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The effect of rare earth elements on the work softening behavior of as-cast Mg-4Al-2Sn

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Abstract

This work explores the addition of 1% Rear Earth (RE) elements on the Mg–4Al–2Sn magnesium alloy, with an emphasis laid on the microstructural evolution during solidification and subsequent hot deformation behavior. The morphology of the α-Mg dendrites changes from the butterfly-like (growth at the non-basal planes) to the snow-flake like (growth at the basal planes) due to the addition of RE elements. Dendrite morphology transition (orientation transition) lead to the formation of the various macro-texture at the solidification interval. Subsequently, an appropriate correlation was established between the dendrite orientation selection, solidification texture and deformation behavior of the as-cast microstructure. The workability increases due to the addition of RE elements, which is related to the initial solidification texture and the morphology of the α-Mg dendrites. The results indicated that the dendrites which have snow-flake like morphology in the RE bearing alloys was more favorable for breaking of as-cast microstructure and occurrence of dynamic recrystallization.

1. Introduction

Magnesium and its alloys are the most promising structure and functional materials due to lightweight, efficient recyclability, high specific strength, and stiffness [1, 2]. However, poor ductility of these alloys hindered their applications, especially at the low and medium temperatures [1, 2]. In this regard, great effort in several ways has been devoting to developing high-performance Mg alloys for commercial applications like alloying [3–5] grain refinement cussed by dynamic recrystallization (DRX) during thermomechanical processing (TMP) [6–11], etc. These methods, however, need a large number of the equipment for applying TMP protocols or expensive alloying elements. Hence by considering the affordability factor, using these methods sound illogical. As a solution, microstructure engineering at the solidification interval is one of the most promising economic methods which could be effective on the mechanical properties of Mg alloys [12–14]. At the solidification interval, various microstructures nucleate and grow, including the primary phase or α-Mg dendrites, together with the precipitates, and impurity segregation [15, 16]. Of particular interest, the dendritic structure is the most common microstructure, which could form at the solidification interval in these alloys [17]. Amauri Garcia et al. [18] reported that the mechanical properties of cast Mg alloys can dramatically increase by the manipulation of the casting process variable such as cooling rate and alloying. Regarding the mentioned study and related reports, several works demonstrated that the mechanical properties of the as-cast structures strongly depend on the secondary dendrite arm spacing (SDAS), which strongly increments by decreasing SDAS [18, 19]. Irrespective of the effect of SDAS on mechanical properties, other microstructural features that distinguishing mechanical properties is dendrite morphology and the preferred growth directions characteristic [20–22], which can also be affected by the manipulation of the casting process variable. Dendrites tend to grow along the various crystallographic directions, each one holding an specific hexagonal-closed packed crystallography stacking order [23]. The preferred growth direction of the α-Mg dendrite is affected by the diffusivity of the heat and solutes, capillary forces of the surface energy effect, and the crystalline anisotropy [20]. According to the effect of
alloying elements on the mentioned factors, the preferred growth direction of the \( \alpha \)-Mg dendrite is affected by the combined type and quantity of additional alloying elements [21, 22]. In general in the most common binary alloys the \( \alpha \)-Mg dendrites exhibit eighteen-primary-branch, which six of them grow along the \( \{11\bar{2}0\} \) in the basal planes that exhibit six-fold symmetry (snow-flake like morphology) and the others grow along the \( \{11\bar{2}x\} \) directions off the basal planes such as \( \{11\bar{2}3\} \) and \( \{22\bar{4}5\} \), which exhibit butterfly-like morphology [24–27]. Accordingly, the macro-texture formation at the solidification interval, was strongly affected by the preferred growth direction of the \( \alpha \)-Mg dendrites [28]. Therefore, the authors claim that the mechanical properties of the as-cast microstructures could be enhanced by the manipulation of the preferred growth direction and affecting subsequent solidification texture.

