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Full length article

Ductility enhancement of EW75 alloy by multi-directional forging

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Abstract

In this study, the Mg−7Gd−5Y−1Nd−0.5Zr alloy can reach a high ductility by the process of multi-directional forging, and the evolution of the microstructure, texture and the mechanical properties were discussed systematically. The results show that after the solutionized sample was multi-forged at 500 °C, its grain size can be refined from 292 um to 58 um. As the forging temperature decreased, fine particles precipitated in the matrix. The volume fraction of the particles increased with the forging temperature decreasing, so the nucleation and growth of crystallization were strongly restricted. There was no recrystallization as the forging temperature fell to 410 °C, and the severe deformed grains distributed as streamlines perpendicular to the final compression axis. The texture intensity decreased with increasing forging passes. The sample with best ductility was obtained after compressed at 470 °C, with an elongation to failure of 21% at room temperature, which is increased by 200%, in comparison with that of the samples in solutionized condition. EBSD results revealed that the mean grain size was 15 um. Refined grains as well as the weakened texture were the key factors to its high ductility.

Keywords: Mg alloys; Ductility; Multi-directional forging; DRX; Precipitates

1. Introduction

Mg and Mg based alloys have attracted intensive researching activities due to their low densities, high specific strength and advantage of easy recycle. Recently, much work has been done in the development of high strength Mg−RE alloy, as it exhibits pronounced age harden response and good creep resistance [1].

The mechanical properties both at ambient and elevated temperatures of Mg−Gd−Y system can be effectively improved by optimizing the microstructure through the process of plastic deformation, such as warm rolling and hot extrusion, and the subsequent annealing process, so the mechanical properties with high strength at room temperature and good creep resistance can be achieved for these Mg−Gd−Y alloys [2]. Rare earth elements Gd and Y showed excellent solid solubility in the Mg matrix, and the combination energy between Mg−Y and Mg−Gd was so strong that the Mg−Gd−Y alloys can reach a high strength. The strong combination energy between Mg−Y and Mg−Gd exhibit obvious brittleness at the same time, which was harmful to the ductility of the alloys. For instance, Mg−9Gd−3Y alloy exhibit an elongation to failure of 1% at cast condition, and reach 2% after solution treatment. Plastic working was an effective method to obtain alloys with high strength property, but in most outcomes, high strength alloys have moderate even

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worse ductility. For instance, Yu, et al. [3] developed a high strength Mg–11Gd–4.5Y–1.5Zn–1-Nd–0.5Zr alloy by hot extrusion and subsequent aging, with an ultimate tensile strength of 473 MPa, but the elongation to failure was merely 4.1% at room temperature. Xu et al. reported that the as-extruded Mg–3.5Al–3.3Ca–0.4Mn alloy exhibited both high tensile strength and ultimate tensile strength, which have nearly equal values of 410 MPa and 420 MPa. The minor differential of tensile proof strength and ultimate tensile strength indicated a low strain-hardening ability, so the ductility was inferior, only with an elongation to failure of 5.6% [4]. Kim et al. applied high ratio differential speed rolling to AZ91 alloy, after two-step hot rolling at a speed ratio of 2, the rolled sheet shows a high 0.2% yield stress of 386 MPa, total elongation of 5% [5]. Obviously, the backwards of low ductility would restrict the extensive application of Mg–Gd–Y high strength alloys, so the research of ductility enhancement on high strength Mg–Gd–Y alloys will be discussed.

An inferior ductility of most of the samples could be ascribed to the strong basal texture formed by extrusion or rolling, so the samples with good ductility must guarantee a weak basal texture. Multi-directional forging process is effective to weaken the basal texture, and it is also crucial to refine the grains as well as the precipitates, so it can produce a uniform material with ideal ductility. According to Xia, the EW75 alloy could reach an elongation to failure of 12% after six passes multi-directional forging [6], which had an obvious improvement compared with the solutionized samples. But, in his work, the recrystallization structure was non-uniform, so the ductility could be further improved through multi-directional forging as long as we can optimize the recrystallization structure by adjusting the forging parameter.

In this paper, an investigation on Mg–7Gd–5Y–1Nd–0.5Zr alloy processed by multi-directional forging was reported. The influence of forging passes and temperature on the evolution of microstructure and mechanical properties was presented.

