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The effect of continuous confined strip shearing deformation on the mechanical properties of AZ31 magnesium alloys

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Abstract

Continuous confined strip shearing deformation (CCSS) was conducted on AZ31 magnesium alloys. The microstructure and texture were modified and special inclined basal texture was obtained through different routes. The newly formed basal texture was favor for the basal slip which brought about lower micro-hardness and yield strength but higher elongation. The strong tensile-compression asymmetry in the base material was weakened because basal slip was the dominating deformation mechanism both in tensile and compression tests. Meanwhile, {10-12} twinning was suppressed because of easier activation of basal slip. The strain hardening behavior was also changed and the strain hardening rate almost decreased along the whole deformation process; and only a slight increase was found at the stage2 of route A in tensile test. The strain hardening exponents were scattered from different stages due to the specific deformation mechanism at each stage.

Keywords: Continuous confined strip shearing; Basal texture; Mechanical properties; Strain hardening behavior

1. Introduction

Magnesium (Mg) and its alloys have attracted great interest due to their low density and high specific strength [1]. However, the poor cold-formability, due to the limited slip systems at room temperature, limited their application in industry [2]. Thus how to improve the formability at room temperature becomes a critical question for the application of Mg alloys. It was frequently reported that grain refinement and texture weakening were effective way to improve the ductility of Mg alloys [3-6]. Many thermo-mechanical processes have been tried on Mg alloys to modify the microstructure and texture, such as friction stir processing (FSP) [7], cross shear rolling (CSR) [8], as well as equal channel angular pressing (ECAP) [9].

ECAP was believed to be a good SPD (several plastic deformation) method which could control both the grain size and texture distribution of Mg alloys [10,11]. Dynamic recrystallization (DRX) usually dominated and caused grain refinement during ECAP, and the grain size could be designed from submicron-scale to micron-scale by adjusting processing parameters, such as temperature, strain rate and quantities passes [12,13]. On the other hand, basal texture was usually changed due to the shearing at the position of channel intersection. Different types of texture component could be obtained by varying processing routes [14]. In this way, mechanical properties could be

improved significantly due to the grain refinement and texture modification [15,16]. However, the ECAP method was not suitable for practical manufacture because it could not do extrusion in a continuous or even semi-continuous way. Recently [17,18], a new processing method: continuous confined strip shearing deformation (CCSS) had been put forward to overcome the drawback, and was successfully applied in many metals, such as aluminum (Al) alloys [19] and steel [20]. Nevertheless, the application of CCSS on Mg and its alloys was scarcely studied, and the effect of CCSS on the microstructure, texture and mechanical properties of Mg alloys remain unclear.

In this study, in order to investigate the effect of CCSS on Mg alloys, the CCSS was conducted on the hot-extruded AZ31 bars with different routes. The microstructure and texture were characterized by the optical microscope and X-ray diffraction. The micro-hardness, tensile and compression properties were measured to investigate the relationship between the microstructure, texture and mechanical properties. The strain hardening behavior was discussed to reveal the deformation mechanism at different condition.

2. Experiment procedures

The material used in this article was commercial hot-extruded AZ31 Mg alloys with the nominal composition of 3%Al, 1%Zn and balance Mg. The original rods were machined into bars with the dimensions of $\Phi 20\text{mm} \times 100\text{mm}$. Before CCSS, the bars and extrusion die were preheated at 400°C for 1 hour. Then CCSS was carried out on the continuous extrusion machine with an oblique angle of 110° and the simple diagram was showed in Fig. 1a. Each bar was processed with two passes with the different route at the second pass, as shown in Fig. 1b. The bar of route A was processed with no rotation between two passes while the bars of route B and C were processed with 180° and 90° rotation between two passes respectively. The interval between two passes was minor and these samples after CCSS were termed as CCSS-A, CCSS-B and CCSS-C.

Microstructure was observed by optical microscope on the ED-TD (Extrusion direction-Transverse direction) plane. The samples were grounded mechanically, polishing and etching with a solution of picric-acetic. Panalytical X-ray diffractometer, equipped with a closed Eulerian cradle in Schulz reflection geometry, was applied to measure the macro-texture evolution during CCSS on ED-TD plane. The micro-hardness was measured on ED-TD plane for all samples with 300g for 10s. Tensile samples were machined along ED with a gauge length of 27mm and a gauge diameter of 4mm according to ASTM E8 standards. And the compression samples were also machined along ED with a dimensions of $\Phi 8\text{mm} \times 10\text{mm}$. Tensile and compression tests were conducted at room temperature with a strain rate of 0.001/s.

