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Mechanism of grain refinement of aluminium alloy in shear spinning under different deviation ratios

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Abstract

To investigate the grain refinement and its mechanism in shear spinning, microstructures of shear spun parts made by aluminium alloy under different deformation conditions, induced by different shear spinning deviation ratios, are studied. The results show that, after shear spinning, the microstructure is distributed symmetrically about a zone in sheet thickness defined as the neutral zone which is located between the inner surface and the middle plane of spun sheet thickness. Various deviation ratios in shear spinning can lead to grain refinement in different regions along thickness direction of the spun part. The microstructure characteristics indicate that the mechanism of grain refinement is due to the formation of deformation bands (DBs). It is observed that in DBs, parallel geometrically necessary boundaries (GNBs) formed by a zero deviation ratio and crossed GNBs formed by positive and negative deviation ratios are due to the different stress states induced by various deviation ratios in shear spinning. Due to the influence of grain refinement, micro hardness increases with the decreasing of the deviation ratio. The average value is increased by 16.04% under a negative deviation ratio compared to the initial micro hardness of the sheet.

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Abstract

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hardness of the sheet.

***Keywords*:** Grain refinement; Shear spinning; Deformation bands; Deviation ratio; Aluminium alloy.

1. Introduction

Shear spinning is one of the metal spinning processes that transform flat sheet metal blanks into hollow shapes, usually with axisymmetric profiles, by inducing continuous and localized plastic deformation of the material [1]. In shear spinning, the wall thickness of spun part is reduced from the initial thickness of metal blank and it may be defined by the Sine law, which calculating the final thickness by using the initial thickness and the angle between inclined wall of the component and the axis of rotation. However the final thickness distribution of spun part is influenced considerably by the deviation ratio, defined as the gap between mandrel and roller, which may result in a deviation of the actual final thickness from the value determined by the Sine law. In shear spinning, various values of deviation ratios can be applied, such as positive, zero and negative deviation ratios, these are also known as under-spinning, true shear spinning and over-spinning respectively [2].

Due to the inherent advantages of the spinning process such as low forming forces, simple and non-dedicated tooling, high material utilization, low production costs and improved mechanical properties, shear spinning process has been increasingly utilized in various industries requiring thin sectioned lightweight parts, such as aviation, aerospace, weapon and automotive industries [1, 3]. 3A21 aluminium alloy is one of the most commonly used alloys for advanced applications because of its versatile properties, economical benefit and no need for-heat-treatment advantages. However, low strength of spun components made of pure aluminium in 3A21 aluminium alloy limits its industrial applications [4]. Therefore, it is necessary to investigate processing methods which can improve the strength of spun parts made of 3A21 aluminium alloy.

Grain refinement is an effective method to improve the material properties. Investigation on grain refinement by spinning processes has been reported in recent years. Zhan et al. [5] investigated the microstructure evolution of the hot-spun parts of TA15 alloy under different forming temperatures and spinning deviation ratios. The results showed that the grain size under a zero deviation ratio was smaller than that under a positive deviation ratio, and a more uniform fibre microstructure was produced compared to that produced under a negative deviation ratio. Xu et al. [6] reported that in hot flow forming, the microstructure of TA15 alloy was gradually transformed into fine fibres, and the microstructure was refined gradually with the increasing of wall thickness reduction. Chen et al. [7] also studied the microstructure evolution of TA15 titanium alloy during hot flow forming. They found when the reduction ratio of wall thickness grew close to or over 40%, the tensile strength of spun parts was increased and elongation was decreased more rapidly owing to the obvious refinement of microstructure. Xia et al. [8] combined spinning processes together with heat treatment procedures to manufacture tubes with nano/ultrafine grain structures by stagger spinning. Their results showed that the ferritic grains with an average initial size of 50μm could be refined to 500 nm after stagger spinning at the thinning ratio of 87% while the tensile strength was increased from 465 MPa to 820 MPa. Radović et al. [9] studied the deformation behaviour and microstructure of AlMg6Mn alloy during hot shearing spinning. Optimal combination of strength and elongation was observed due to grain refinement and dislocation reactions with particles and atoms of Mg and Mn in solid solution. These studies suggest that shear spinning is a feasible method to improve the material strength of spun components made of 3A21 aluminium alloy through grain refinement under larger deformation. However these reported studies mainly focused on the characteristics of microstructure and its effect on mechanical properties of spun parts after shear spinning or flow forming. However, the mechanism of grain refinement during spinning has not been investigated.

