Tension–Compression Yield Asymmetry Influenced by the Variable Deformation Modes in Gradient Structure Mg Alloys

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Abstract

Surface mechanical attrition treatment (SMAT) was carried out on hot-rolled AZ31 Mg samples along two orthogonal directions; as a result, two types of gradient structures with different grain sizes and texture components in different layers were produced. The tension–compression yield asymmetry (YA) was studied using samples with different thicknesses, in order to elucidate the effect of combinations of variable deformation modes operating in different layers of the two oriented SMAT samples. The 0° oriented SMAT sample containing layers with strong basal texture displayed significant YA, because of either dislocation slip or extension twinning domination during tension or compression. By contrast, the 90° oriented SMAT sample containing layers with coexisting orthogonal texture components had an obviously weakened YA, which was attributed to the multi-deformation modes cooperating during tension or compression, i.e., extension twinning or detwinning in conjunction with dislocation slips, leading to close yield stresses compared between tension and compression.

Keywords Mg alloy · Gradient structure · Yield asymmetry · Texture · Deformation mechanism

1 Introduction

Magnesium alloys have attracted increasing interest due to their low-density and high specific properties, which are good candidates for lightweight structural applications [1–3]. However, Mg alloys usually suffer from the drawback of limited strength and poor formability at room temperature, compared to other widely used metals such as Al alloys and steels [4–6].

Moreover, Mg alloys usually exhibit anisotropy in service properties [7–11], among which tension–compression yield asymmetry attracts a wide attention [7–9, 12–14]. The anisotropic properties are generally related to the low-asymmetry hexagonal close-packed (HCP) lattice structure of Mg alloys, as well as the easily formed texture resulted from plastic

processing [1, 5, 7–9, 15]. The yield asymmetry restricts the structural applications of Mg alloys subjected to load with tension and compression simultaneously or alternatively. Several avenues were manifested to be effective for reducing yield asymmetry (YA), such as grain refinement [8], precipitation treatment [12], texture control [13] and pre-twinning [9, 14].

Recently, gradient-structured (GS) metallic materials were developed based on the extensively studied nanostructured (NS) materials [16–18], exhibiting excellent combination of strength and ductility. Several researches [19–22] have manifested the advantages of gradient structure for improving the mechanical properties in commercial Mg alloys free of additive alloying elements, e.g., rare-earth elements. This provides a strategy to fabricate compositionally lean, low-cost Mg alloys with good balance of strength and ductility [23].

The gradient structure of Mg alloys produced by surface peening can be viewed as a pile of layers with gradually changed grain size and texture. Thus, mechanical properties of combinations of layers could vary with their thickness, resulting from the variable deformation modes operating in the different layers [19–22]. However, the previous works [19–22] mainly used uniaxial tensile tests to evaluate the mechanical behaviors of GS Mg alloys. Very few studies

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have addressed the tension–compression YA of GS Mg alloys so far.

In this work, slices were cut off from a hot-rolled (HR) AZ31 Mg plate along two orthotropic directions to generate different initial textures. The slices were subjected to surface mechanical attrition treatment (SMAT) to produce gradient structures comprising layers with different grain sizes and texture components. The tension–compression YA of the two GS samples started from different initial textures was investigated, in relation to the variable deformation modes operating in the different layers.

2 Experimental

The original material for this study was a commercial HR AZ31B Mg alloy with a chemical composition (wt%) of 2.95 Al, 0.85 Zn, 0.40 Mn and Mg in balance. As shown in Fig. 1a, the initial sample has a typical HR structure showing a bimodal grain structure [24, 25], in which the predominant coarse grains were surrounded by fine recrystallized grains. The average grain sizes of the coarse and fine grains were measured to be 82 μm and 7 μm , respectively. The coarse grains possessed an area fraction of 88% in the structure, which could dominate the macrotexture and mechanical properties of the HR plate. The initial sample showed a typical basal texture with most of the c -axes approximately parallel to the normal direction (Fig. 1b).

Round disks with dimensions of $\varnothing 49 \text{ mm} \times 5 \text{ mm}$ for SMAT were machined in two different directions from the HR plate: 0° and 90° with respect to the rolling plane to generate different initial textures, as depicted in Fig. 2. Throughout this work, ND, TD, RD and LD refer to normal, transverse, rolling and loading directions, respectively. Hereafter, the two oriented samples were termed as SMAT 0° and 90° samples, respectively.

Fig. 2 Schematic illustration of two sample orientations used for SMAT process and tensile and compression tests

The surface on the one side of the disk was subjected to the SMAT process performed on a surface nanocrystallization device [26, 27], implemented by a SPEX SamplePrep 8000M Mixer/Mill with a frequency of 50 Hz. The disk sample was impacted by stainless steel balls with high strain rates in multi-directions; each disk sample was processed for 60 min under protection air environment of argon at room temperature.