2. Experimental procedure

The nominal composition of the Mg–7.5Gd–4.5Y–1Nd–0.5Zr (wt%) (EW75) alloy was prepared with high purity (99.9%) Mg, Y, Nd, Mg–30Gd and Mg–30Zr (wt%) master alloys in electric resistance heating furnace under the protection of a mixed atmosphere of SF_6 (1 vol%) and CO_2 (bal). The melt was held at 780 °C for 30 min then cast into ingot with a diameter of 250 mm. The ingot was homogenized at 535 °C for 16 h followed by air cooling, and some rectangular shaped samples were cut from the center of the ingot. The principle of the forging process was presented in Fig. 1. At first, the samples were multi-directional forged for one cycle at certain temperature. A pass strain of 0.4 was employed. Then, some of the forged samples were selected to be compressed to plate with a large strain of 0.75, at the same temperature, while the other ones continued to the multi-directional forging process of next cycle at a lower temperature. The forging temperature decreased from 500 °C to 410 °C and the forging speed was 1.5 mm/min. The samples were quenched in cold water after each forging or compressing pass, and were lubricated with graphite oil and hold in the furnace for 10 min before each forging or compressing pass. The specimens for OM and SEM were cut parallel to the plate and perpendicular to the plate. Texture of the samples was examined by X-ray diffraction in the final compressed plane of the plates, i.e. the TD–TD plane (TD: transverse direction parallel to the final compressed plane). EBSD specimens were prepared by electric polishing in the 10% perchloric acid ethanol solution. The tensile specimens were cut parallel to the final compressed plate for tensile testing at a strain rate of 0.001 s^{-1} at room temperature, and the tensile fracture was observed through the SEM.

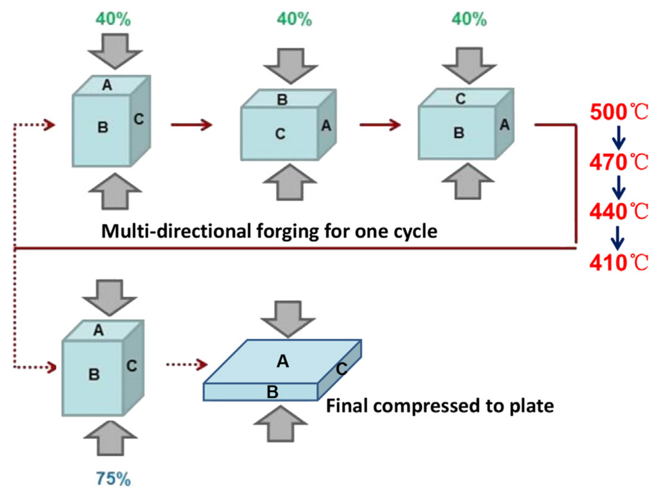

Fig. 1. The principle of multi-directional forging process.

3. Results and discussion

3.1. Initial microstructure

Fig. 2 shows OM and SEM images of the solutionized Mg–7.5Gd–4.5Y–1Nd–0.5Zr alloy. After homogenization treatment, the eutectic phases dissolved into the matrix, and only small number of block shaped particles exist, as shown in Fig. 2b. The average grain size was about 224 um, and the EDX results shows that these blocked phases were rich of Y elements.

3.2. Microstructure after multi-directional forging at different temperature

Fig. 3 shows the microstructures of alloys processed by multi-directional forging at 500 °C, 470 °C, 440 °C and 410 °C, respectively. It is clear from Fig. 3a that recrystallization occurred after the forging process at 500 °C, but the grains were coarse and non-uniform because of the abnormal grain growth. When continued forging was conducted at subsequent temperature, more and more fine particles precipitated both at the boundaries and interior of the grains.

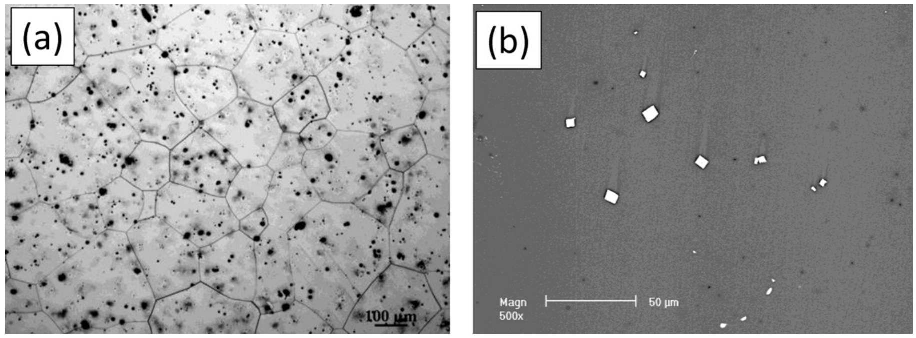

Fig. 2. Structure of EW75 alloy after solution: (a) OM (b) SEM.