Accordingly, in the current study, we present an extensive investigation on the effect of dendrite orientation selection and their morphology on the solidification texture and subsequent hot deformation behavior. In this regard, according to the industrial applications of Mg-Al-Sn based alloy [29], this alloy with an optimum chemical composition of 4Al wt% and 2Sn wt% was chosen in the current study [30]. Additionally, in consideration of RE beneficial for mechanical properties in the Mg–4Al–2Sn alloy [30], the effect of RE addition on the microstructure and texture evolution during solidification and they're the subsequent effect on the thermomechanical properties are systematically studied.

2. Methodology

2.1. Materials preparation

Mg–4Al–2Sn–xRE magnesium alloy with different content of RE elements at the range of 0 wt% and 1 wt% were selected in the current study, to determine the influence of RE elements on the thermomechanical behavior due to their effect on the as-cast microstructure. At first, these alloys melted in an electrical resistance furnace (3 kW) with high purity magnesium (99.95%), aluminum (99.99%), tin (99.9%) and commercial Mischmetal alloy (49% La, 29%Ce, 9%Nd, 3%Pr and 10%Zn) under an oxidation covering flux (50% MgCl\(_2\), 20% KCl, 15% MgO and 15% CaF\(_2\)). The melt was prepared and held at the 750 °C for 30 min, and mechanically stirred before preparation for final casting. After removing oxidation flux and in order to minimize the turbulence of melted material purring the mold, tilt casting method was chosen. The mold, which was preheated up to 200 °C, was made of commercial H13 steel and holding dimensions of 130 \( \times \) 70 \( \times \) 10 mm. The same casting producer was chosen for preparing RE bearing Mg–4Al–2Sn alloy, too. Mechanical stirring and holding for additional 15 min at 750 ± 1 C after adding RE elements were guaranteed the complete solution and reaction between melt and alloying elements. Cubic samples of size 10 \( \times \) 10 \( \times \) 2 mm\(^3\) were cut out from a constant section of the casting billets perpendicular to the thermal direction (TD) using the electro-discharge machine (EDM) for subsequent investigation of microstructural evolution during solidification.

2.2. Microstructure characterization

In order to trace the effect of RE elements on the microstructural evolution at the solidification interval, scanning electron microscopy (SEM, VEGA II TESCAN) was used to analyzing the as-solidified samples. These samples were grounded using hard to soft SiC sand papers, while the sample and sand papers lubricated by stilled water. Final mechanical polishing section was done using the mixture of ethanol, stilled water and 0.25 \( \mu \)m fine Al\(_2\)O\(_3\) particles. The last prepared samples were carefully cleaned using neutral detergent and were dried. The etching solution containing 5 vol% nitric acid + ethyl alcohol was used as etching media. Additionally, the x-ray diffraction (XRD) analysis was carried out using a PHILIPS PW17C instrument with Cu K(alpha) radiation and step size of 0.2 \( \mu \)m, to explore the constituent phase of the initial microstructures.

2.3. Macro-texture characterization

To obtained the effect of RE elements on the texture evolution at the solidification interval, macro-texture was metered for the both alloys using an x-ray texture goniometer based on Schulz reflection geometry (D8 Discover, Bruker AXS, Germany). The samples were irradiated on the horizontal surface (ingot axis perpendicular to the measurement plane) with Cu K(alpha) radiation. Two incomplete pole figures, i.e. \{10\bar{1}0\}, \{0002\} were measured experimentally and represented directly without any further processing.

2.4. Hot compression test and microstructure characterization

Cylindrical specimens with a length and diameter of 7 mm and 10.5 mm respectively, were cut out from the casting billets perpendicular to the (TD) using the electro-discharge machine (EDM). Uniaxial compression test was performed using a GOTECH 7000 LAC universal testing machine under the condition of 250 °C and 350 °C at an initial strain rate of 10\(^{-3}\) s\(^{-1}\). The samples heated to the compression test and held to this temperature for 5 min to ensure the temperature uniform. After hot compression, the specimens were quenched immediately
into water within 5 s. Compressed samples were sectioned parallel to the TD using to the EDM, and were grounded and prepared for microstructural studies using same producer.