It has been shown that there are different mechanisms of grain refinement in forming processes. Continuous dynamic recrystallization has been recognised as one of the main reasons for fine grain formation during cold or warm working [10-12]. Grains were fragmented by the development of deformation-induced small angled dislocation boundaries, and this was followed by a gradual increase in their misorientation, finally led to their transformation into usual grain boundaries [13]. Li et al. [14] reported that the grains were refined by discontinuous recrystallization by studying the microstructure of Inconel 625 superalloy in hot compression tests. Zhu and Lowe [15] investigated mechanisms of grain refinement during equal channel angular pressing (ECAP) process. They found that the interaction of shear plane with texture and crystal structure played a primary role in grain refinement, while the accumulative strain played a secondary role. Miura et al. [16] reported that the mechanical twinning contributed notably to grain refinement at small strains while continuous dynamic recrystallization took place at medium to high strains, however, kinking contributed to grain fragmentation at all strains. Sitdikov et al. [17] found that the microstructural changes in hot multidirectional compression of 7475 aluminium alloy were characterized by grain fragmentation due to frequent development of microshear bands in various directions, followed by an increase in their numbers and misorientations and finally the evolution of new grains at high strains. Chrominski et al. [18] believed the activation of different slip systems and the lack of redundant strain result in grain size refinement and high angle boundaries formation in incremental EACP process of aluminium. Zhao et al. [19] investigated the microstructure evolution of pure hafnium when subjected to cold rolling. They believed that the grain refinement was realized via formation and subdivision of microbands and thin laths structures in original coarse grains. Liu and Hansen [20] found that the grains were subdivided into four macroscopic bands, termed as deformation bands (DBs), which were parallel to the rolling plane. Between the four bands, there were three transition bands in which the orientation changed continuously from that of DB to that of the adjoining band. Lee and Duggan [21] studied the microstructure of copper-type material in rolling and found that DB was an important deformation mode in fcc metals and alloys. Huang et al. [22] proposed that the evolution of the continuous dynamic recrystallization during multiaxial forging could be summarized as such a process that DBs crossing each other subdivided an austenite grain into several subgrains, and these subgrains were gradually angled to form new independent grains with their boundaries being transformed into big angled boundaries in subsequent deformation. In spinning, Xia et al. [8] found that the microstructure evolution of ASTM 1020 steel during stagger spinning could be regarded as the grain subdivision. Dislocations were increased gradually inside grains to form cellular structures which were caused by severe plastic deformation. Then these cellular structures were transformed into subgrains under further plastic deformation. Finally, new grains with high-angle grain boundaries were generated. According to the above reported studies, it can be concluded that the mechanism of microstructure evolution is closely related to initial grains, material type, forming processes and forming conditions. At present, there are few reported studies on the mechanism of grain refinement of aluminium alloys in shear spinning at room temperature. It is necessary to study the mechanism of grain refinement to improve the mechanical properties of spun parts of aluminium alloy.

To investigate grain refinement and its mechanism of 3A21-O aluminium alloy in shear spinning, the characteristics of microstructure of spun components under different deviation ratios are investigated in this study. Then the mechanism of grain refinement during shear spinning is further examined and the effects of grain refinement on micro hardness are evaluated.

2. Experimental investigation

The material used in this study is a rolled sheet blank of 3A21-O aluminium alloy with a nominal thickness of 6 mm. The chemical composition of the alloy is given in Table 1.

Table 1 Chemical composition of 3A21 aluminium alloy (mass fraction, %)

Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
0.6	0.7	0.2	1.3	0.05	0.10	0.15	Bal.

