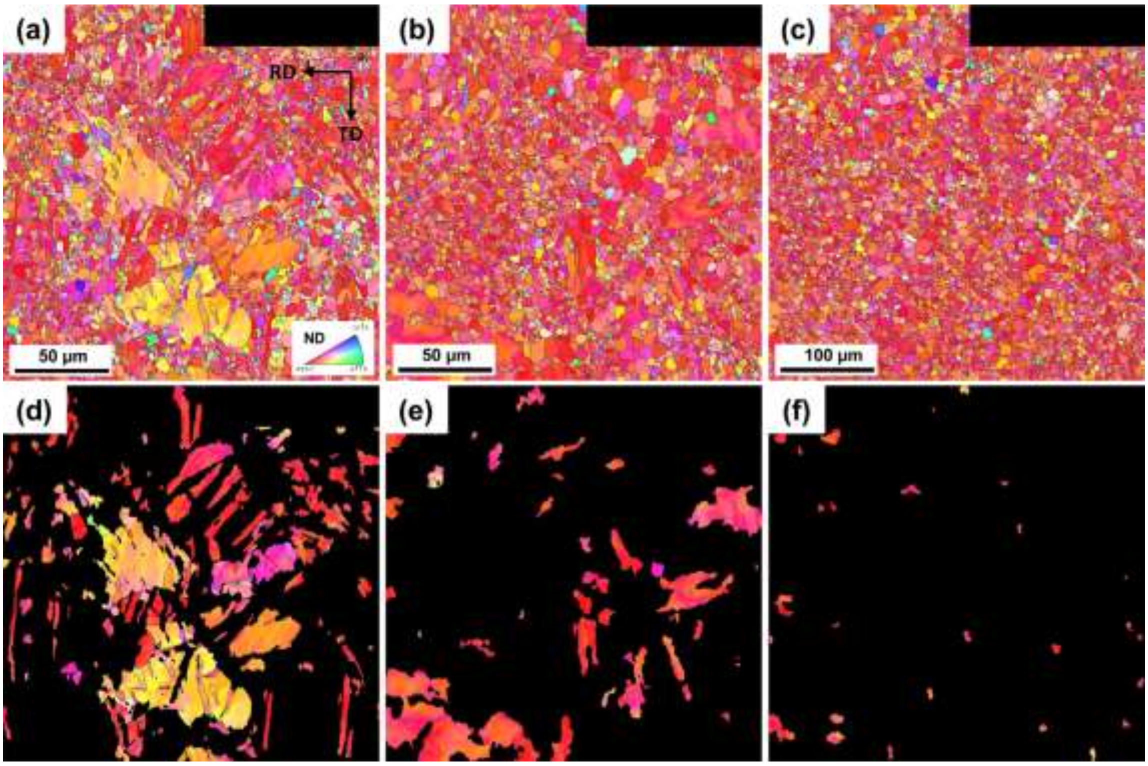


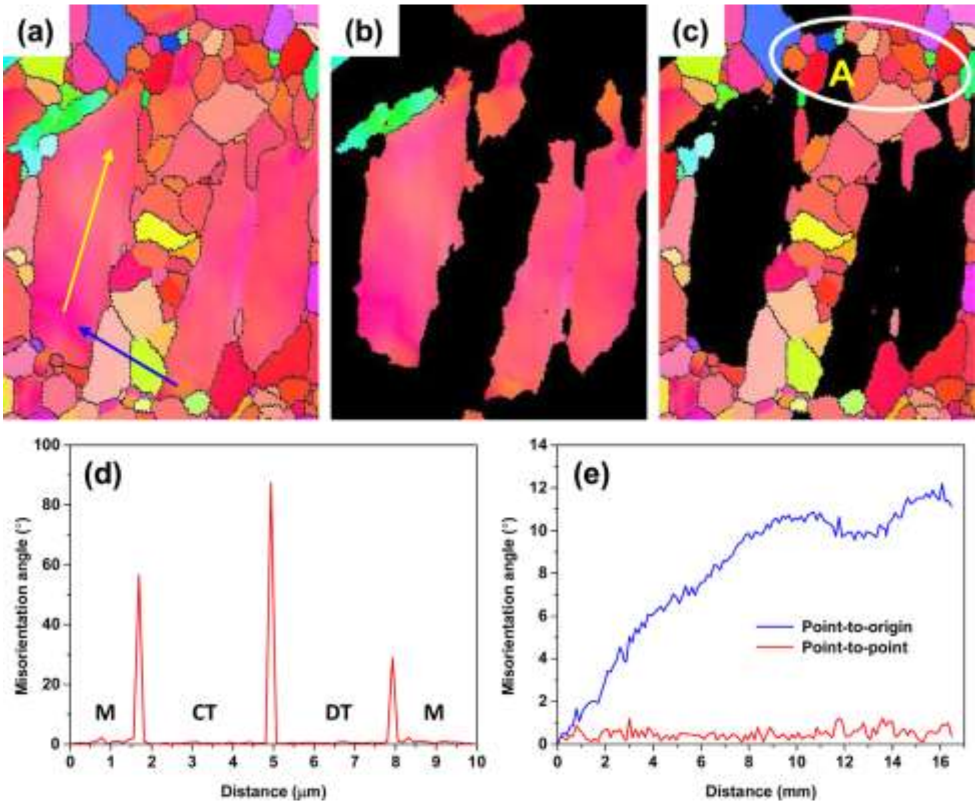
Fig. 3 – Inverse pole figure maps of (a, d) HSR300, (b, e) HSR350, and (c, f) HSR400 samples: (a–c) total region and (d–f) unDRXed region. d_{avg} and f_{unDRX} denote the average grain size and the area fraction of the unDRXed region, respectively.

DRX fraction of the HSRed samples does too. Numerous dislocations continuously accumulate during HSR in the residual matrix region that is not recrystallized, resulting in significant lattice distortion; it is confirmed that the deviation of the misorientation angle inside a grain is as high as ~12° (Fig. 4(e)).

3.3. Texture Characteristics of HSRed alloy

The entire region of the HSRed samples as well as the (0 0 0 2) pole figures of the DRXed and unDRXed regions are displayed in Fig. 6. The maximum pole intensity falls from 12.1 to 7.4 as the rolling temperature rises; this texture weakening is caused by the unDRXed region's reduced area fraction, which has substantially higher texture intensities (31.4–48.3) than the DRXed region (7.1–8.4). Furthermore, the HSR300 sample exhibits a significant deviation from the ND toward the RD at the position of maximum pole intensity in the DRXed region; this position progressively approaches the ND as the rolling temperature increases. The variation in the area fraction of the DRXed grains in relation to the ND's basal poles' deviation angle is depicted in Fig. 7. As the rolling temperature rises, the deviation angle corresponding to the maximum area fraction gradually drops from 37.5° to 7.5°. Furthermore, as rolling temperature rises, the deviation angle's distribution range also contracts. For example, in the HSR400 sample, the basal poles of approximately 92% of the DRXed grains are distributed

Fig. 4 – Inverse pole figure maps showing twinning-induced DRX behavior in HSR300 sample: (a) total region, (b) unDRXed region, and (c) DRXed region. (d, e) Misorientation line profiles along directions indicated by blue and yellow arrows, respectively, in (a). M, CT, and DT denote the matrix, {1 0 −1 1} compression twin, and {1 0 −1 1}–{1 0 −1 2}



double twin, respectively. DRX denotes dynamic recrystallization.