3. Result and discussion

3.1. As-cast microstructure

Figure 1 shows the XRD patterns for both investigated alloys. Accordingly, three different phases observed in the Mg–4Al–2Sn case alloy include $\alpha$-Mg, Mg$_{17}$Al$_{12}$, and Mg$_5$Sn (figure 1(a)). By the addition of RE elements, the volume fraction of the Mg$_{17}$Al$_{12}$ phase decreased while the new thermal stabilized intermetallic (Al$_{11}$RE$_3$) formed, which is agree well with previous investigations [31–34]. Additionally, SEM analysis also performed on the as-cast samples for investigating the effect of RE elements on the microstructural evolution during the solidification process. Figures 2(a) and (b) demonstrate the backscattered electron micrographs of the RE bearing and RE free Mg–4Al–2Sn alloys, respectively. Accordingly, the EDS results (figure 2(A)–(D)) support the XRD results and subsequent phase transformation (Mg$_{17}$Al$_{12}$ to Al$_{11}$RE$_3$) resulted by adding RE elements.

The dendritic structure observed in both alloys, which their morphology is different towards each other. Moreover, the type of precipitates and their morphology is also different in the investigated alloys. In line with these observations, the effect of RE elements on the microstructural evolution at the solidification interval was rationalized, by tracing their influence on the dendrite growing tendency and the type of precipitates.

The first deference was the type and the characteristics of the precipitates (figure 2(a) and (b)). Two different precipitates with various morphology observed in the RE free alloy. According to figure 2(a), the Mg$_5$Sn precipitate with cubic morphology located at the dendrite inter-spacing area (white arrows). Additionally, the road-like Mg$_{17}$Al$_{12}$ phase has located at the grain boundaries, which marked by red arrows in figure 2(a).

Comparing RE bearing alloy with primary alloy indicates the Mg$_{17}$Al$_{12}$ phase approximately disappeared and a considerable fraction of needle-like Al$_{11}$RE$_3$ phase formed in this alloy (yellow arrows in the figure 2(b)). More detailed illustration was highlighted by white arrows which apparently point to Mg$_5$Sn precipitate at the dendrite interspacing area in figure 2(b).

Regardless of latter observation, it was clearly observed that the dendrite morphology was transformed due to the addition of RE elements (figure 2(a) and (b)). According to the previous investigations, dendrites tend to...
grow along the different crystallographic directions \([22, 33]\), which led to the formation of the crystallographic stacking order \([35]\). In general, dendrites in the Mg and its alloys can be recognized by the six primary branch with six-fold symmetric morphology (snow-flake like morphology) at the basal plane and the twelve primary branch at the non-basal plane, which exhibited butter-fly like morphology \([22, 36]\). Therefore, detailed examination and detail analysis of the SEM micrograph enable us to finding the preferred growth direction of the \(\alpha\)-Mg dendrites according to their morphology. According to the figure 2(a) butterly like structure was clearly observed in the RE free alloys, which marked with squares with yellow dash line. This morphology could be attributed to the dendrites, which growth at the non-basal planes \([36]\). On the other hand, the snow-flake like dendritic morphology (squares with green dash line) is clearly observed in the RE bearing alloys (figure 2(b)), which could be attribute to the dendrites that growth at the basal planes. In this regard, it could be concluded that the preferred growth direction of the \(\alpha\)-Mg dendrites leaks out to the basal planes (similar to the pure Mg \([37, 38]\)) as a result of RE addition in the Mg–4Al–2Sn based alloy. Additionally, the solidification texture strongly affected by the dendrite growing tendency \([37]\). In these regards, the effect of the RE elements on the dendrite growing tendency also could be examined with the texture study.

The other characteristics of the as-cast microstructures for both investigated alloys are summarized in the table 1. The secondary dendrite arm spacing (SDAS) increased as a result of RE addition. According to the previous investigations, the SEAS decreased by an increase in the coarsening phenomenon at the solidification interval \([38]\). Therefore, the dendrite coarsening phenomenon increased by the addition of RE elements in the Mg–4Al–2Sn alloy. Also, the volume fraction of the intermetallic was similar in both investigated alloys.