The fine equiaxed grains demonstrate that fully recrystallization was obtained at 470 °C. When the samples were continue forged at 440 °C and 410 °C, the grain size was unchanged, which may be result from the recrystallization behavior restricted by the more precipitates.

Fig. 4 shows the microstructures which were parallel and perpendicular to the final compressed plate. The fine recrystallization structure was obtained, after the sample was compressed at both 500 °C and 470 °C, and the microstructure of the sample compressed at 470 °C was hard to identify. It was worth to notice that the grain refinement of the sample compressed at 470 °C was more remarkable, because a large amount of phases which precipitated along the original grain boundaries play an important role in restricting the growth of the recrystallization [7]. The refinement of the grains was result from dynamic recrystallization during multi-directional forging, and the microstructures were similar when observed parallel and perpendicular to the plate.

When the samples were compressed at a lower temperature of 440 °C and 410 °C, there was an obvious distinction between the microstructures parallel and perpendicular to the plate. As illustrated in Fig. 4e and f, compressed streamlines which parallel to the plate were observed in the orientation perpendicular to the final compression axis. Recrystallization was restricted in these samples, and the grain size remains the condition before final compression, and more phases precipitates at boundaries and interior of the grains, which may contributed to the resistance of recrystallization [8]. According

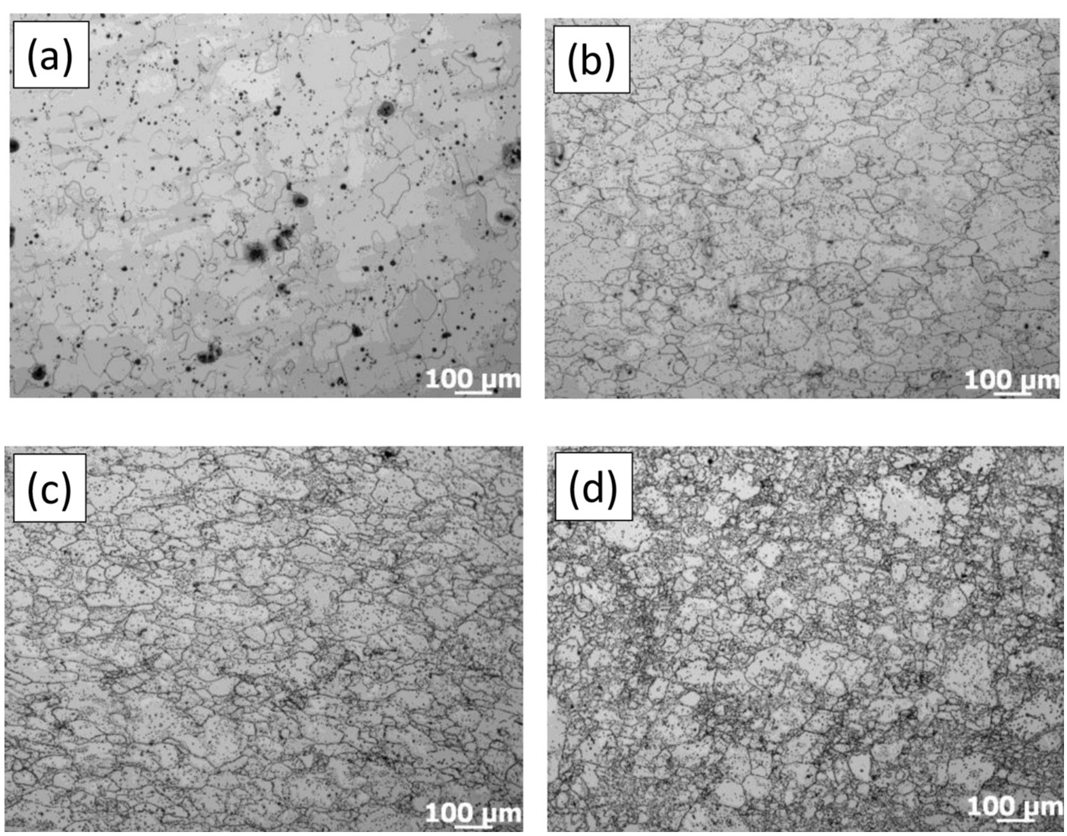

Fig. 3. Microstructure of the alloys processed by multi-directional forging at different temperature: (a) 500 °C (b) 470 °C (c) 440 °C (d) 410 °C.