Experiments of shear spinning are carried out on a CZ900/CNC spin forming machine. Fig. 1 illustrates main components involved and key process parameters used in shear spinning experiments, as listed in Table 2. The dimensions of mandrel and spinning rollers are shown in Fig. 2. Negative, zero and positive deviation ratios are designed to produce the spun parts to examine the effect of the deviation ratio on microstructure refinement of 3A21-O aluminium alloy. In this study, three values of the gaps between mandrel and rollers are used, which are 3.86mm, 3mm and 2.33mm, respectively. Based on the definition given early, the deviation ratio can be determined by Eq. (1):

$$\chi = \frac{t_1 - t_f}{t_f} \times 100\% \qquad (1)$$

where, t_1 is the gap between mandrel and roller giving the final wall thickness of spun part; t_f is the theoretical thickness according to the Sine Law, which can be expressed as:

$$t_f = t_0 \sin\alpha \tag{2}$$

where, t_0 is the initial thickness of aluminium alloy sheet blank; α is the half angle of mandrel. Thus, when the half angle of mandrel α is 30°, the deviation ratios χ are 28.66%, 0 and -22.33%, corresponding to the three values of the gap used in this study.

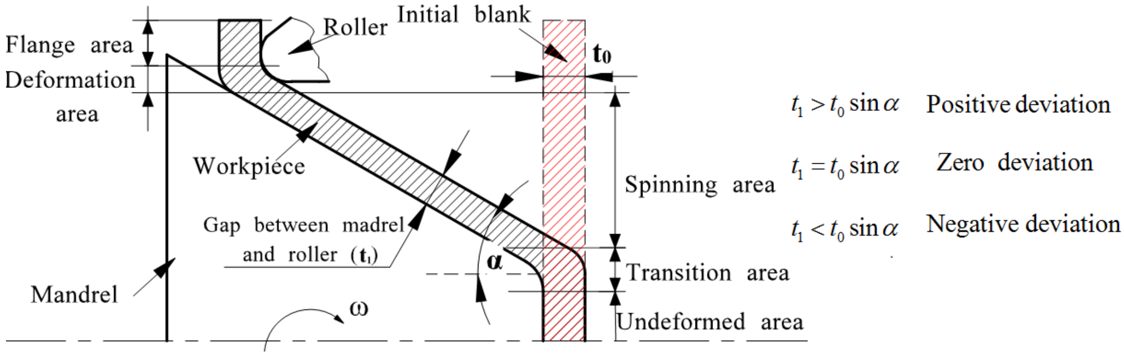

Fig. 1 Illustration of shear spinning

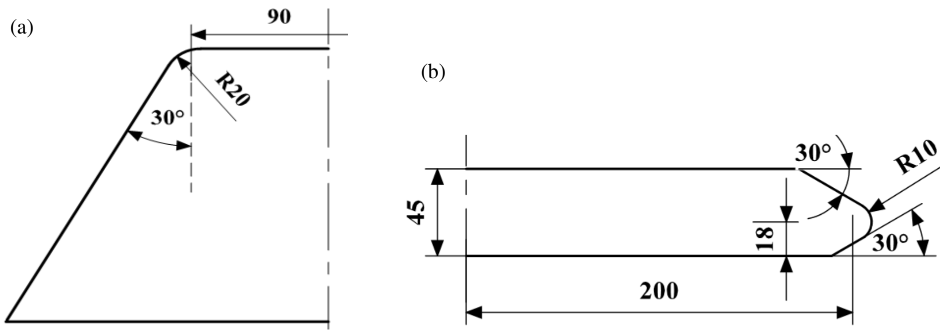

Fig. 2 Dimension of (a) mandrel and (b) rollers (unit: mm)

Table 2 Main process parameters of shear spinning

Forming parameters	Values
Diameter of performed blank (mm)	290
Roller feed rate (mm/r)	1
Mandrel rotational speed (r/min)	100