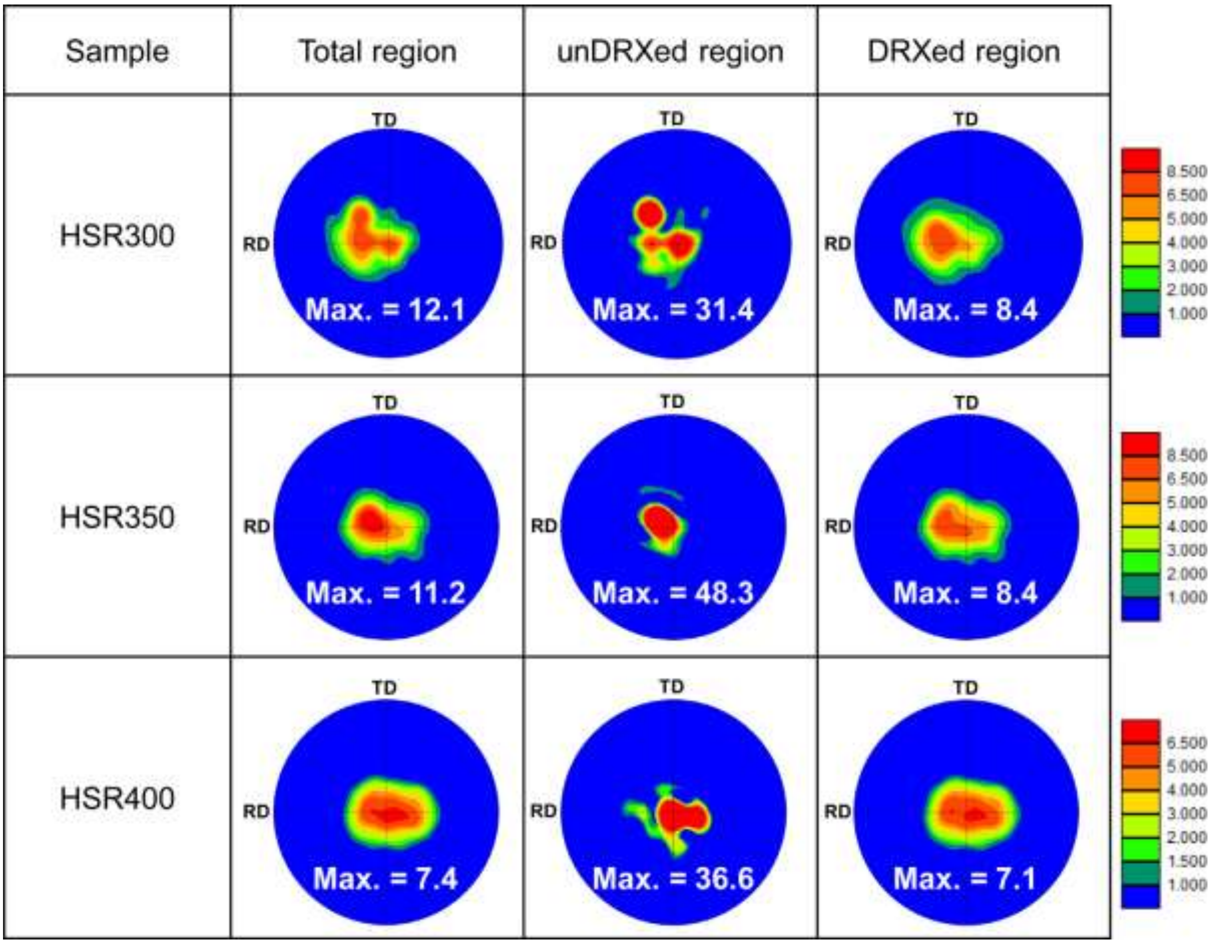


Fig. 6 – (0 0 0 2) Pole figures of unDRXed and DRXed regions and total region of HSR300, HSR350, and HSR400 samples.