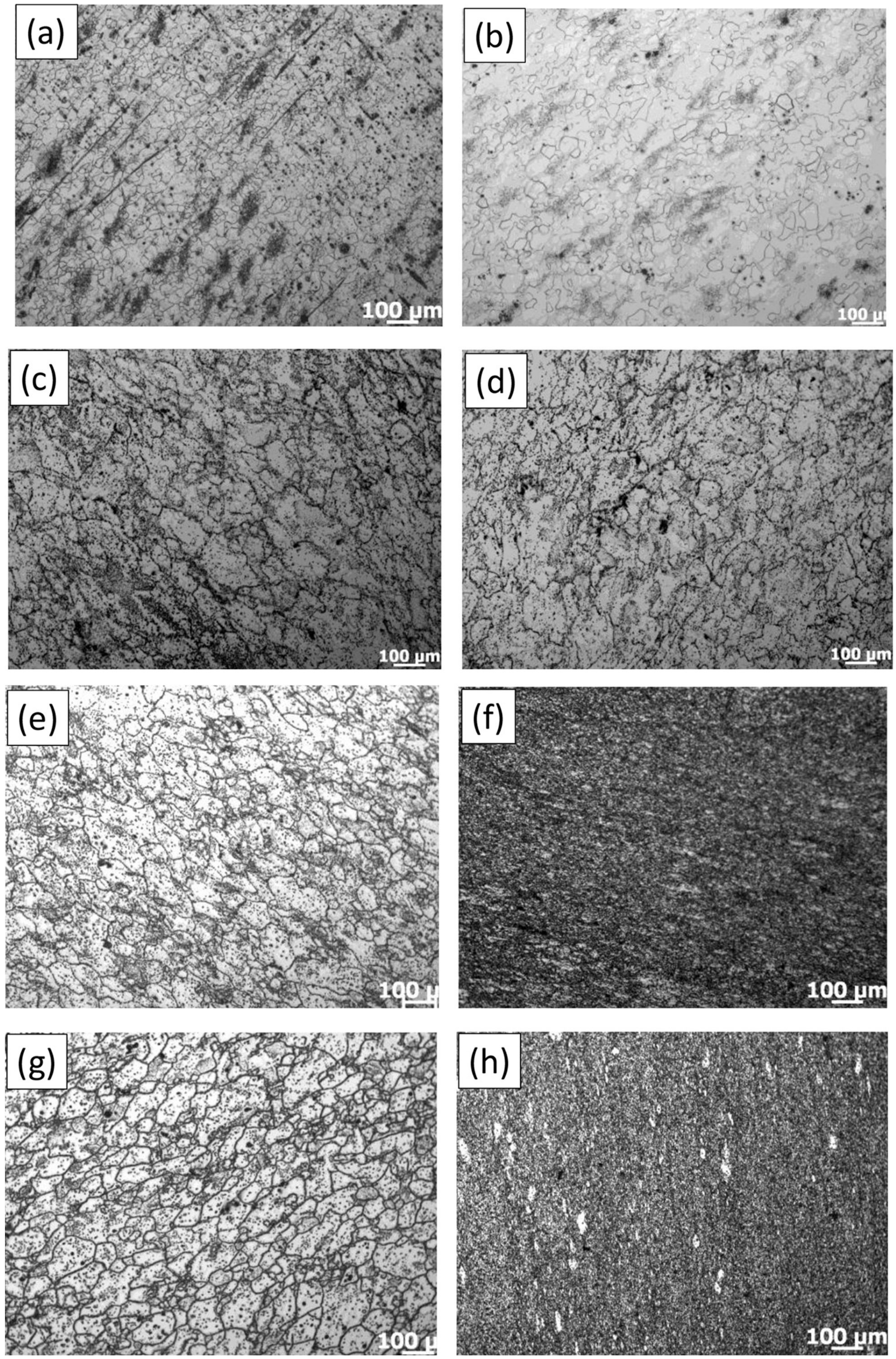

Fig. 4. Microstructure observed perpendicular (a, c, e, g) and (b, d, f, h) parallel to the final compressing direction of the plate compressed at different temperature: 500 °C (a, b), 470 °C (c, d), 440 °C (e, f), 410 °C (g, h).

to the above speculation, the formation of the streamlines can be explained by the effect of severe deformation, that the globular grains were compressed into slices with minor thickness, so we could not identify the whole grain morphology.