The microstructure of aluminium alloy sheet and spun parts are analysed by optical microscope and electron backscatter diffraction (EBSD) technique in R-N plane (Rolling direction - Normal direction) because the main deformation of the sheet blank during shear spinning can be observed in this plane, as illustrated in Fig. 3. Metallographic samples are prepared using electrolytic polishing in perchloric acid first, then anodic film technique is adopted for samples in solution consisting of 5.5g H_3BO_3 + 15ml HF + 100ml distilled water, to prevent deformation and scratches to occur in 3A21-O aluminium alloy. Measurements of micro hardness are conducted in R-N plane (Fig. 4) at a load of 200g in a HX-1000TM/LCD machine. The experiment error for the micro hardness measurement is symbolized as the standard deviation (SD) and relative standard deviation (RSD) which can be expressed as:

$$SD = \sqrt{\left(\sum_{i=1}^{n}(x_i - \bar{x})^2\right) \Big/ (\mathrm{n}-1)} \tag{3}$$

and

$$RSD = \frac{SD}{\bar{x}} \times 100\% \tag{4}$$

where, x_i is the value of the micro hardness; $\bar{x}$ is an average value of a certain position in thickness direction; the symbol n is nine because micro hardness is measured three times along rolling direction in three samples under the same deviation ratio. And in each sample, micro hardness is measured at an interval of 200μm along thickness direction, as shown in Fig. 4.

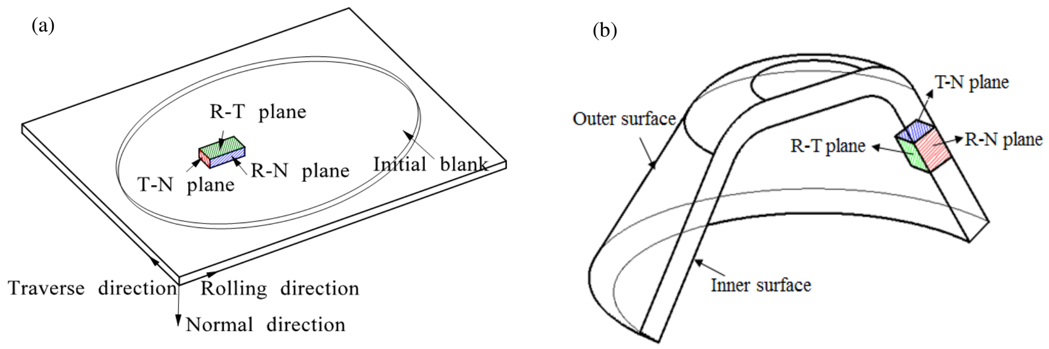

Fig. 3 Illustrations of sampling location in: (a) Initial blank in a rolling plate and (b) Spun part

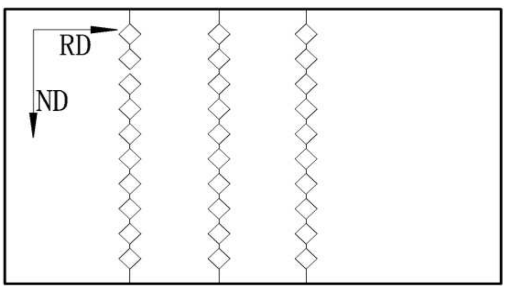

Fig. 4 Positions of the micro hardness measurement

3. Results and discussion

3.1 Initial microstructure

The initial microstructure of the 3A21-O sheet is obtained by optical microscope, as shown in Fig. 5. It can be seen that after hot rolling process, microstructure is uniform along the thickness direction. Grains in R-N plane are compressed in the normal direction (thickness direction) and elongated in the rolling direction both in near-surface and middle of the thickness section (Figs. 5(a) and (b)). Fig. 5(c) shows an EBSD orientation image of original sample near surface in R-N plane. As can be seen from Fig. 5(c), grains after rolling have a certain orientation, mainly near <111> direction, which represents the rolling direction.