The gradient structures of the two oriented SMAT samples were observed on the ND–RD cross sections by a Zeiss Axiovert 200 MAT optical microscope. The specimens were etched by an etchant of 5 g picric acid, 5 ml glacial acetic acid, 100 ml ethyl alcohol and 10 ml distilled water. For detailed structural characterization, electron backscatter diffraction (EBSD) mapping was performed with a HKL-EBSD system. The samples were mechanically ground and electrochemically polished in an AC2 electrolyte at 20 V for 90 s. The EBSD data were analyzed with the Channel 5 software.

X-ray diffraction (XRD) was used to investigate the texture at different depth of the SMAT samples, before and after the tensile or compression tests. The investigated sections were parallel to the treated surface. XRD was conducted

Fig. 1 a Optical micrograph, b (0001) pole figure of RD–TD cross section of as-received HR plate

using a Philips X'Pert diffractometer with $\text{CuK}\alpha$ radiation at the voltage of 40 kV and current of 30 mA. The X'Pert Texture software was used to plot the pole figures (PFs) based on the scanning data.

An Instron-3382 mechanical tester equipped with video extensometer (AVE 2[®]) was used for the tensile and compression tests of the different oriented samples. The tensile samples were cut into dog-bone shape with 15 mm gauge length, 3 mm width and prescribed thickness. The compression samples were cut into cuboids with a height/width ratio of 2:1, corresponding to the prescribed thickness of the tensile samples. The gradient structures induced by SMAT were set to be along the thickness/width of the tensile/compression samples, so that the LDs during tests were parallel to the interfaces of the gradient layers (i.e., the treated surfaces), as shown in Fig. 2. Samples with different thicknesses/widths were prepared to test the tension–compression YA of the different parts of the GS samples. The compression tests were carried out carefully to insure the compression axes of the samples parallel to the LD; for this purpose, a tweezer was usually used at the early stage of loading concerning the small width of the samples. All the tensile/compression tests were performed at room temperature and at an initial strain rate of $5 \times 10^{-4} \text{ s}^{-1}$. The tests were repeated for at least thrice for each condition.

3 Results

3.1 Gradient structures induced by SMAT

Figure 3 shows the optical micrographs of the ND–RD cross sections from the SMAT 0° and 90° samples with thickness

of 1.5 mm. Both the samples were studied by assigning two typical depths: 0.7 mm and 1.5 mm corresponding to the thicknesses of tensile and compression samples.

Figure 3a shows the structure of the SMAT 0° sample. The region with 0.7 mm thickness can be further classified into two layers: The severely deformed layer, from the treated surface to the depth of 350 μm , showed an unresolved morphology due to the dramatically grain refinement [22]; and the medium deformed layer, from the depth of 350 μm to 700 μm , displayed remarkable deformation markings while the extent of grain refinement declined compared to the top layer. Subsequently, the layer from the depth of 700 to 1500 μm exhibited almost the same morphologies with the as-received HR alloy, implying remarkable attenuation of strain far away from the surface peening.

Figure 3b shows the structure of the SMAT 90° sample. Similarly, the severely deformed layer was seen from the treated surface to the depth of 350 μm . The medium deformed layer, from the depth of 350 μm to 700 μm , also showed remarkable deformation markings; besides, deformation twins were observed in some local area; the twins possessed an area fraction of 6.0% in this layer. From the depth of 700 μm to 1500 μm , although the strain magnitude declined markedly, deformation twins were still observed in some coarse grains, which possessed an area fraction of 8.2% in this layer.

3.2 Change of texture along depth

Figure 4 displays the (0001) PFs at different depth scanned from the planes parallel to the treated surface. Both the SMAT 0° and 90° samples displayed change in textures as the depth increased.

Fig. 3 Optical micrographs of ND–RD sections of **a** SMAT 0°, **b** SMAT 90° samples

Fig. 4 (0001) PFs at different depths scanned from planes parallel to the treated surface: 350 μm in the SMAT **a** 0°, **b** 90° samples; 700 μm in the SMAT **c** 0°, **d** 90° samples; 1500 μm in the SMAT **e** 0°, **f** 90° samples

The SMAT 0° sample exhibited scattered (0001) poles around the vertical axis (VA) of the sample at the depth of 350 μm , implying a weakened basal texture (Fig. 4a). The PF at the depth of 700 μm displayed a basal texture with the intensity approximately equivalent to the original HR plate (Fig. 4c). Subsequently, the PF at the depth of 1500 μm showed a strong basal texture with the maximum intensity slightly increasing (Fig. 4e).

The SMAT 90° sample exhibited scattered (0001) poles around the VA of the sample at the depth of 350 μm (Fig. 4b), indicating a weakened basal texture. The PF at the depth of 700 μm showed that mainly two types of textures coexisted: The first one had the *c*-axes almost parallel to the VA of the sample with stronger intensity; and the second possessed the *c*-axis distributing around the LD with relatively weak intensity (Fig. 4d). Subsequently, the PF at the depth of 1500 μm also showed the coexistence of two textures similar to the PF at 700 μm depth; however, the intensity of the component with *c*-axes parallel to VA decreased, while the intensity of that with *c*-axes around LD slightly increased (Fig. 4f).