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**Figure 2.** Backscattered electron micrographs of the as-cast alloys: (a) Mg–4Al–2Sn, (b) Mg–4Al–2Sn–1RE, (A)–(D) EDS analysis of the precipitate. (For the interpretation to the references in these Fig legend, the red arrow showing the Mg\(_{17}\)Al\(_{12}\) eutectic phases, the with arrows showing the Mg\(_2\)Sn phases, the yellow arrow showing the Al\(_{11}\)RE\(_3\) phases, the green square showing the snow-flake like dendrite morphology and the yellow square showing the butterly dendrite morphology).
3.2. Solidification texture

According to the previous literature, the solidification texture was strongly affected by the dendrite growing tendency [39]. Therefore, the effect of the RE elements on the dendrite growing tendency examined with the texture study in the current study. As mentioned before, both alloys in the current study had dendritic structures with different growing tendency and morphologies. Results demonstrated that the $\alpha$-Mg dendrites tend to grow at the non-basal planes in the RE free alloys, while in the RE bearing alloys tend to grow at the basal planes. This difference results in the formation of various texture components.

According to the crystallography knowledge of the hcp structure, the growth direction of the $\alpha$-Mg dendrites in the basal plane could be either $\langle 10 \bar{1} 0 \rangle$ or $\langle 11 \bar{2} 0 \rangle$, while that direction could be $\langle 10 \bar{1} x \rangle$ or $\langle 11 \bar{2} x \rangle$ in the non-basal planes [15, 16, 22]. The $\langle 11 \bar{2} 0 \rangle$ and $\langle 11 \bar{2} x \rangle$ are more favorable compared to the other directions at the basal and non-basal planes respectively [40]. In this regard, figure 3(a) scheme out any possibility of the growth directions based on the hcp lattice structure compared to the thermal direction (TD). Moreover, the location of any possible texture components compared to the TD are schematically demonstrated in figure 3(b) in terms of basal pole figure. Figure 3(c) and (d) shows the macro-texture for both investigated alloys, which presents in term

| Alloying composition | Volume fraction of the intermetallic | Secondary dendrite arm spacing |
|----------------------|-------------------------------------|-------------------------------|
| Mg–4Al–2Sn           | 2.11                                 | 19.3 ±1                       |
| Mg–4Al–2Sn-1RE       | 2.32                                 | 23.6 ±1                       |

Figure 3. (a) Shows the schematic of the any possible dendrite growth direction in hcp lattice structure according to the TD, (b) schemes out the hypostasized about macro texture formation in term of the basal pole during solidification with TD reference axis (c) and (d) shows the basal pole figure of the as-cast samples (b) Mg–4Al–2Sn and (c) Mg–4Al–2Sn-1RE.
of basal (0002) recollected pole figures. Accordingly, the macro-solidification texture for both investigated alloys is well consistent with the hypothesis in figure 3(b). Additionally, it should be noted that this observation agrees well with the experimental finding in section 3.1.

Moreover, using an identical intensity color scale for each type of the basal pole figure, the intensity of the pole figure significantly decreased from 3.44 to 2.3 due to the addition of RE elements.

3.3. True stress—strain curves

3.3.1. The classical characteristics of the flow responses

In general, to consider the effect of initial texture on the deformation behavior in the Mg and its alloys, hot compression tests usually done at the temperature lower than 300 °C [41]. In this regard in the current study, hot compression tests were done at 250 °C to investigate the effect of solidification texture on the hot deformation behavior in the program alloys. Figure 4(a) demonstrated flow curves for both investigated alloys at the 250 °C. As clearly figured out, the general appearance of the flow curves shows different deformation behavior. According to the figure 4(a), the characteristic sigmoidal profile is observed in the RE free alloy, while it was disappeared by adding RE elements. According to the previous investigations, these profiles was associated by the activation of the deformation twins and their subsequent interplay with dislocations, which resulted in hardening at the primary stage of the deformation [42]. This difference could be attributed to the effect of RE elements on the deformation mechanisms as a result of their effects on the initial solidification texture (section 3.2) and the activation of the non-basal slip systems. Previous investigations demonstrated that the formability of the Mg alloys increased due to the addition of RE elements by decreasing the critical resolved shear stress for activation of the non-basal slip systems. Activation of the non-basal slip systems could be hinder the nucleation of the mechanical twins in the Mg alloys [43].