3. Results and discussion

3.1 The microstructure and texture evolution during CCSS

Fig. 1c showed the bars after CCSS with one and two passes, respectively. It was clearly seen that the bars stayed intact and the metallic luster was retained though some micro crack and oxidation were found at the surface of the bar with two passes due to the high temperature during CCSS. The microstructure of the base material (BM) and the bars for different routes were showed in Fig. 2.

The original bars showed inhomogeneous grains with the grain size ranging from $5\mu\text{m}$ - $75\mu\text{m}$.

After CCSS, the grains were refined by the dynamic recrystallization (DRX) [21,22] due to the shearing deformation and high temperature during CCSS. Meanwhile the effectiveness of grain refinement was diverse from each other. The CCSS-B showed the smallest grains, but the microstructure was more inhomogeneous. A lot of small grains were found distributing diffusely between the big grains which indicated that the DRX was not sufficient for CCSS-B. For CCSS-A and CCSS-C, the grains were quite uniform with an average grain size of 15 μ m and 10 μ m respectively. In brief, the grains were refined during CCSS through DRX and these bars showed varying microstructure due to the different deformation process.

In order to investigate the effect of shearing deformation on the texture during CCSS, firstly, XRD measurement was conducted on samples before and after CCSS, as shown in Fig. 3a. The characteristic peaks of (10-10), (0002) and (10-11) planes were marked on diffraction patterns. The intensity of each peak both before and after CCSS were measured and plotted in Fig. 3b. It could be seen that the (0002) plane of the BM had extreme high intensity while the intensity of (10-10) and (10-11) planes were relatively low. After CCSS, it was hard to see evident (0002) peaks for all samples. This means that the basal planes were heavily rotated away from its original orientation, which was nearly paralleled to the ED-TD plane. On the other hand, the intensity of (10-10) and (10-11) planes all increased after Route A, B, C. In order to reveal the texture evolution during CCSS in more details, (0002) and (10-10) pole figures were measured by X-ray diffractometer.

It could be seen that the original bar owned a typical $\langle 10\text{-}10 \rangle$ /ED texture prior to CCSS. Such texture was changed after CCSS. There was only one strong (0002) peak for CCSS-A, and the (0002) poles inclined about 60° from ND (paper normal direction) to ED-TD plane. For CCSS-B and CCSS-C, two or three strong (0002) poles were found in the pole figures with similar inclining angle-(60° from ND to ED-TD plane). It should be also noted that the (0002) poles for CCSS-B and CCSS-C showed central and mirror symmetry respectively.

As shown in fig. 5, the schematic diagram of the crystal orientation was drawn to reveal the specific crystal transition during CCSS. Before entering into the shearing deformation zone (SDZ), the crystal orientation was almost unchanged. When passing SDZ, the shearing deformation and the crystal orientation occurred simultaneously. The (0002) planes deviated from the axial direction of the bar gradually. Thus the inclined (0002) basal texture came into being after CCSS. The (0002) pole inclined to one direction when there was no rotation between the two passes for CCSS-A. For CCSS-B and CCSS-C, lattice rotation was different between the two passes. As a result, the center and mirror symmetric poles were obtained for route B and route C due to the 180° and 90° rotation between the two passes, respectively.

3.2 The effect of microstructure and texture on the mechanical properties

As state above, the microstructure and texture had experienced huge changes during CCSS which would had great effect on the mechanical properties. Thus, the micro-hardness measurement, uniaxial tensile and compression tests were conducted on the samples before and after CCSS to study the effect of these changes on the mechanical properties.

Fig. 6 showed the variation of micro-hardness on the ED-TD plane. The micro-hardness of the BM and CCSS-A, B, C were 51HV, 45HV, 49HV and 44HV respectively. Interestingly, the

micro-hardness of the samples after CCSS was even lower than BM though the grains were refined during CCSS. Generally speaking, the micro-hardness would be higher due to the refinement strengthening effect. However, the universal law was not applicable here. As we had reported [23], the crystal orientation also had great effect on the micro-hardness due to different deformation mechanism at different crystal orientation. The micro-hardness was the highest when micro-hardness was measured on the (0002) plane of a single crystal. With the increase of the angle between $\langle 0001 \rangle$ and loading direction, the micro-hardness decreased firstly, then increased slightly. Since the BM showed $\langle 10\text{-}10 \rangle$ //ED texture, the micro-hardness would be high when testing on ED-TD plane. After CCSS, the $\langle 10\text{-}10 \rangle$ //ED texture was changed and inclined basal texture was obtained due to the shearing deformation during CCSS, as shown in Fig. 3 and Fig. 4. As there was a high angle (about 60°) between ND and ED-TD plane, the Schmid factor for basal slip increased significantly. Consequently when measuring micro-hardness on ED-TD planes, the loading direction was in soft orientation where the grains were favor for basal slip. Thus, after CCSS, the micro-hardness was slightly lower than the BM though the grains were refined.