3.3 Tensile and compression behaviors and yield asymmetry

For comparison purpose, tensile and compression tests were conducted along LDs with 0° and 90° angles relative to the rolling plane of the original HR plate (Fig. 2), denoted as HR 0° and 90° samples. The samples had thickness/width of 1.5 mm. Both the two oriented samples exhibited marked difference between the tensile and compression curves, as shown in Fig. 5a, b. The HR 0° sample displayed a concave-down-shaped curve under tension, showing a high tensile yield stress (TYS), while the compression curve of this sample exhibited a sigmoid shape, presenting a low compression yield stress (CYS). By contrast, the shapes of tensile and compression curves of the HR 90° sample reversed relative to those of the HR 0° sample (Fig. 5b); thus, the CYS was higher than the TYS. This is consistent with the previous reports [8, 9, 12–14], which stated that the basal texture leads to different deformation modes under tension and compression, resulting in remarkable tension–compression YA.

It is known that YA is generally expressed by the ratio of compression and tensile yield stress, CYS/TYS, or the reciprocal, TYS/CYS [8, 9, 12–14]. Thus, both the HR 0° and 90° samples presented obvious yield asymmetry, with the values of 0.30 and 0.51, respectively, as shown in Table 1.

Subsequently, tensile and compression samples with different thicknesses were cut from the SMAT samples, corresponding to different combinations of layers with different strain magnitude induced by SMAT. Thus, the mechanical behaviors and yield asymmetries of different parts of the GS Mg alloys were reflected.

Figure 5c, d shows the tensile and compression curves of the SMAT 0° and SMAT 90° samples with thickness of 0.7 mm. The SMAT 0° sample still displayed different tensile and compression behaviors: the parabolic shape with high TYS in comparison with sigmoid shape with relatively low CYS. By contrast, the SMAT 90° sample displayed similar shapes of the tensile and compression curves, though its TYS was slightly higher than its CYS. Thus, the SMAT 0° sample still showed some extent of YA, though the value of YA was markedly enhanced compared to that of HR 0° sample (Table 1). However, the SMAT 90° sample showed nearly an elimination of YA with the 0.7-mm-thick samples, giving a value of 0.92 (Table 1).

Figure 5e, f shows the tensile and compression curves of the SMAT 0° and SMAT 90° samples with thickness of 1.5 mm. The SMAT 0° sample exhibited almost the same tensile and compression behaviors compared with their HR 0° counterparts. However, compared to the distinct tensile and compression behaviors of HR 90° sample, the SMAT 90° sample exhibited nearly coordinate tensile and compression curves by 1.5-mm-thick samples. Thus, the 1.5-mm-thick SMAT 0° sample still displayed remarkable YA with a

Fig. 5 Tensile and compression true stress–true strain curves of HR **a** 0°, **b** 90° samples, SMAT **c** 0°, **d** 90° samples with 0.7 mm thickness, SMAT **e** 0°, **f** 90° samples with 1.5 mm thickness

Table 1 Yield stresses of SMAT 0° and 90° samples with different thicknesses obtained by tension and compression in comparison with the HR 0° and 90° samples

Sample	Thickness (mm)	CYS (MPa)	TYS (MPa)	CYS/TYS or TYS/CYS
HR 0°	1.50	55	186	0.30
SMAT 0°	0.70	228	278	0.82
	1.50	130	254	0.51
HR 90°	1.50	144	73	0.51
SMAT 90°	0.70	195	212	0.92
	1.50	164	146	0.91

value of 0.51, while the SMAT 90° sample exhibited almost elimination of YA with a value of 0.91 using the same thick samples (Table 1).

3.4 Deformation modes at different depths of the SMAT samples

3.4.1 Deformation modes during tension

Figure 6 displays the optical micrographs of ND–RD sections of the SMAT 0° and 90° samples with thickness of

Fig. 6 Optical micrographs of ND–RD sections of SMAT **a** 0°, **b** 90° samples with thickness of 1.5 mm after tension to strain of 5%

1.5 mm; both the samples were tensioned to a strain of 5%. Figure 7 shows the inverse pole figure maps of the same sections of the two samples by EBSD from the treated surfaces to the depths of ~1.0 mm after tension.

EBSD technique was used to analyze the microstructural features and deformation modes in different layers during tension. The layer from 0 to 350 μm of the SMAT 0° sample gave an average grain size of 7.8 μm. The calculated Schmid factors (SFs) of this layer exhibited moderate values for basal slip, while relatively high values for prismatic slip

(Fig. 8a, d). This was in line with the XRD-measured PF at the depth of 350 μm (Fig. 4a), showing a weakened basal texture. Hence, though basal slip accommodated a certain amount of deformation in this layer, prismatic slip played the dominant role during tension.