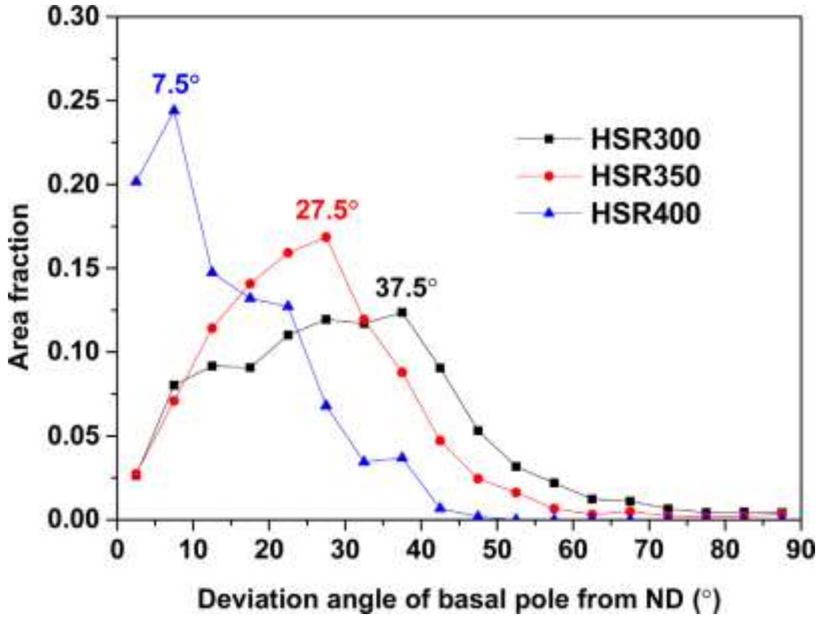


Fig. 7 – Variations in area fraction of grains as a function of deviation angle of their basal pole from normal direction of rolling plane of HSRed samples.

within 30◦from the ND, but in the HSR300 sample, only approximately 52% of the DRXed grains have their basal poles within 30◦from the ND. Figure 7 shows the variation in the area fraction of the DRXed grains with respect to the deviation angle of the ND's basal poles. The deviation angle corresponding to the maximum area fraction gradually decreases from 37.5° to 7.5° as the rolling temperature rises. Moreover, the distribution range of the deviation angle decreases with increasing rolling temperature. For instance, the basal poles of roughly 92% of the DRXed grains in the HSR400 sample are distributed within 30° from the ND, whereas only roughly 52% of the DRXed grains in the HSR300 sample have their basal poles within 30° from the ND.

4. Conclusion

In this work, hot rolling at a high speed of 470 m/min at three different temperatures—300, 350, and 400 degrees Celsius—was used to examine the effects of rolling temperature on the microstructural and textural variations of a HSRed AZ31alloy. Shear bands linked to localized homogeneous deformation were seen in all of the HSRed samples; however, as the rolling temperature rose, the shear band's density and intensity decreased. The promotion of twin formation and TDRX behavior is responsible for the increase in the area fraction of the DRXed grains with increasing rolling temperature. The average grain size of the HSRed samples dropped when the rolling temperature was raised from 300°C to 350°C because the area fraction of coarse unDRXed grains decreased. However, this average grain size increased due to a significant increase in the DRXed grain size with a further increase in rolling temperature from 350◦C to 400◦C. Despite the fact that every sample had a strong basal texture, the maximum texture intensity decreased as rolling temperature increased due to a decrease in the area fraction of the high-texture-intensity unDRXed region. Furthermore, because of the intense shear deformation caused by the HSR process, the location in the DRXed region with the maximum pole intensity tilted toward the RD as the rolling temperature dropped.

References

[1] Wang W, Chen W, Zhang W, Cui G, Wang E. Effect of deformation temperature on texture and mechanical properties of ZK60 magnesium alloy sheet by multi-pass lowered-temperature rolling. Mater Sci Eng A 2018;712: 608–15.

[2] Ferdowsi MRG, Mazinani M, Ebrahimi GR. Effect of hot rolling and inter-stage annealing on the microstructure and texture evolution in a partially homogenized AZ91 magnesium alloy. Mater Sci Eng A 2014; 606: 214–27.