The tensile true stress-strain curves of the samples before and after CCSS were showed in Fig. 7a. The yield strength of the BM was 207MPa and it decreased significantly after CCSS. The yield strength of CCSS-A, B, C, which showed small deviation (78MPa, 80MPa and 83 MPa respectively), was only about 39% of that of the BM. In addition, the ultimate tensile strength of the BM was also slightly higher than that of CCSS-A, B, C. Fortunately, the elongation had a significant improvement after CCSS, from around 15% for BM and 30% for CCSS-A. Furthermore, compression tests were also conducted on samples before and after CCSS along ED, as shown in Fig. 7b. The yield strength and ultimate tensile strength of the BM were all higher than that of CCSS-A, B, C while the elongation was improved significantly, as that in tensile test. Clearly the BM showed the typical concave characteristic. However, this feature disappeared after CCSS.

Considering the difference in the tensile and compression behaviors, the deformation mechanism should be different for BM and CCSS-A during tensile and compression tests. As shown in Fig. 4a, the BM owned a typical $\langle 10\text{-}10 \rangle$ //ED texture. Basal slip and $\{10\text{-}12\}$ twinning were suppressed during tensile test due to low Schmid factors. Thus, prismatic slip and $\{10\text{-}11\}$ twinning would be the main deformation mechanisms resulting in a high yield strength and low elongation [24]. During compression, the grains had a high Schmid factor for $\{10\text{-}12\}$ twinning, so the yield strength of the BM was low during compression test and a typical $\{10\text{-}12\}$ twinning related concave stress-strain curve was obtained [25,26]. The value of the YS-T/YS-C (yield strength for tensile/compression test) was also calculated, as shown in Fig. 8. The value of BM was extremely high which showed a strong tensile-compression asymmetry in the BM.

After CCSS, the texture was modified due to shearing in CCSS. The newly formed inclined (0002) basal texture was favor for basal slip both in tensile and compression tests, so the yield strength of CCSS-A, B, C had a low value and small difference existed between tensile and compression tests. The values of YS-T/YS-C were almost equal to 1 which indicated that the strong tensile-compression asymmetry in BM was weakened significantly due to the texture modification. According to the previous studies [27,28], the CRSS of basal slip was smaller than that of $\{10\text{-}12\}$ twinning, so the yield strength of CCSS-A,B,C was lower than that of the BM during compression test. In addition, the activation of basal slip could accommodate more plastic deformation during

straining, so the elongation of CCSS-A, B, C was higher than BM. However some difference was still observed for elongation for CCSS-A, B, C, and the CCSS-C had the lowest elongation. It seemed that the inclined basal texture with mirror symmetry, as found in CCSS-B, was adverse to accommodate greater plasticity compared with others obtained in CCSS-A and B.

3.3 The effect of CCSS on the strain hardening behavior

In order to investigate the strain hardening behavior, the strain hardening rate (SHR) $\theta = d\sigma/d\varepsilon$ was calculated for tensile (SHR-T) and compression tests (SHR-C) of the BM and CCSS-A, as shown in Fig. 9. It could be seen that the SHR decreased sharply at the first stage due to narrow elastoplastic transition both in tensile and compression test. It was interesting that, for the BM, the SHR-T decreased to fracture at the stage2 while three stages were observed in compression test. The SHR-C increased from 1144MPa to 3477MPa at the stage2 and decreased at the stage3. As described in section 3.1, the BM owned a $\langle 10\text{-}10 \rangle // \text{ED}$ texture. During compression, extensive $\{10\text{-}12\}$ twins were formed in original grains, such twin boundaries could separate matrix into many sub-zones and thus reduced the effective slip distance of dislocation which contributed to a increase in SHR[29]. On the other hand, the crystal orientation would rotate from soft orientation into a hard orientation after $\{10\text{-}12\}$ twinning. This brought about significant texture strengthening effect which led to an increase in SHR [25]. In this way such $\{10\text{-}12\}$ twinning related texture modification also played an important role in the increased SHR-C at stage2. $\{10\text{-}12\}$ twinning was thus believed to be responsible for the increased SHR-C of BM in stage2.