The layer from 350 to 700 μm of the SMAT 0° sample exhibited a gradual increase in grain size with increasing depth; the grain size at the depth close to 700 μm was close to that of the original HR sample. The SFs of this layer exhibited relatively low values for basal slip, while high

Fig. 7 Inverse pole figure maps of ND–RD sections of the SMAT **a** 0°, **b** 90° samples after tension to strain of 5%

Fig. 8 Calculated SFs for basal and prismatic slips of different layers in SMAT 0° sample after tension: **a** 0 μm –350 μm , **b** 350 μm –700 μm , **c** 700 μm –1000 μm for basal slip; **d** 0 μm –350 μm , **e** 350 μm –700 μm , **f** 700 μm –1000 μm for prismatic slip

values for prismatic slip (Fig. 8b, e). This was in alignment with the XRD-measured PF at the depth of 700 μm (Fig. 4c), showing a basal texture with similar intensity to the original HR plate. Hence, prismatic slip is the domination in this layer during tension, while basal slip played a minor role. The XRD-measured PF at the depth of 700 μm after tension exhibited the *c*-axes maintained around the VA of the sample (Fig. 9a), corresponding to the effect of prismatic slip [19, 22, 28].

The layer from 0 to 350 μm of the SMAT 90° sample presented an average grain size of 9.3 μm . The calculated SFs exhibited similar results with the same layer of SMAT 0° sample: moderate values for basal slip and relatively high values for prismatic slip (Fig. 10a, c). This was also in alignment with the XRD-measured PF at the depth of 350 μm (Fig. 4b). Hence, basal slip played partial role, while prismatic slip is the domination during tension in this layer of SMAT 90° sample.

The layer from 350 to 700 μm of the SMAT 90° sample also exhibited a gradual increase in grain size as depth increased; the coarse grains at the depth close to 700 μm had similar grain size to the original HR sample, showing the occurrence of twins. The SFs of this layer exhibited similar values with the top layer (Fig. 10b, d), implying that prismatic slip is the domination with basal slip complementing during tension. The XRD-measured PF at the depth of 700 μm (Fig. 4d) showed a major texture with *c*-axis nearly parallel to the VA of the sample, while the orientations with

Fig. 9 (0001) PFs at different depths scanned from planes parallel to the treated surface after tension to strain of 5%: 700 μm in the SMAT **a** 0°, **b** 90° samples; 1500 μm in the SMAT **c** 0°, **d** 90° samples

c-axes nearly parallel to LD, as well as those distributing between VA and LD, coexisted. This also suggested the primary and secondary roles of prismatic and basal slips during tension in this layer. Besides, at the depth close to 700 μm , deformation twins were observed both by optical microscope and EBSD (Figs. 6b, 7b). EBSD analysis showed that

Fig. 10 Calculated SFs for basal and prismatic slips of different layers in SMAT 90° sample after tension: **a** 0 μm–350 μm, **b** 350 μm–700 μm for basal slip; **c** 0 μm–350 μm, **d** 350 μm–700 μm for prismatic slip

they were $\{10\bar{1}2\}$ extension twins (ETs), the area fraction of which was measured to be 8.7% in this layer. This was in alignment with the XRD-measured PF at the depth of 700 μm after tension, showing a considerable amount of c -axes distributed around the VA of the sample (Fig. 9b). This implied that the occurrence of ETs rotated the c -axis from the direction parallel to LD to that parallel to VA.

The layer from 700 to 1500 μm of the SMAT 0° sample remained the same morphology after tension observed by optical microscope (Fig. 6a). The calculated SFs from this layer showed low values for basal slip, while markedly high values for prismatic slip (Fig. 8c, f). This suggested that prismatic slip is the domination in this layer during tension, while basal slip hardly occurred. This was consistent with the XRD-measured PF at the depth of 1500 μm before tension (Fig. 4e), showing strong basal texture. After tension, the XRD-measured PF at the depth of 1500 μm showed c -axes maintained around VA of the sample (Fig. 9c), implying the dominant role of prismatic slip.

The layer from 700 to 1500 μm of the SMAT 90° sample showed a large number of deformation twins after tension (Figs. 6b, 7b). EBSD analysis manifested that they were $\{10\bar{1}2\}$ ETs. The ETs possessed an area fraction of 16.6% in this layer after tension, which was markedly higher than that before tension (8.2%). This implied that plenty of ETs occurred during tension in this layer. The XRD-measured PF at the depth of 1500 μm showed considerable amounts of c -axes distributing around VA of the sample after tension (Fig. 9d), implying $\sim 90^\circ$ rotation of the c -axes from the direction parallel to LD to that parallel to VA (Fig. 4f). This confirmed the extensive occurrence of ETs during tension in this layer.

3.4.2 Deformation modes during compression

Figure 11 exhibits the optical micrographs of ND–RD sections of the SMAT 0° and 90° samples with thickness of 1.5 mm; both the samples were compressed to a strain of 5%. Figure 12 displays the inverse pole figure map of the

Fig. 11 Optical micrographs of ND–RD sections of SMAT **a** 0°, **b** 90° samples with thickness of 1.5 mm after compression to strain of 5%

Fig. 12 Inverse pole figure maps of ND–RD sections of SMAT **a** 0°, **b** 90° samples after compression to strain of 5%

same sections of the two samples by EBSD from the treated surfaces to the depths of ~ 1.0 mm after compression.