On the other hand, to the comprehensive examinations of the deformation behavior in the program alloys showed these flow curves resulted from compression tests at 250 °C could be divide into the three sections as shown in figure 4(a). At the section (I), in the conventional metallic materials, flow stress rapidly increased to the critical value for initiation of dynamic recrystallization (DRX) [44]. For the as-cast microstructures, however, this rapid hardening could be attributed to the strength of the as-cast microstructure (dendrites and coarse
intermetallic). Therefore, in this stage, the stress rapidly increased to the critical value for initiation of the DRX and the breaking of cast structure (dendritic structures and coarse intermetallic). By continuing deformation and through the section (II) work hardening rate decreased gradually by the breaking of the as-cast structure and restoration phenomenon until to the pick stress \([44]\). Additionally, continuing plastic deformation (through the section (iii)), the flow stress decreased gradually due to the breaking of the cast structure.

In another word, for better illustration of the deformation behavior in the investigated alloys at 250 °C, the corresponding strain hardening rates are also figured out by figure 4(b). These curves could be divided into the three sections for both alloys. By the starting plastic deformation (stage I), the staring hardening rate gradually decreased for both RE free and RE bearing alloys. By containing plastic deformation (stage (II)), RE bearing alloy demonstrated significant difference deformation behavior compared to the RE free alloy. This difference is related to the deformation mechanisms at this stage of plastic deformation. As can be seen, the strain hardening rate increased by the activation of the mechanical twins and their exhaustion at this stage in the RE free alloys \([42]\). On the other hand, the strain hardening decreased in the RE free alloy. This difference in the deformation mechanisms could be attributed to the initial solidification texture (figure 3) and the effect of RE elements on the deformation mechanisms \([45]\). Finally, at the stage (III), the strain hardening rate decreased gradually. Finally, at the stage (III), the strain hardening rate decreased gradually by the breaking cast structure and restoration phenomenon.

According to the previous investigations, the rate of DRX would be increased by increasing deformation temperatures \([45]\). Therefore, in the current study, the hot compression test also conducted at 350 °C to investigation the DRX behavior in the investigated alloys during the hot deformation process. Figure 4(c) demonstrated flow curves of both investigated alloys at the 350 °C, which divided into three sections. By starting the plastic deformation in section (I) and by considering deformation temperature, the flow stress rapidly increased to the critical value for the occurrence of DRX. Additionally, with further plastic deformation during stage (II), the flow stress rose slower until to a peak value. By continuing plastic deformation in the stage (III), the flow stress decreased gradually by softening resulted from DRX.

Of particular interest in the deformation behavior at all temperatures, the stress level of the RE bearing alloys is lower compared to the RE free alloys, which is contrast with previous observation \([31–34]\). This behavior could be related to the initial dendritic structures (figure 2) and the initial solidification texture as a result of various dendrite growth direction (figure 3).

### 3.3.2. Estimation of DRX and breakdown of cast structure by the flow response

The critical stress and strain of DRX or breaking cast structure cannot be determined directly from the \(\theta—\varepsilon\) and flow curves. Nonetheless, the strain hardening rate-flow stress curves could accurately determine the characteristic of the flow curves. According to the approach of Poliak and Jonas, in the curves of \(\theta—\sigma\) the point at which the work hardening rate equals zero (\(\theta = 0\)) represents the peak stress (\(\sigma_p\)). Also, the inflection point of \(\theta—\sigma\) curves indicates the critical stress (\(\sigma_c\)) for the initiation of DRX \([45, 46]\). Of particular interest, the breaking of the as-cast structures resulted in the flow softening in the flow curves. Therefore, the inflection points in the \(\theta—\sigma\) curves also could be attributed to the critical stress for braking cast structure during hot compression tests. Also, the required critical strain for both initiations of DRX and braking cast structures could be calculated by the obtained from flow curves. In this regard, in order to represent a better illustration of the deformation behavior of the investigated alloys and the calculation of the critical stress and strain for breaking cast structures during hot compression tests, the strain hardening rate-flow stress curves are figure out by figure 5(a) and (b) at both deformation temperature (250 °C and 300 °C).