After CCSS, the SHR-T and SHR-C showed three and two stages respectively which was inverse to that of BM. The typical $\langle 10\text{-}10 \rangle // \text{ED}$ texture of BM was modified during CCSS and an inclined (0002) basal texture formed in the samples where the grains was favor for basal slip. However the (0002) basal texture was not ideal, some grains were still in a favorable orientation for $\{10\text{-}12\}$ twinning. Thus SHR-T had three stages and the $\{10\text{-}12\}$ twinning related refinement strengthening and texture strengthening was reflected in the increase of SHR in the stage2. Nevertheless, the volume fraction of grains favoring $\{10\text{-}12\}$ twinning was so small that the SHR-T increased slightly at a small strain range. During compression test, the SHR-C decreased to fracture although some grains were favor for $\{10\text{-}12\}$ twinning. The $\{10\text{-}12\}$ twinning related increment in SHR would be compensated by basal slip induced softening because the frequency of $\{10\text{-}12\}$ twinning was small. Therefore, the deformation in tensile and compression test of CCSS-A was principally dominated by the basal slip due to the texture modification during CCSS.

On the other hand, the $\ln\sigma - \ln\varepsilon$ (L-L) curves were also plotted in Fig. 10 according to the Homollon equation $\sigma = k\varepsilon^n$. The slopes of curves were strain hardening exponent (SHE) n . The SHE of each stage was fit and plotted in Fig. 10c. Similar to the SHR curves, the L-L curves could also be divided into two or three stages, that was, the value of SHE at different stage was different. It should be noted there was a one-to-one correspondence between these stages during the L-L curves and the SHR curves (Fig 9). For example, two stages were found in the SHR curve of the BM in tensile test, the L-L curve was also divided into two stages. Thus different deformation mechanism would responsible for the difference in SHE at each stage.

The SHE at the stage1 had relatively high values which corresponded to the elastic deformation where the value of SHE was 1 in theory. At the stage2, the values of SHE had a great reduction for the BM and CCSS-A in tensile and compression tests. They showed considerable difference.

Firstly, for these curves with two stages (BM-T, CCSS-A-C), the SHE of BM in tensile test was only 0.14 due to the limited slip systems. After CCSS, the modified (0002) basal texture was in favor for basal slip, so the SHE was still maintained at a high value of 0.44 due to the activation of abundant basal dislocation. Secondly, the curves with three stages (CCSS-A-T, BM-C), the SHE of the stage2 was much lower than that of the other two stages. As stated above, {10-12} twinning had played a dominated role during stage2 for BM-C and CCSS-A-T, a small number of dislocations would come into being in matrix during this stage and brought about low strain hardening. Consequently the value of SHE in the stage2 was much lower than that of the other two stages. In addition, the SHE of BM-C was higher than that of CCSS-T, the stronger {10-12} twinning related refinement strengthening and texture strengthening for BM-C would be the primary reason.

Finally, for the stage3 (only for CCSS-A-T and BM-C), the values of SHE increased significantly which was almost equal to that of stage1 (elastic deformation). It seemed that there was ultra-strong strain hardening in this stage. During tensile test, basal slip was activated and generated abundant basal dislocation in the CCSS-A which would be the primary reason of the high value of SHE. And for the BM in compression, the grains were in hard orientation due to the {10-12} twinning related crystal orientation rotation at the stage2. Basal slip would thus be suppressed in this stage. However, at the stage3, the stress increased to a high level which could surpass the critical stress to activate $\bar{c} + \bar{a}$ slip [30]. Therefore, the activation of multiple dislocation slip generated abundant dislocation and the dislocation accumulation brought about a high SHE in the stage3 for the BM and CCSS-A.

4. Conclusion

In summary, CCSS was conducted on hot-extruded AZ31 Mg alloys with different routes. Original grains were effectively refined and the morphology of different routes were different from each other. Texture was modified due to the shearing deformation and the (0002) basal planes inclined from ND to the ED-TD plane. The (0002) basal texture inclined to one direction for route A while a centrosymmetric pole figure and a mirror symmetric pole figure were obtained for route B and C respectively. The rotation of the bars between the two passes was responsible for the special texture component.

The micro-hardness had a slightly reduction after CCSS due to texture modification. The newly formed basal texture was in favor for the activation of basal slip during tensile and compression. Thus the elongation was improved significantly accompanied by a decrease in yield strength. In addition, the strong tensile-compression asymmetry in the BM was weakened due to the activation of basal slip during in mechanical tests. The strain hardening behavior could be divided into different stages due to the special deformation mechanism. The {10-12} twinning related increase in SHR was subdued due to the widespread activation of basal slip. At the stage3, abundant dislocation were generated due to the activation of multiple dislocation slip systems and brought about a high SHE at the stage3.

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Abstract

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Keywords: Continuous confined strip shearing; Basal texture; Mechanical properties; Strain hardening behavior

1. Introduction

Magnesium (Mg) and its alloys have attracted great interest due to their low density and high specific strength [1]. However, the poor cold-formability, due to the limited slip systems at room temperature, limited their application in industry [2]. Thus how to improve the formability at room temperature becomes a critical question for the application of Mg alloys. It was frequently reported that grain refinement and texture weakening were effective way to improve the ductility of Mg alloys [3-6]. Many thermo-mechanical processes have been tried on Mg alloys to modify the microstructure and texture, such as friction stir processing (FSP) [7], cross shear rolling (CSR) [8], as well as equal channel angular pressing (ECAP) [9].