The average grain size of the layer from 0 to 350 μm of the SMAT 0° sample after compression was measured to be 7.4 μm , which was in line with that measured after tension. That implied the grain size was not much influenced by the tensile and compression tests at this layer. The measured SFs from this layer exhibited moderate values for both basal slip and prismatic slip, as depicted in Fig. 13a, b. That implied both slip modes operated in this layer during compression.

No twin was observed in this layer after compression (Fig. 12a). These were consistent with the XRD-measured PF at the depth of 350 μm before compression, showing the weakened basal texture (Fig. 4a).

In the layer from 350 to 700 μm of the SMAT 0° sample, the relatively coarse grains with sizes of several tens of microns showed occurrence of ETs after compression (Figs. 11a, 12a). The area fraction of ETs in this layer was measured to be 9.5%. This corresponded to the XRD-measured PF at the depth of 700 μm before compression, showing

Fig. 13 Calculated SFs in the layer of 0–350 μm of the two samples after compression: **a** basal slip, **b** prismatic slip for the SMAT 0° sample; **c** basal slip, **d** prismatic slip for the SMAT 90° sample

an intense basal texture (Fig. 4c), which favored the occurrence of ETs under compression applied perpendicular to the c -axes [8, 9, 28]. The PF derived by EBSD from this layer showed c -axes nearly parallel to LD after compression (Fig. 14a), implying the rotation of c -axes induced by extension twinning compared to their orientations before compression (Fig. 4c).

The layer from 0 to 350 μm of the SMAT 90° sample gave an average grain size of 9.5 μm after compression, in line with that measured after tension, implying that no noticeable change in grain size happened during tension or compression in this layer. The measured SFs from this layer exhibited moderate values for basal and prismatic slips (Fig. 13c, d), implying that both slip modes operated during compression in this layer. Either, no twin was observed in this layer after compression (Fig. 12b). Thus, the deformation modes in this layer of SMAT 90° sample were similar to those in the same layer of SMAT 0° sample. This was consistent with the similar textures depicted by PFs at the depth of 350 μm

of the two samples, both showing weakened basal texture (Fig. 4a, b).

The layer from 350 to 700 μm of the SMAT 90° sample showed a reduction in ETs after compression, observed both by optical microscope and by EBSD (Figs. 11b, 12b). The area fraction of ETs was measured to be 2.1% in this layer, dramatically decreased compared to that before compression (6.0%). The XRD-measured PF at the depth of 700 μm before compression showed two textures coexisted (Fig. 4d), the main one of which showed c -axis parallel to the VA of the sample. That was induced by the ETs which occurred during SMAT. After compression, the PF derived by EBSD showed most of the c -axes turned to nearly parallel to LD (Fig. 14b). This implies the ETs induced by SMAT detwinned as compression applied perpendicular to the c -axes of the preformed ETs [29, 30], while the second texture in the PF before compression retained the orientation with c -axes almost parallel to LD during compression (Fig. 14b).

Fig. 14 (0001) PFs after compression to strain of 5%: derived by EBSD from the layer of 350–700 μm of the **a** SMAT 0°, **b** SMAT 90° samples; derived by XRD scanned from planes parallel to the treated surface at the depth of 1500 μm of the **c** SMAT 0°, **d** SMAT 90° samples

The layer from 700 to 1500 μm of the SMAT 0° sample showed a large number of deformation twins after compression (Figs. 11a, 12a). EBSD manifested that they were $\{10\bar{1}2\}$ ETs. The area fraction of ETs in this layer was measured to be 18.7% in this layer. This was in alignment with the XRD-measured PF at the depth of 1500 μm before compression, showing a strong basal texture (Fig. 4e), which facilitated the occurrence of ETs under compression applied perpendicular to the c -axis [8, 9, 28]. The PF at the depth of 1500 μm after compression showed rotation of c -axis from the direction parallel to VA to that nearly parallel to LD of the sample (Fig. 14c), corroborating the occurrence of ETs during compression.

The layer from 700 to 1500 μm of the SMAT 90° sample showed a reduction in ETs after compression, revealed both by optical microscope and by EBSD (Figs. 11b, 12b). The area fraction of ETs was measured to be 1.7% in this layer, markedly less than that before compression (8.2%). The XRD-measured PF at the depth of 1500 μm before compression showed two textures coexisted (Fig. 4f). The main texture with c -axes parallel to the VA led to detwinning as compression applied perpendicular to the c -axis of the preformed ETs, as revealed by the PF after compression (Fig. 14d), while the second texture in the PF before compression retained the orientation with c -axes parallel to the LD during compression (Fig. 14d).

4 Discussion

4.1 Formation of the gradient structures

SMAT induces gradient magnitudes of strain and stress along the depths of the treated samples, thus causing structures with gradient features throughout the thickness [19–22]. For the different initial textures of the SMAT 0° and 90° samples, the different layers of the two samples displayed variable structural features, respectively.