To analysis the vague microstructure of the plate compressed at 470 °C, we characterize it with EBSD technology to get a detailed understanding. As illustrated in Fig. 5, recrystallization grains were uniform with a mean size of 15um. The final compression could significantly refine the microstructure,

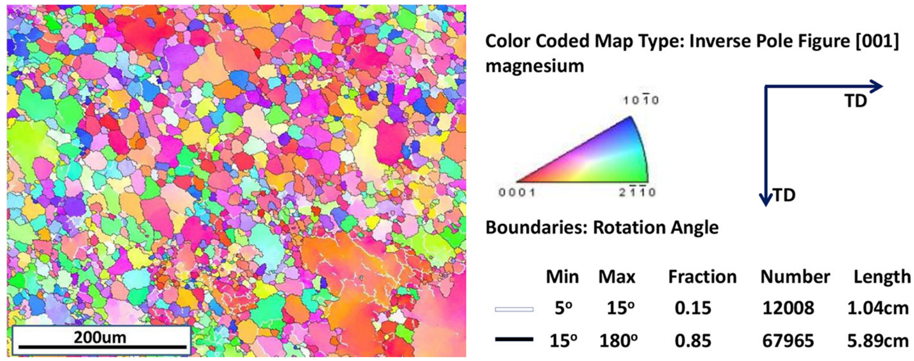

Fig. 5. EBSD results showing the IPF map of the plate final compressed at 470 °C.

and the misorientation angle revels that a high proportion of boundaries were high-angle recrystallization boundaries and a small number of low-angle boundaries exist in some large grains. Refined recrystallization grains with a messy orientation could coordinate the deformation and favor to the basal slip, so the ductility could be enhanced [9].

Fig. 6 shows the phase distribution of the plate in the orientation perpendicular to the final compression axis. There was a big difference about precipitates in the SEM outcome, in both quantity and distribution. The sample compressed at 500 °C has an uniform microstructure with some block Y-rich phases. When the sample was compressed at 470 °C, most globular phases precipitated along the grain boundary, as shown in Fig. 6c and d, and complete recrystallization microstructure was obtained. The precipitates dispersed at the original grain boundary, so it is difficult to identify the microstructure of the fine recrystallizations. The dispersed phases at original boundary could restrict grain growth, so it is beneficial to obtain fine recrystallization microstructure. When the samples were compressed at 440 °C and 410 °C, the volume fraction of precipitates increased sharply. Large quantity of precipitates restricted the recrystallization, and the grains were compressed severely in thickness, so the stream-line morphology was in