ECAP was believed to be **a good SPD (several plastic deformation)** method which could control both the grain size and texture distribution of Mg alloys [10,11]. Dynamic recrystallization (DRX) **usually** dominated and caused grain refinement during ECAP, and the grain size could be designed from **submicron-scale to micron-scale by adjusting** processing parameters, such as temperature, strain rate and quantities passes [12,13]. On the other hand, **basal** texture was **usually** changed due to the shearing at the position of channel intersection. Different types of texture component could be obtained by varying processing routes [14]. **In this way**, mechanical properties could be

improved significantly due to the grain refinement and texture modification [15,16]. However, the ECAP method was not suitable for practical manufacture because it could not do extrusion in a continuous or even semi-continuous way. Recently [17,18], a new processing method: continuous confined strip shearing deformation (CCSS) had been put forward to overcome the drawback, and was successfully applied in many metals, such as aluminum (Al) alloys [19] and steel [20]. Nevertheless, the application of CCSS on Mg and its alloys was scarcely studied, and the effect of CCSS on the microstructure, texture and mechanical properties of Mg alloys remain unclear.

In this study, in order to investigate the effect of CCSS on Mg alloys, the CCSS was conducted on the hot-extruded AZ31 bars with different routes. The microstructure and texture were characterized by the optical microscope and X-ray diffraction. The micro-hardness, tensile and compression properties were measured to investigate the relationship between the microstructure, texture and mechanical properties. The strain hardening behavior was discussed to reveal the deformation mechanism at different condition.

2. Experiment procedures

The material used in this article was commercial hot-extruded AZ31 Mg alloys with the nominal composition of 3%Al, 1%Zn and balance Mg. The original rods were machined into bars with the dimensions of $\Phi 20\text{mm} \times 100\text{mm}$. Before CCSS, the bars and extrusion die were preheated at 400°C for 1 hour. Then CCSS was carried out on the continuous extrusion machine with an oblique angle of 110° and the simple diagram was showed in Fig. 1a. Each bar was processed with two passes with the different route at the second pass, as shown in Fig. 1b. The bar of route A was processed with no rotation between two passes while the bars of route B and C were processed with 180° and 90° rotation between two passes respectively. The interval between two passes was minor and these samples after CCSS were termed as CCSS-A, CCSS-B and CCSS-C.

Microstructure was observed by optical microscope on the ED-TD (Extrusion direction-Transverse direction) plane. The samples were grounded mechanically, polishing and etching with a solution of picric-acetic. Panalytical X-ray diffractometer, equipped with a closed Eulerian cradle in Schulz reflection geometry, was applied to measure the macro-texture evolution during CCSS on ED-TD plane. The micro-hardness was measured on ED-TD plane for all samples with 300g for 10s. Tensile samples were machined along ED with a gauge length of 27mm and a gauge diameter of 4mm according to ASTM E8 standards. And the compression samples were also machined along ED with a dimensions of $\Phi 8\text{mm} \times 10\text{mm}$. Tensile and compression tests were conducted at room temperature with a strain rate of 0.001/s.

3. Results and discussion

3.1 The microstructure and texture evolution during CCSS

Fig. 1c showed the bars after CCSS with one and two passes, respectively. It was clearly seen that the bars stayed intact and the metallic luster was retained though some micro crack and oxidation were found at the surface of the bar with two passes due to the high temperature during CCSS. The microstructure of the base material (BM) and the bars for different routes were showed in Fig. 2.

The original bars showed inhomogeneous grains with the grain size ranging from $5\mu\text{m}$ - $75\mu\text{m}$.

After CCSS, the grains were refined by the dynamic recrystallization (DRX) [21,22] due to the shearing deformation and high temperature during CCSS. Meanwhile the effectiveness of grain refinement was diverse from each other. The CCSS-B showed the smallest grains, but the microstructure was more inhomogeneous. A lot of small grains were found distributing diffusely between the big grains which indicated that the DRX was not sufficient for CCSS-B. For CCSS-A and CCSS-C, the grains were quite uniform with an average grain size of 15 μ m and 10 μ m respectively. In brief, the grains were refined during CCSS through DRX and these bars showed varying microstructure due to the different deformation process.