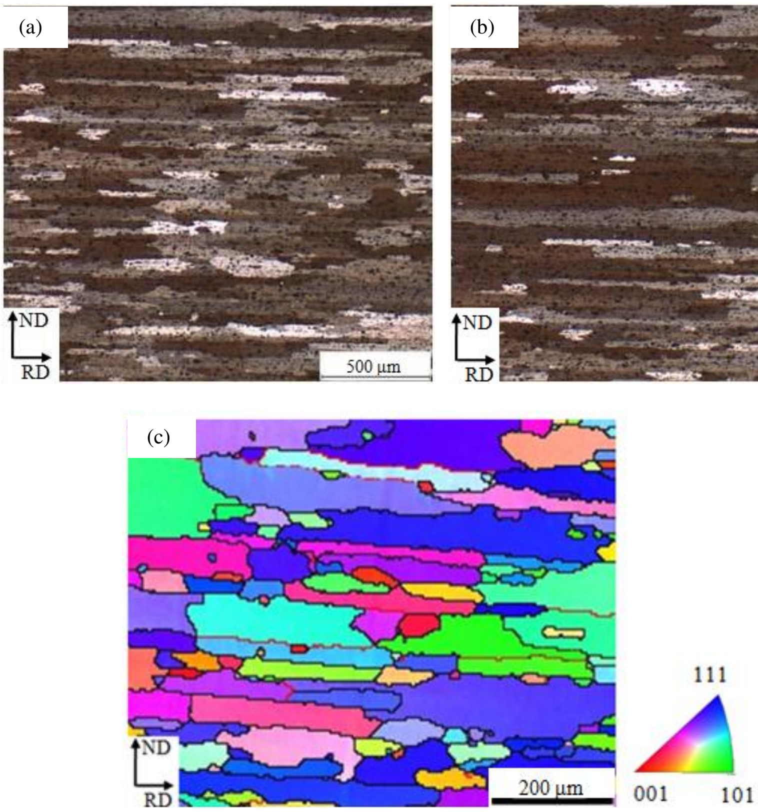

Fig. 5 Initial microstructure: (a) Initial microstructure near surface, (b) Initial microstructure in middle of the thickness and (c) EBSD orientation image near surface

3.2 Characteristics of microstructure after shear spinning

The optical microstructures of shear spun workpieces in R-N plane under different deviation ratios are obtained, as shown in Fig. 6. It can be seen that after shear spinning, initial grains are further flatten and elongated in R-N plane and grain orientations tend to be consistent with that of the initial grains (Fig. 5). Furthermore, with the decreasing of deviation ratio, grains gradually become thinner and longer while the grain boundaries become obscure.

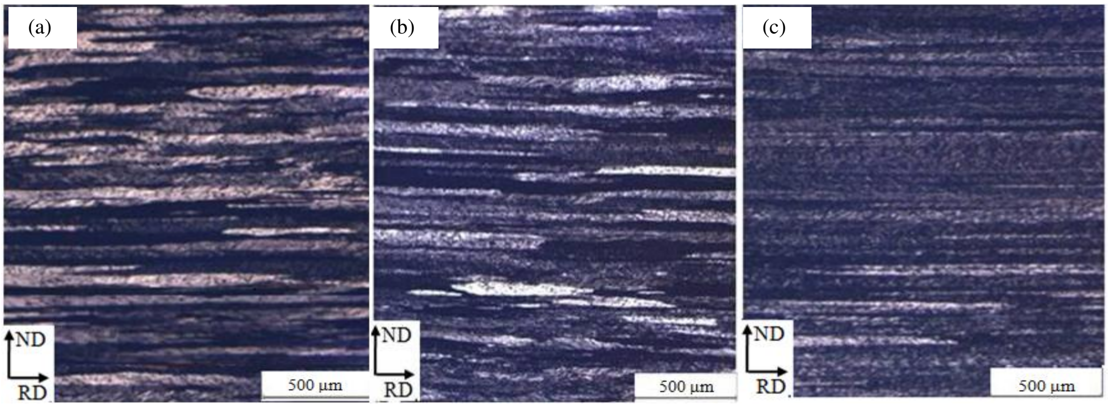

Fig. 6 Microstructure of spun parts obtained under different deviation ratios at α=30° : (a) χ=28.66% , (b) χ=0 and (c) χ= - 22.33%

Considering that grains are elongated significantly along rolling direction, EBSD technique at low magnification is adopted to obtain the variation of grain size, as shown in Fig. 7. The black lines in these figures represent the angle boundaries that are greater than 15°. It can be seen that, after spinning, the major axes of some grains even exceed 600μm under positive and zero deviation conditions. With the deformation increasing, minor axes of grains are decreased and the amount of small grains is increased. After measurement, average grain diameters are decreased from 48.6μm of initial microstructure to 9.6μm, 9.2μm and 8.7μm under χ=28.66% , χ=0 and χ=-22.33% , respectively. Rapid decrease of grain size is mainly due to the number of refined grains generated after shear spinning. Average radius ratios of coarse lath-shaped grains in