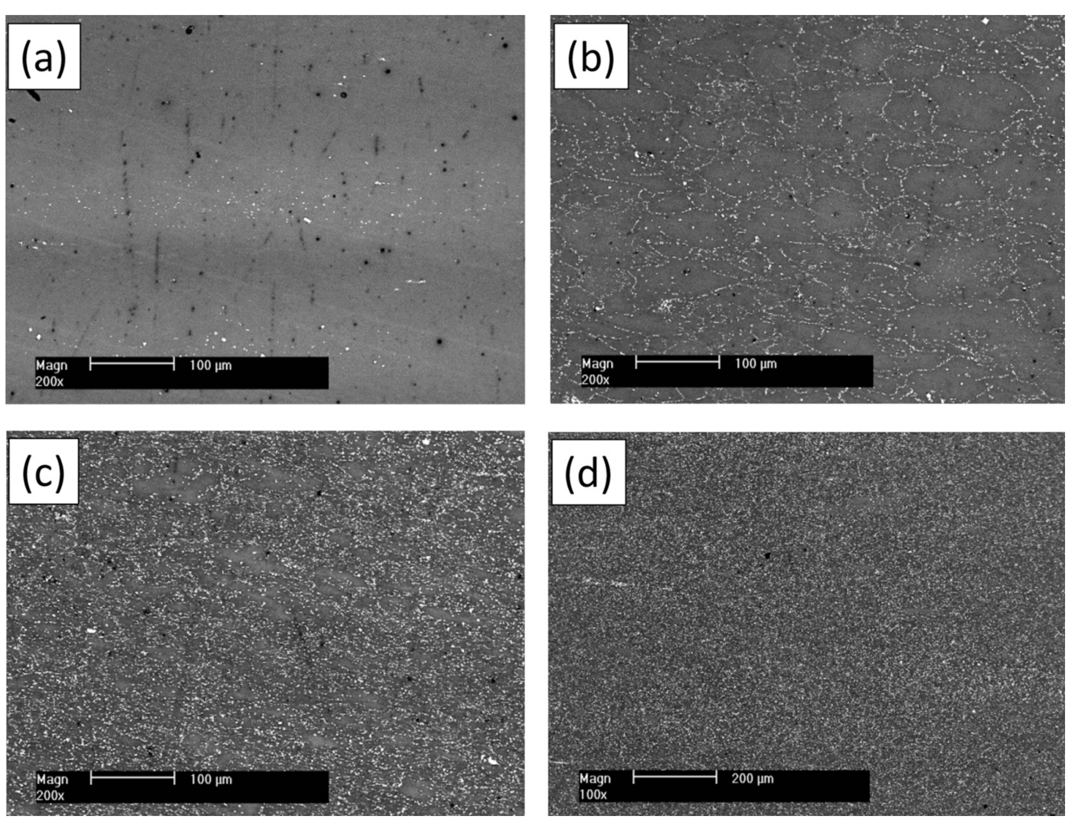

Fig. 6. SEM in orientation perpendicular to the plate final compressed at different temperature: (a) 500 °C (b) 470 °C (c) 440 °C (d) 410 °C.

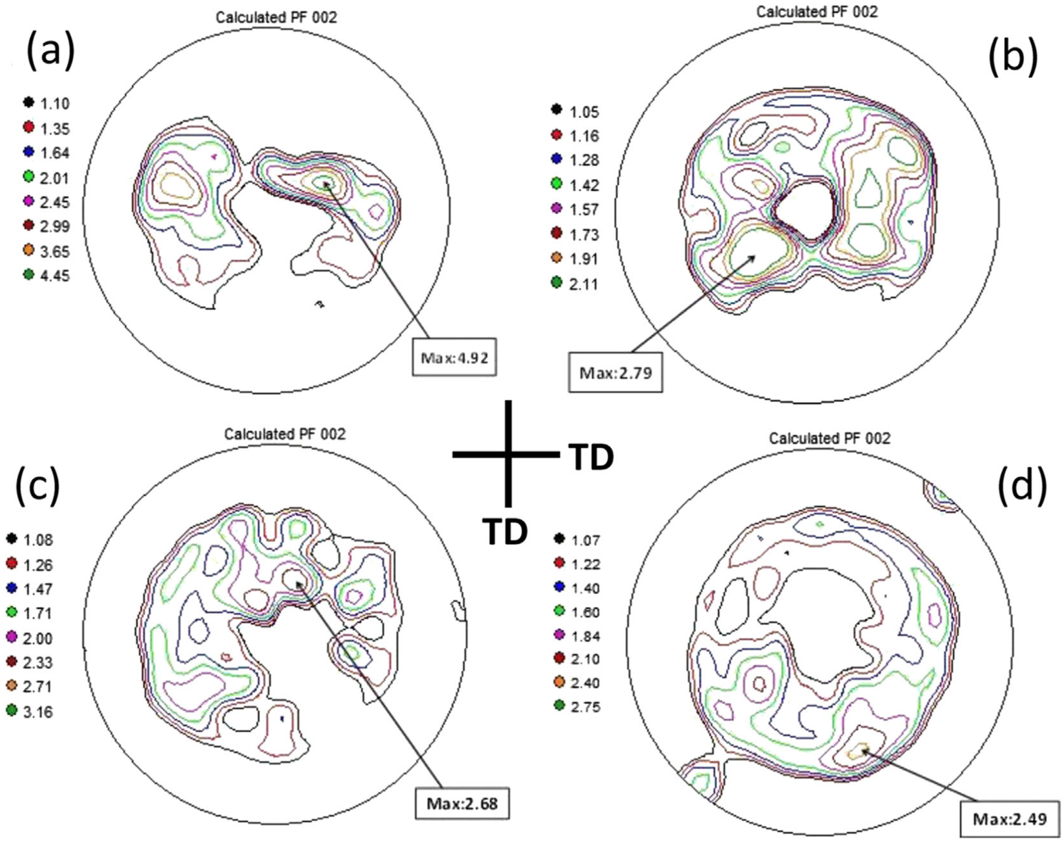

Fig. 7. (0002) Pole figures of the plate final compressed at different temperature: (a) 500 °C, (b) 470 °C, (c) 440 °C, (d) 410 °C.

fact the deformed grains with precipitates along its boundaries.