In order to investigate the effect of shearing deformation on the texture during CCSS, firstly, XRD measurement was conducted on samples before and after CCSS, as shown in Fig. 3a. The characteristic peaks of (10-10), (0002) and (10-11) planes were marked on diffraction patterns. The intensity of each peak both before and after CCSS were measured and plotted in Fig. 3b. It could be seen that the (0002) plane of the BM had extreme high intensity while the intensity of (10-10) and (10-11) planes were relatively low. After CCSS, it was hard to see evident (0002) peaks for all samples. This means that the basal planes were heavily rotated away from its original orientation, which was nearly paralleled to the ED-TD plane. On the other hand, the intensity of (10-10) and (10-11) planes all increased after Route A, B, C. In order to reveal the texture evolution during CCSS in more details, (0002) and (10-10) pole figures were measured by X-ray diffractometer.

It could be seen that the original bar owned a typical <10-10>||ED texture prior to CCSS. Such texture was changed after CCSS. There was only one strong (0002) peak for CCSS-A, and the (0002) poles inclined about 60° from ND (paper normal direction) to ED-TD plane. For CCSS-B and CCSS-C, two or three strong (0002) poles were found in the pole figures with similar inclining angle-(60° from ND to ED-TD plane). It should be also noted that the (0002) poles for CCSS-B and CCSS-C showed central and mirror symmetry respectively.

As shown in fig. 5, the schematic diagram of the crystal orientation was drawn to reveal the specific crystal transition during CCSS. Before entering into the shearing deformation zone (SDZ), the crystal orientation was almost unchanged. When passing SDZ, the shearing deformation and the crystal orientation occurred simultaneously. The (0002) planes deviated from the axial direction of the bar gradually. Thus the inclined (0002) basal texture came into being after CCSS. The (0002) pole inclined to one direction when there was no rotation between the two passes for CCSS-A. For CCSS-B and CCSS-C, lattice rotation was different between the two passes. As a result, the center and mirror symmetric poles were obtained for route B and route C due to the 180° and 90° rotation between the two passes, respectively.

3.2 The effect of microstructure and texture on the mechanical properties

As state above, the microstructure and texture had experienced huge changes during CCSS which would had great effect on the mechanical properties. Thus, the micro-hardness measurement, uniaxial tensile and compression tests were conducted on the samples before and after CCSS to study the effect of these changes on the mechanical properties.

Fig. 6 showed the variation of micro-hardness on the ED-TD plane. The micro-hardness of the BM and CCSS-A, B, C were 51HV, 45HV, 49HV and 44HV respectively. Interestingly, the

micro-hardness of the samples after CCSS was even lower than BM though the grains were refined during CCSS. Generally speaking, the micro-hardness would be higher due to the refinement strengthening effect. However, the universal law was not applicable here. As we had reported [23], the crystal orientation also had great effect on the micro-hardness due to different deformation mechanism at different crystal orientation. The micro-hardness was the highest when micro-hardness was measured on the (0002) plane of a single crystal. With the increase of the angle between $\langle 0001 \rangle$ and loading direction, the micro-hardness decreased firstly, then increased slightly. Since the BM showed $\langle 10\text{-}10 \rangle$ //ED texture, the micro-hardness would be high when testing on ED-TD plane. After CCSS, the $\langle 10\text{-}10 \rangle$ //ED texture was changed and inclined basal texture was obtained due to the shearing deformation during CCSS, as shown in Fig. 3 and Fig. 4. As there was a high angle (about 60°) between ND and ED-TD plane, the Schmid factor for basal slip increased significantly. Consequently when measuring micro-hardness on ED-TD planes, the loading direction was in soft orientation where the grains were favor for basal slip. Thus, after CCSS, the micro-hardness was slightly lower than the BM though the grains were refined.

The tensile true stress-strain curves of the samples before and after CCSS were showed in Fig. 7a. The yield strength of the BM was 207MPa and it decreased significantly after CCSS. The yield strength of CCSS-A, B, C, which showed small deviation (78MPa, 80MPa and 83 MPa respectively), was only about 39% of that of the BM. In addition, the ultimate tensile strength of the BM was also slightly higher than that of CCSS-A, B, C. Fortunately, the elongation had a significant improvement after CCSS, from around 15% for BM and 30% for CCSS-A. Furthermore, compression tests were also conducted on samples before and after CCSS along ED, as shown in Fig. 7b. The yield strength and ultimate tensile strength of the BM were all higher than that of CCSS-A, B, C while the elongation was improved significantly, as that in tensile test. Clearly the BM showed the typical concave characteristic. However, this feature disappeared after CCSS.