The stress-strain curves of both investigated alloys which compressed at 250 °C exhibited an initial hardening transient, a peak flow stress, and then a large continues flow softening (figure 4(a)). Such behavior in the conventional metallic materials is often associated with discontinues dynamic recrystallization \([46]\). However, for the as-cast microstructure with a dendritic structure, this behavior could be attributed to the dynamic braking of the as-cast microstructures.

The inflection point in the \(\theta—\sigma\) curves at 250 °C was related to the critical stress for breaking cast structures. By considering figure 5(a), the critical stress for breaking cast structures of the RE free and RE bearing alloys is 105 MPa and 96 MPa, respectively. Furthermore, the critical strain for braking cast structures is 0.1 and 0.12 for RE free and RE bearing alloys, respectively. The growth of the critical strain for breaking cast structure due to the addition of RE elements could be attributed to the initial solidification texture (figure 3) and dendritic structures (figure 2). Therefore, it could be concluded that the dendritic structure in the RE bearing alloy had more potential for strain accommodation.

The stress-strain curves of both investigated alloys that compressed at 350 °C exhibited an initial hardening transient, a peak flow stress, and then flow softening until to the balanced state between flow hardening and flow softening (figure 4(b)). Such behavior in the flow curves has attributed to the occurrence of DRX during the hot
compression test [46]. Therefore, based on Poliak and Jonas investigation [46, 47], the critical stress for DRX at 350 °C is 58 MPa and 52 MPa for RE free and RE bearing alloys, respectively (figure 5(b)). Moreover, the corresponding critical strain is 0.05 for Mg–4Al–2Sn and 0.06 for RE bearing alloy. Accordingly, the DRX retarded by the addition of RE elements in the Mg–4Al–2Sn alloy, which agrees well with previous investigations [47]. Present authors believed that the Zener pinning effect of RE element superseded grain boundary migration was the main reason for observed retardation. Stanford et al [47].

3.3.3. Microstructure evolution during hot compression tests

Figure 6 shows the optical micrographs of both investigated alloys that deformed at 250 °C for the strain of 0.6. As its clear, the microstructure of both RE free and RE bearing alloys, which was dominated by dendritic structures (figure 2), deformed and distorted after hot compression test (figure 6). Results demonstrated that there are many lenticulars banded features in the dendrites area (white sorrows) in the RE free alloys, which could attribute to the mechanical twins in the Mg alloys (figure 6(a)) [48]. Formation of the mechanical twins in the RE free alloys agrees well with experimental findings in section 3.3 (figure 4(a) and (b)), which demonstrated rapid hardening at the primary stage of the plastic deformation as a result of twin exhaustion [42]. Moreover, the dendrite arms were bent along with the deformation directions (figure 6(a)). Of particular interest, there are many grooves at these dendrites interface, which decreased the dendrite thickness (red arrows in figure 6(a)). According to decreasing thickness of the dendrite branches, it could hypostases, the dendrites tend to be fragmented during the hot deformation process, which agree well with experimental finding in section 3.3.1 (figure 4(a)). On the other hands, in the RE bearing case alloy (figure 6(b)), the volume fraction of the mechanical twins dramatically decreased as a result of more activation of the non-basal slip systems [49], which agree well with experimental finding in section 3.3 (figure 4(b)). Similar to the RE free alloy microstructure consists of the high-volume fraction of the bent dendrites (red arrows in figure 6(b)). The volume fraction of the bent dendrites in the RE bearing alloy was higher in comparison with the RE free alloys. Therefore, the dendrites with snowflake like morphology (figure 2(b)) are more favorable for breaking during the hot deformation process compared to the butterfly-like morphology (figure 2(a)). Additionally, for further clarifications of the microstructural evolution through the hot compression test at 250°C, SEM analysis was also performed on both investigated alloys (figure 7). Accordingly, the eutectic morphology of the Mg17Al12 intermetallic in the RE free alloy (figure 2(a)), was strongly modified after hot compression tests (red arrows in figure 7(a)). This modification was related to the fragmentation of this precipitate during the hot deformation process. According to the previous investigations, precipitate with a size larger than 1 μm is the preferred site for dislocation accumulation during the hot deformation process [30]. Dislocations pile-up followed by the lead dislocation caused the stress concentration, which could be reached to the critical value for intermetallic penetration (fragmentation) [51]. The plate-like Al11RE3 precipitates in the RE bearing alloy (figure 2(b)) breached in some area (red arrows in figure 7(b)) similar to the RE free alloy. Particle and intermetallic fragmentation during hot compression tests also led to softening in the flow curves (figure 4).