3.3. Texture evolution

The (0002) pole figures in Fig. 7 shows the texture of the plate final compressed at 500 °C, 470 °C, 440 °C and 410 °C respectively. It can be seen the basal plane pole have an inclination about 40° from the normal direction of the plate and the inclination increased with decreasing forging temperature, suggesting that the grain orientation became more dispersed. In addition, the max-value of texture intensity was relatively low, so the alloys exhibit a weak texture after multi-directional forging. Recrystallization can be the reason for the weak texture of the samples when compressed from 500 °C to 470 °C, and the texture intensity decreased sharply from 4.92 to 2.79. In comparison with coarse recrystallization grains obtained at 500 °C, the finer and more uniform structure was obtained at 470 °C as a result of restriction of grain growth by precipitates, and the precipitates could prevent the grain rotation by inhibiting grain boundary sliding or lock grain boundaries during deformation, avoiding the formation of the deformation textures [10]. There is no recrystallization at 440 °C and 410 °C, but the maximum values of the texture intensity continue decreased, so the weak texture could be ascribe to the increased forging passes, which means that the changed load direction make more dispersed grain orientation [11].

3.4. Mechanical properties

The ambient mechanical properties of the solutionized samples and samples compressed at different temperatures were presented in Fig. 8. As shown in Fig. 8a, after forging and final compression, the samples have a remarkably improvement in its mechanical properties compared with the solutionized alloys. As shown in Fig. 8b, both the UTS and YS increased with decreasing forging temperature. The best ductility of 21% reached at 470 °C, which is increased by 200% in comparison with the solutionized condition of 1%, and the fine recrystallization grains, weak texture contributed to its excellent ductility. Fig. 9 shows the fracture to failure of these tensile specimens. At solutionized condition, the brittle fracture was the main characteristic because of coarse grains, which was the same with the specimens compressed at 500 °C as a result of coarse recrystallization grains. Ductile fracture was the key mechanism to failure in tensile specimens compressed at 470 °C, and the fine dimples indicated a good ductility of these samples [12]. There is an obvious decrease in ductility of these samples compressed at 440 °C and 410 °C, because too many precipitates restricted recrystallization which result in a sever deformed microstructure with a high level of residual stress. The micro-crack generated easily from these coarse particles, and as a result of high volume of precipitates, too many micro-cracks initiated from these precipitates and connected to each other till the formation of the macro-cleavage [13]. It is the residual stress and high volume

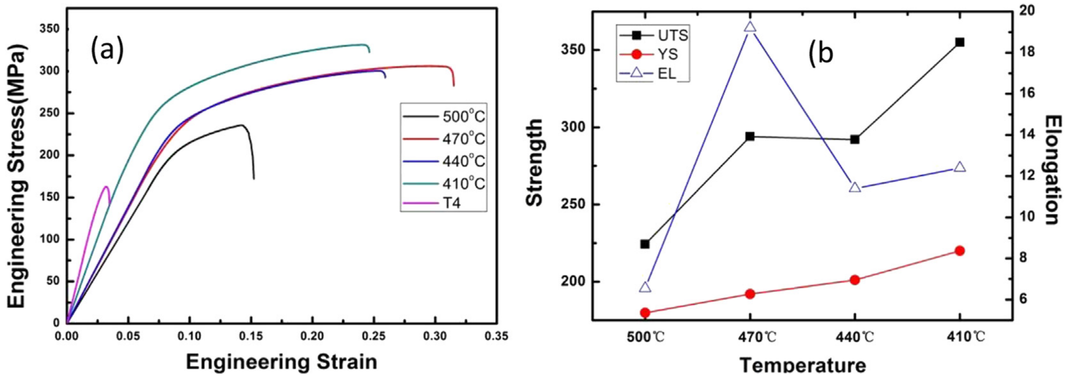

Fig. 8. Tensile properties of EW75 alloys at solutionized condition and final compressed at different temperatures: (a) tensile curves of samples at different state (b) comparison of the mechanical properties.