Considering the difference in the tensile and compression behaviors, the deformation mechanism should be different for BM and CCSS-A during tensile and compression tests. As shown in Fig. 4a, the BM owned a typical $\langle 10\text{-}10 \rangle$ //ED texture. Basal slip and $\{10\text{-}12\}$ twinning were suppressed during tensile test due to low Schmid factors. Thus, prismatic slip and $\{10\text{-}11\}$ twinning would be the main deformation mechanisms resulting in a high yield strength and low elongation [24]. During compression, the grains had a high Schmid factor for $\{10\text{-}12\}$ twinning, so the yield strength of the BM was low during compression test and a typical $\{10\text{-}12\}$ twinning related concave stress-strain curve was obtained [25,26]. The value of the YS-T/YS-C (yield strength for tensile/compression test) was also calculated, as shown in Fig. 8. The value of BM was extremely high which showed a strong tensile-compression asymmetry in the BM.

After CCSS, the texture was modified due to shearing in CCSS. The newly formed inclined (0002) basal texture was favor for basal slip both in tensile and compression tests, so the yield strength of CCSS-A, B, C had a low value and small difference existed between tensile and compression tests. The values of YS-T/YS-C were almost equal to 1 which indicated that the strong tensile-compression asymmetry in BM was weakened significantly due to the texture modification. According to the previous studies [27,28], the CRSS of basal slip was smaller than that of $\{10\text{-}12\}$ twinning, so the yield strength of CCSS-A,B,C was lower than that of the BM during compression test. In addition, the activation of basal slip could accommodate more plastic deformation during

straining, so the elongation of CCSS-A, B, C was higher than BM. However some difference was still observed for elongation for CCSS-A, B, C, and the CCSS-C had the lowest elongation. It seemed that the inclined basal texture with mirror symmetry, as found in CCSS-B, was adverse to accommodate greater plasticity compared with others obtained in CCSS-A and B.

3.3 The effect of CCSS on the strain hardening behavior

In order to investigate the strain hardening behavior, the strain hardening rate (SHR) $\theta = d\sigma/d\varepsilon$ was calculated for tensile (SHR-T) and compression tests (SHR-C) of the BM and CCSS-A, as shown in Fig. 9. It could be seen that the SHR decreased sharply at the first stage due to narrow elastoplastic transition both in tensile and compression test. It was interesting that, for the BM, the SHR-T decreased to fracture at the stage2 while three stages were observed in compression test. The SHR-C increased from 1144MPa to 3477MPa at the stage2 and decreased at the stage3. As described in section 3.1, the BM owned a $\langle 10\text{-}10 \rangle // \text{ED}$ texture. During compression, extensive $\{10\text{-}12\}$ twins were formed in original grains, such twin boundaries could separate matrix into many sub-zones and thus reduced the effective slip distance of dislocation which contributed to a increase in SHR[29]. On the other hand, the crystal orientation would rotate from soft orientation into a hard orientation after $\{10\text{-}12\}$ twinning. This brought about significant texture strengthening effect which led to an increase in SHR [25]. In this way such $\{10\text{-}12\}$ twinning related texture modification also played an important role in the increased SHR-C at stage2. $\{10\text{-}12\}$ twinning was thus believed to be responsible for the increased SHR-C of BM in stage2.

After CCSS, the SHR-T and SHR-C showed three and two stages respectively which was inverse to that of BM. The typical $\langle 10\text{-}10 \rangle // \text{ED}$ texture of BM was modified during CCSS and an inclined (0002) basal texture formed in the samples where the grains was favor for basal slip. However the (0002) basal texture was not ideal, some grains were still in a favorable orientation for $\{10\text{-}12\}$ twinning. Thus SHR-T had three stages and the $\{10\text{-}12\}$ twinning related refinement strengthening and texture strengthening was reflected in the increase of SHR in the stage2. Nevertheless, the volume fraction of grains favoring $\{10\text{-}12\}$ twinning was so small that the SHR-T increased slightly at a small strain range. During compression test, the SHR-C decreased to fracture although some grains were favor for $\{10\text{-}12\}$ twinning. The $\{10\text{-}12\}$ twinning related increment in SHR would be compensated by basal slip induced softening because the frequency of $\{10\text{-}12\}$ twinning was small. Therefore, the deformation in tensile and compression test of CCSS-A was principally dominated by the basal slip due to the texture modification during CCSS.

On the other hand, the $\ln\sigma - \ln\varepsilon$ (L-L) curves were also plotted in Fig. 10 according to the Homollon equation $\sigma = k\varepsilon^n$. The slopes of curves were strain hardening exponent (SHE) n . The SHE of each stage was fit and plotted in Fig. 10c. Similar to the SHR curves, the L-L curves could also be divided into two or three stages, that was, the value of SHE at different stage was different. It should be noted there was a one-to-one correspondence between these stages during the L-L curves and the SHR curves (Fig 9). For example, two stages were found in the SHR curve of the BM in tensile test, the L-L curve was also divided into two stages. Thus different deformation mechanism would responsible for the difference in SHE at each stage.