[3] Zhu SQ, Yan HG, Chen JH, Wu YZ, Su B, Du YG, et al. Feasibility of high strain-rate rolling of a magnesium alloy across a wide

temperature range. Scr. Mater 2012;67(4):404–7.

[4] Su J, Sanjari M, Kabir ASH, Jung I-H, Jonas JJ, Yue S, et al. Characteristics of magnesium AZ31 alloys subjected to highspeed rolling. Mater Sci Eng A 2015;636:582–92.

[5] Li H, Hsu E, Szpunar J, Utsunomiya H, Sakai T. Deformation mechanism and texture and microstructure evolution during high-speed rolling of AZ31B Mg sheets. J Mater Sci2008;43(22):7148–56.

[6] Zhu SQ, Yan HG, Chen JH, Wu YZ, Liu JZ, Tian J. Effect of twinning and dynamic recrystallization on the high strain rate rolling process. Scr Mater 2010;63(10):985–8.

[7] Sanjari M, Kabir ASH, Farzadfar A, Utsunomiya H, Essadiqi E,Petrov R, et al. Promotion of texture weakening in magnesium by alloying and thermomechanical processing. II: rolling speed. J Mater Sci 2014;49(3):1426–36.

[8] Sanjari M, Farzadfar A, Kabir ASH, Utsunomiya H, Jung I-H,Petrov R, et al. Promotion of texture weakening in magnesium by alloying and thermomechanical processing:(I) alloying. J Mater Sci 2014;49(3):1408–25.

[9] Asgari H, Szpunar JA, Odeshi AG, Zeng LJ, Olsson E. Experimental and simulation analysis of texture formation and deformation mechanism of rolled AZ31B magnesium alloy under dynamic loading. Mater Sci Eng A2014;618:310–22.

[10] Sanjari M, Farzadfar SA, Utsunomiya H, Sakai T, Essadiqi E,Yue S. High speed rolling of Mg–3Al–1Zn alloy: texture and microstructure analysis. Mater Sci Technol 2012;28(8):928–33.

[11] Lee JH, Lee JU, Kim SH, Song SW, Lee CS, Park SH. Dynamicrecrystallization behavior and microstructural evolution ofMg alloy AZ31 through high-speed rolling. J Mater Sci Technol 2018;34(10):1747–55, http://dx.doi.org/10.1016/j.jmst.2018.03.002.

[12] Yu H, Kim YM, You BS, Yu HS, Park SH. Effects of cerium addition on the microstructure, mechanical properties andhot workability of ZK60 alloy. Mater Sci Eng A2013;559:798–807.

[13] Chun YB, Davies CHJ. Texture effects on development of shear bands in rolled AZ31 alloy. Mater Sci Eng A2012;556:253–9.

[14] Galiyev A, Kaibyshev R, Gottstein G. Correlation of plastic deformation and dynamic recrystallization in magnesium alloy ZK60. Acta Mater 2001;49(7):1199–207.

[15] Su J, Kaboli S, Kabir ASH, Jung I, Yue S. Effect of dynamic precipitation and twinning on dynamic recrystallization of micro-alloyed Mg–Al–Ca alloys. Mater Sci Eng A2013;587:27–35.

[16] Bettles C, Barnett M. Advances in wrought magnesium alloys: fundamentals of processing, properties and applications. Philadelphia: Woodhead Publishing; 2012.

[17] Hamada G, Sakai T, Utsunomiya H. Effect of rolling speed on deformability and microstructure in rolling of AZ31Bmagnesium alloy. Adv Mater Res 2010;89–91:227–31.

[18] Christian JW, Mahajan S. Deformation twinning. Progr. Mater. Sci 1995;39(1–2):1–157.

[19] Murr LE, Esquivel EV. Observations of common microstructural issues associated with dynamic deformation phenomena: twins, microbands, grain size effects, shear bands, and dynamic recrystallization. J Mater Sci2004;39(4):1153–68.