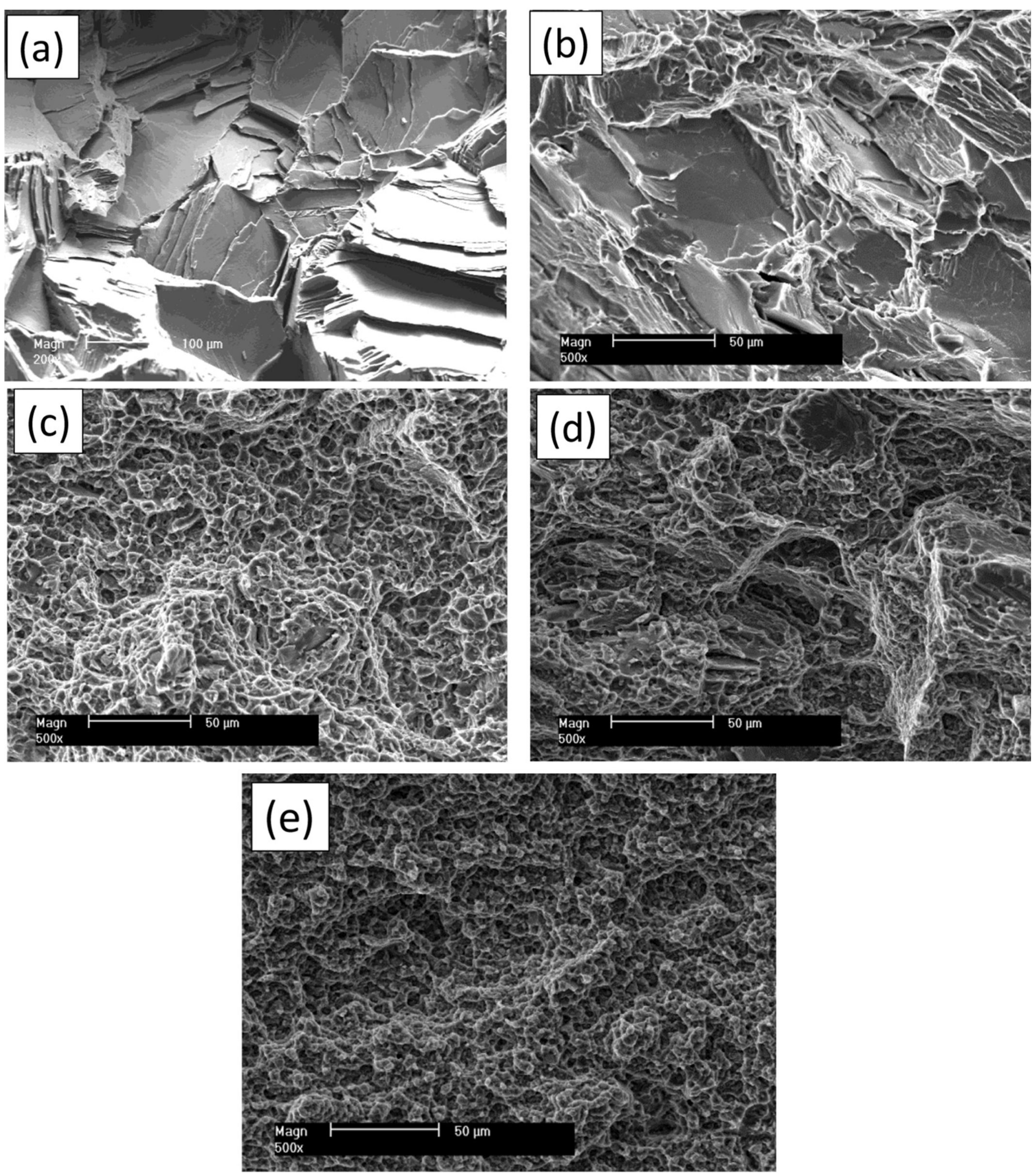

Fig. 9. Fracture appearance of tensile specimens at solutionized condition (a) and final compressed at (b) 500 °C, (c) 470 °C, (d) 440 °C and (e) 410 °C.

of precipitates deteriorating the ductility of the samples forged and compressed at lower temperature [14].

4. Conclusions

(1) Due to the precipitation of high volume of fine particles, only deformed stream-lines could be observed when the samples were compressed at 410 °C and 440 °C.
(2) Fine microstructure has formed when compressed at 470 °C because of the grain growth was restricted by the precipitates. The EBSD results revealed that the grains have been refined to 15um, and the high proportion of high angle grain boundary indicated a fully recrystallization structure.
(3) The texture intensity gets weaker during the MDF process, resulting in a high Schmid factor for basal slip when the tension is tested in direction parallel to the final compressed plate.
(4) The highest ductility of 21% was obtained when the sample was compressed at 470 °C, which is increased by 200%, in comparison with that of the initial solutionized sample. The excellent ductility of the sample can be attributed to its fine recrystallization grains and weak texture.

Acknowledgments

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