As the deformation induced by SMAT always starts from the top surface and then extends to the substrate along the depth, the layers at different depths of the samples correspond to different strain stages [31]. That means the process of grain refinement and texture variation can be well exhibited by the structural features from the deep layer to the topmost layer as strain increases.

In the layer with depths from 700 to 1500 μm away from the treated surface, the strain induced by surface peening has largely attenuated. Thereby, this layer in the SMAT 0° sample exhibited coarse-grained structure similar to that of the original HR plate (Fig. 3a). The PF measured at the depth of 1500 μm exhibited strong basal texture with the maximum intensity slightly higher than the original HR plate (Fig. 4e). This could be a result of the compressive stress along the VA of the sample caused by SMAT [19, 22].

The layer with the depths from 700 to 1500 μm in the SMAT 90° sample showed a considerable amount of ETs (8.2% as shown in Fig. 3b). That was because of the compressive stress induced by SMAT applied vertically to the c -axis of crystal structures in the 90° oriented sample, which facilitates the occurrence of ETs [28–30]. In that case, the c -axis will rotate $\sim 90^\circ$ from the original orientation to that parallel to the direction of compressive stress [29, 30]. Thereby, the major texture of this layer in SMAT 90° sample was that with c -axes nearly parallel to the VA of the sample. Secondly, the remaining orientations with c -axis distributing around the LD corresponded to the residual matrix untwined (Figs. 3b, 4f). Actually, the sample surface was impacted by steel balls in multi-directions during SMAT. Thus, except the compressive stress vertical to the treated surface, stresses with random directions were also applied on the sample. Besides, the imperfect basal texture implied some grains had divergent orientations. Thereby, untwined original grains could remain in the layers sustaining low/moderate strain, if the relationship between their orientations and the stress directions they sustained was not favorable for twinning.

The layer with depths from 350 to 700 μm away from the treated surface sustained the moderate magnitude of strain during SMAT. The EBSD results (Figs. 7, 12)

indicate that grain refinement occurred in these layers of both SMAT 0° and 90° samples compared to the original HR plate. The structures in these layers of both samples possessed coexistence of high- and low-angle boundaries (HABs and LABs), implying that the process of grain refinement proceeded to a moderate extent [22, 31–33]. ET was not observed in this layer of SMAT 0° sample (Fig. 3a), mostly because of the unfavorable orientation of the *c*-axes relative to the direction of compressive stress during SMAT. The PF at the depth of 700 µm of SMAT 0° sample showed the basal texture with similar intensity to the original HR plate (Fig. 4c). It implied that the moderate extent of grain refinement could hardly cause a marked change in the original texture at this depth, in line with the previous researches [22, 31–33].

The layer from 350 to 700 µm in the SMAT 90° sample exhibited a certain amount of ETs (6.0% as shown in Fig. 3b), which were caused by the compressive stress applied vertical to the *c*-axis of the crystal structures. The observed ETs were mainly close to the depth of 700 µm. This was because the structure close to the depth of 350 µm sustained higher strain, and dynamic recrystallization (DRX) tended to occur [31–33]. The DRX could cover the morphology of the former ETs. The PF at the depth of 700 µm showed the major texture with *c*-axis nearly parallel to the VA of the sample (Fig. 4d); this corresponded to the occurrence of ETs, and the spread of *c*-axis around the VA was due to the formation of LABs and occurrence of DRX. The second texture at this depth showed *c*-axis distributing around the LD (Fig. 4d), corresponding to the residual untwinned matrix.

The top layer from the treated surface to the depth of 350 µm was the most severely deformed region in the SMAT samples. The structures of these top layers in both the SMAT 0° and 90° samples were composed of nano- and submicron-scaled grains (Figs. 7, 12). Previous researches [32, 33] have elucidated that the grain refinement of Mg alloys during SMAT is mainly attributed to dynamic rotation recrystallization. During the plastic deformation induced by SMAT, subgrains/subcells tend to form at the early stage of straining; subsequently, dislocations propagate and glide to the sub-boundaries, resulting in an increase in the misorientation of boundaries by annihilation of dislocations. Nano- and submicron-scaled grains with HABs are formed as strain finally accumulates to high level [32, 33]. The subgrains/subcells formed at the early stage can be developed from the dislocation boundaries, or from the intersection of twin lamellae [32, 33]. Therefore, according to the structure features of the SMAT 0° and 90° samples at the low and moderate strain stages, it can be inferred that the subcells in the 0° sample were mainly induced by dislocation boundaries, while those in the 90° sample mainly evolved from subdivision of twins. Consequently, the rotation recrystallization

and the formation of HABs led to the weakened basal texture [19, 22, 32, 33], as revealed by the *c*-axes spreading around the VA of the two samples, shown in the PFs at the depth of 350 µm (Fig. 4a, b).