The SHE at the stage1 had relatively high values which corresponded to the elastic deformation where the value of SHE was 1 in theory. At the stage2, the values of SHE had a great reduction for the BM and CCSS-A in tensile and compression tests. They showed considerable difference.

Firstly, for these curves with two stages (BM-T, CCSS-A-C), the SHE of BM in tensile test was only 0.14 due to the limited slip systems. After CCSS, the modified (0002) basal texture was in favor for basal slip, so the SHE was still maintained at a high value of 0.44 due to the activation of abundant basal dislocation. Secondly, the curves with three stages (CCSS-A-T, BM-C), the SHE of the stage2 was much lower than that of the other two stages. As stated above, {10-12} twinning had played a dominated role during stage2 for BM-C and CCSS-A-T, a small number of dislocations would come into being in matrix during this stage and brought about low strain hardening. Consequently the value of SHE in the stage2 was much lower than that of the other two stages. In addition, the SHE of BM-C was higher than that of CCSS-T, the stronger {10-12} twinning related refinement strengthening and texture strengthening for BM-C would be the primary reason.

Finally, for the stage3 (only for CCSS-A-T and BM-C), the values of SHE increased significantly which was almost equal to that of stage1 (elastic deformation). It seemed that there was ultra-strong strain hardening in this stage. During tensile test, basal slip was activated and generated abundant basal dislocation in the CCSS-A which would be the primary reason of the high value of SHE. And for the BM in compression, the grains were in hard orientation due to the {10-12} twinning related crystal orientation rotation at the stage2. Basal slip would thus be suppressed in this stage. However, at the stage3, the stress increased to a high level which could surpass the critical stress to activate $\bar{c} + \bar{a}$ slip [30]. Therefore, the activation of multiple dislocation slip generated abundant dislocation and the dislocation accumulation brought about a high SHE in the stage3 for the BM and CCSS-A.

4. Conclusion

In summary, CCSS was conducted on hot-extruded AZ31 Mg alloys with different routes. Original grains were effectively refined and the morphology of different routes were different from each other. Texture was modified due to the shearing deformation and the (0002) basal planes inclined from ND to the ED-TD plane. The (0002) basal texture inclined to one direction for route A while a centrosymmetric pole figure and a mirror symmetric pole figure were obtained for route B and C respectively. The rotation of the bars between the two passes was responsible for the special texture component.

The micro-hardness had a slightly reduction after CCSS due to texture modification. The newly formed basal texture was in favor for the activation of basal slip during tensile and compression. Thus the elongation was improved significantly accompanied by a decrease in yield strength. In addition, the strong tensile-compression asymmetry in the BM was weakened due to the activation of basal slip during in mechanical tests. The strain hardening behavior could be divided into different stages due to the special deformation mechanism. The {10-12} twinning related increase in SHR was subdued due to the widespread activation of basal slip. At the stage3, abundant dislocation were generated due to the activation of multiple dislocation slip systems and brought about a high SHE at the stage3.

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Figure1

Fig. 1. Schematic illustration of (a) the continuous confined strip process and (b) the routes at the second pass and (c) the morphology of the bars after one and two passes. (1.5 column)

Fig. 2. The microstructure of the (a) base material, (b) CCSS-A, (c) CCSS-B and (d) CCSS-C. (1.5 column)

Figure3

Fig. 3. (a) XRD patterns of the samples before and after CCSS and (b) the variation of the intensity of (0002), (10-10) and (10-11) planes. (Single column)

Figure4

Fig. 4. The (0002) and (10-10) pole figures of the (a) base material, (b) CCSS-A, (c) CCSS-B and (d) CCSS-C. (1.5 column)

Figure5

Figure5. (a) Schematic illustration for orientation transition during CCSS and (b) the characteristic crystal of A, B and C. (Single column)

Figure6

Fig. 6. The micro-hardness variation of the samples before and after CCSS. (Single column)

Figure7

Fig. 7. The (a) tensile and (b) compression true stress-strain curves of the samples before and after CCSS. (Single column)

Figure8

Fig. 8. The variation of yield strength (YS) in tensile and compression tests and the value of YS-tensile/YS-compression. (Single column)

Figure9

Fig. 9. The strain hardening rate-true strain curves of the base material and CCSS-A during (a) tensile and (b) compression tests. (Single column)

Figure10

Fig. 10. The $\ln\sigma - \ln\epsilon$ curves of the base material and CCSS-A in (a) tensile and (b) compression tests and (c) the variation of the strain hardening exponent at different stage. (1.5 column)