By increasing the deformation temperature (350 °C), dendritic structures (figure 2) strongly modified after hot compression tests (figure 8). Accordingly, microstructures contained residual particle dendrites and the DRX grains (figure 8(a) and (b)). For further clarification of the DRX behavior in both alloys, SEM analysis was also performed on the deformed samples. Figure 9 demonstrated that some of the DRX grains located around
the intermetallic (Mg\(_{17}\)Al\(_{12}\) and Al\(_{11}\)RE\(_3\)). According to the previous investigations, particles or intermetallic phases which have an average size coarser than 1 \(\mu\)m may hinder dislocation motions. Due to the interaction between dislocation and these particles, the compatibility between matrix and particles preserved case by the generation of geometrically necessary dislocations around the particles that provide the driving force for DRX. The latter mechanism is classified as particle stimulated nucleation (PSN) [51].

Figure 10 presents the percentage of the DRX grain and residual dendrites at 350 °C. The volume fraction of the DRX grain in the RE bearing alloy was higher compared to the RE free alloy, which is in contrast with the previous investigation [52]. According to the previous investigation, the addition of RE in Mg alloys was retarding the DRX phenomenon, due to the Zener pinning effect [53]. Therefore, the variation of the DRX behavior in the current study compared to the previous investigations was related to the initial dendritic structure and solidification texture. As mention before, due to the addition of RE elements, dendrites tend to grow at the basal plane (snow-flake like structures), which resulted on the formation of different texture components compared to the RE free alloy. Additionally, the initial solidification texture was weekend due to the addition of RE elements (figure 3). Accordingly, the dendrites which have snow-flake like morphology

Figure 6. Shows the optical micrograph of the as-cast samples, which deformed at 250 °C (a) Mg–4Al–2Sn, (b) Mg–4Al–2Sn–1RE (the white arrows show the mechanical twins and the red arrows show the dendrite fragmentation phenomenon).
**Figure 7.** Shows the SEM microstructure of the as-cast samples, which deformed at 250 °C (the arrows show the dynamic dissolution of the intermetallic).

**Figure 8.** Show the optical micrograph of the as-cast samples that deformed at 350 °C (a) Mg–4Al–2Sn, (b) Mg–4Al–2Sn-1RE (the square shows the deformed snow-flake like dendrite morphology).
(dendrites which growth at the basal planes) are more favorable for fragmentation and DRX during the hot deformation process.

4. Conclusion

This paper was provided to investigate the effect of RE elements on the microstructural evolution at the solidification interval and subsequent hot compression tests. The main findings could be summarized as follows:

The overall morphology of the dendritic structures changed from the butterfly-like structure to the snowflake like structure by the addition of RE elements in the Mg–4Al–2Sn alloy.

The solidification texture was strongly affected by the dendrite growth tendency.

The α-Mg dendrites with snow-flake like structures (dendrites at the basal planes) in the RE bearing alloy were more favorable for breaking compared to the butterfly-like structure in RE free alloy during hot deformation process at 250 °C.

The volume fraction of the DRX grain was higher in the RE bearing alloy compared to the RE free alloy, which attributed to the initial dendritic structures and initial solidification texture.

The above research results will provide theoretical support for further research on the hot deformation behaviors of as-cast Mg–4Al–2Sn–xRE and the new process of the deformation on cast structure compound.
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