4.2 Yield asymmetry

The tension–compression yield asymmetry is usually ascribed to the basal texture that is readily formed during plastic processing [8, 9]. Thus, only one of the two deformation modes, i.e., dislocation slip or {10 $\bar{1}$ 2} twinning, will be the domination during tension or compression applied along the basal plane. Because the {10 $\bar{1}$ 2} twinning has a much lower critical resolved shear stress (CRSS) than that of the non-basal slips, e.g., prismatic slip, significantly different yield stresses will be exhibited between tensile and compression tests [30]. Weakening the texture can balance the activities of slip and twinning, leading to reduced YA [9, 30]. Besides, decreasing grain size increases the twinning stress more rapidly than the stress required to activate slip [8, 13, 34], thus reducing the tension–compression YA. Recently, a composite/hybrid twin structure was introduced into Mg alloys, resulting in multi-deformation modes during both tension and compression deformation. That also led to a reduction in the tension–compression YA [9, 14, 30].

In the present study, the two SMAT Mg samples had gradient structures which can be regarded as combinations of layers with different grain sizes and textures. The different layers exhibited different deformation modes under tension and compression, which would cause different behaviors of tension–compression YA.

The SMAT 0° sample with 0.7 mm thickness displayed a certain extent of YA (0.82), while the SMAT 90° sample with the same thickness exhibited nearly diminished YA (0.92), as depicted in Fig. 5c, d. Both the two samples can be looked as a combination of two layers of 0–350 µm and 350–700 µm. The two samples exhibited similar grain sizes and weakened textures in the topmost layers of 0–350 µm (Figs. 4a, b, 7a, b, 12a, b). Therefore, similar deformation modes operated in the topmost layers of the two samples during tension or compression, i.e., prismatic slip and basal slip cooperated (Figs. 8a, d, 10a, c, 13). Besides, ET was not observed in the topmost layers, mostly ascribed to the small grain sizes induced by the severe plastic deformation near the treated surface. That is rational because a critical grain size exists below which twinning is absent, which is normally several microns [7, 8, 19, 35, 36]. Thus, it can be deduced that the topmost layers of 0–350 µm did not contribute to YA of the two samples.

However, the layers of 350–700 µm of the SMAT 0° and 90° samples displayed markedly different deformation modes during tension and compression. The SMAT 0° sample exhibited primary prismatic slip with basal slip

complementing in this layer during tension (Fig. 8b, e), while extension twinning played an important role during compression (Figs. 12a, 14a). This corresponded to the structure of this layer with strong basal texture (Fig. 4c), as well as grain sizes large enough for the occurrence of ETs (Fig. 12a). Thus, this layer in the SMAT 0° sample would lead to marked tension–compression YA.

The layer of 350–700 μm of the SMAT 90° sample exhibited a coexistence of two textures (Fig. 4d). During tension, the first texture (*c*-axis parallel to VA) led to the deformation modes of prismatic slip is the domination with basal slip complementing (Fig. 10b, d); the second texture (*c*-axis parallel to LD) led to the occurrence of ETs (Figs. 7b, 9b). During compression, the preformed ETs with orientations correspond to the first texture detwinned (Figs. 12b, 14b). Detwinning was found to occur under reverse reloading or compression along the *c*-axis of the parent structure after the formation of primary ETs [29, 30, 37, 38]. At the same time, the second texture led to prismatic slip and basal slip during compression, which did not cause a marked change in the orientation of the *c*-axis (Figs. 4d, 14b). Therefore, the coexisting two textures induced twinning or detwinning in addition to dislocation slips during tension or compression, leading to close yield stresses between tension and compression in this layer.

Many researchers have calculated the values of CRSS of the different deformation modes in polycrystalline AZ31 Mg alloy with ordinary grain sizes (at least $> 10 \mu\text{m}$): 10–50 MPa for basal slip [39], 55–110 MPa for prismatic slip [39], 15–55 MPa for extension twinning (CRSS_{ET}) [40, 41] and approximately half of the CRSS_{ET} for detwinning [30]. Thus, the difference between the CRSS values of prismatic slip and extension twinning is 4–55 MPa, while the difference between extension twinning and detwinning is only 7–27 MPa.

Thereby, the different values of CRSS of the predominant deformation modes during tension and compression in the layer of 350–700 μm of the SMAT 0° and 90° samples could lead to different extent of tension–compression YA. Then, the extents of tension–compression YA of the two 0.7-mm-thick samples were both primarily determined by their 350–700 μm layers, because the layer of 0–350 μm exhibited similar deformation modes during tension and compression.

Both the SMAT 0° and 90° samples exhibited consistent deformation modes in their adjacent layers of 350–700 μm and 700–1500 μm during tension and compression. This was because the layers from 350 to 1500 μm possessed similar texture components with gradient grain sizes; both layers had large numbers of coarse grains with sizes large enough for extension twinning (Figs. 7, 12). The SMAT 0° sample exhibited primary prismatic slip complemented by basal slip during tension (Fig. 8c, f), and prevalent extension twinning

during compression in the 700–1500 μm layer (Figs. 11a, 12a, 14c). Thus, this layer in the SMAT 0° sample would lead to tension–compression YA.

The SMAT 90° sample exhibited a coexistence of two textures in the 700–1500 μm layer (Fig. 4f), which led to the occurrence of extension twinning and detwinning during tension and compression, respectively, in addition to dislocation slips (Figs. 6b, 7b, 9d, 11b, 12b, 14d). That would cause small difference of yield stresses between tension and compression for this layer.

The two samples with 1.5 mm thickness can both be looked as combinations of different layers of 0–350 μm , 350–700 μm and 700–1500 μm . The topmost layers from 0 to 350 μm of the two samples neither contribute to tension–compression YA, while the layers from 350 to 1500 μm of the two samples exhibited consistent texture components, respectively, both containing grains large enough for ET nucleation. Thus, the behaviors of tension–compression YA of the two 1.5-mm-thick samples were both determined by the deformation modes in their layers deeper than 350 μm .

It should be pointed out that the original bimodal structure of the HR plate employed by this work did not influence the present discussion. This is comprehensive as follows.

The topmost layers of 0–350 μm of the two SMAT samples underwent efficient grain refinement and texture weakening, both showing an average grain size below 10 μm . The initial bimodal structure had been eliminated in these topmost layers, which did not contribute to yield asymmetry.

As to the layers below 350 μm , the structures had not been severely deformed or refined; thus, the original coarse grains largely remained. Therefore, the YA behaviors of the layers ranging from 350 to 1500 μm were predominantly determined by the coarse grains inherited from the initial HR plate. Actually, only when grain size is decreased below several microns, extension twinning can be suppressed so that YA is reduced [7, 8, 19, 35]. However, the EBSD analysis indicated that the fractions of grains with sizes $< 10 \mu\text{m}$ were below 15% and 12% in the layers of 350–700 μm and 700–1500 μm in the two samples. In other words, the large amount of remaining coarse grains in the layers below 350 μm significantly influenced the mechanical behaviors and yield asymmetry of the two SMAT samples.

Table 2 lists the deformation modes operating in various layers of the two samples during tension and compression. The SMAT 0° sample only exhibited similar deformation modes during tension and compression in the top layer of 0–350 μm , the volume fraction of which influenced the YA of the samples with thicknesses 0.7 mm and 1.5 mm (Table 1). The SMAT 90° sample exhibited similar deformation modes during tension and compression in the layer of 0–350 μm ; meanwhile, the deformation modes operated in the layers below 350 μm led to declined difference of yield stresses between tension and compression. Thus, the SMAT

Table 2 Variable deformation modes dominating in different layers of SMAT 0° and 90° samples during tension or compression

Sample	Layers (μm)	Tension	Compression
SMAT 0°	0–350	Prismatic and basal slips	Prismatic and basal slips
	350–700	Prismatic and basal slips	Extension twinning
	700–1500	Prismatic and basal slips	Extension twinning
SMAT 90°	0–350	Prismatic and basal slips	Prismatic and basal slips
	350–700	Extension twinning; prismatic and basal slips	Detwinning; prismatic and basal slips
	700–1500	Extension twinning; prismatic and basal slips	Detwinning; prismatic and basal slips

90° samples with the thicknesses of 0.7 mm and 1.5 mm exhibited diminished YA (Table 1).

with coexisting two texture components can be readily obtained in prescribed depth of the GS sample, which has been verified to benefit the reduction in YA.

5 Conclusions

1. SMAT was conducted on HR AZ31 Mg samples along two orthogonal directions. The obtained two GS Mg samples were both constituted by different layers with different grain sizes and texture components. The tension–compression YA behaviors of the samples with thicknesses of 0.7 mm and 1.5 mm were reflection of combined effects of the variable deformation modes operating in different layers of the GS samples. The SMAT 0° samples exhibited remarkable YA with both 0.7 mm and 1.5 mm thickness. Though the top layer of 0–350 μm had positive effect in reducing YA due to the weakened texture and small grain sizes, the layers from 350 to 1500 μm led to significant YA. That was because the layers below 350 μm possessed strong basal texture; thus, either dislocation slips or extension twinning is the domination during tension or compression, respectively. Thereby, the 0.7-mm-thick and 1.5-mm-thick samples both exhibited marked YA, while the YA values were different owing to the influence of different fractions of the top layer.
2. The SMAT 90° samples exhibited diminished YA with both 0.7 mm and 1.5 mm thickness. The top layer of 0 μm–350 μm had structural features resembling the same layer of the SMAT 0° sample, implying reduced YA. Besides, the layers from 350 to 1500 μm possessed a coexistence of two textures with orthogonal *c*-axes, which led to primarily extension twinning or detwinning supplemented by dislocation slips during tension or compression, respectively. The multi-deformation modes cooperating in the layers below 350 μm during tension or compression resulted in reduced YA, either for the 0.7-mm-thick or for the 1.5-mm-thick sample.
3. This work suggests an avenue to fabricate GS Mg alloy with enhanced strength and diminished tension–compression YA, compared to its original HR counterpart. Using appropriate process of SMAT, a structure

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