EBSD images are increased from 12.60 of initial microstructure to 22.08 and 32.08 under χ=28.66% and χ=0, respectively. Then the average radius ratio is decreased to 19.38 under χ=-22.33%, which can be attribute to the grain refined more under negative deviation ratio. Meanwhile, compared with the orientation of initial grains as shown in Fig. 5(c), there are some substructures in elongated grains. The distribution of misorientation angle under different deviation ratios is shown in Fig. 8. It can be seen that with the deformation increasing, low angle boundaries transform into high angle boundaries gradually and the percentage of high angle boundaries is increased from 17% to 28%, which indicates a greater degree of grain refinement.

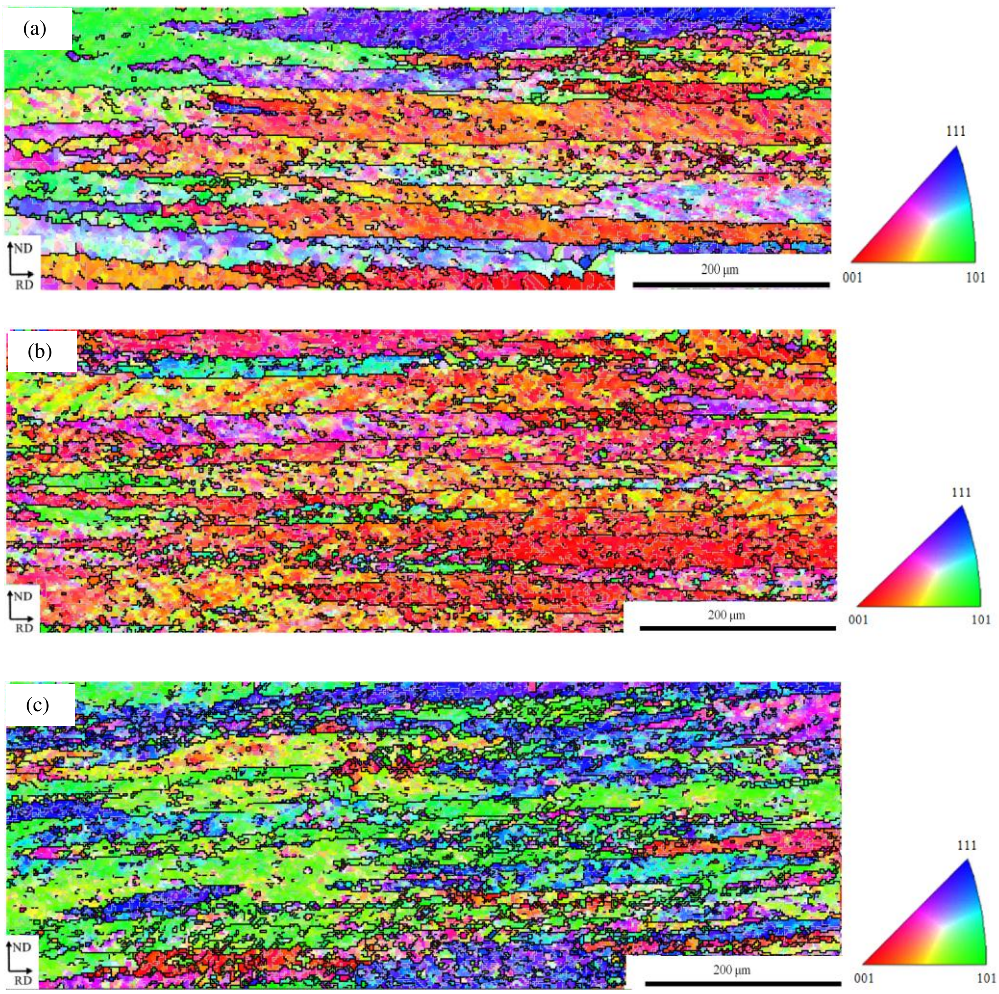

Fig. 7 EBSD images of 3A21-O alloy after shear spinning under (a) χ=28.66%, (b) χ=0 and (c) χ= - 22.33%

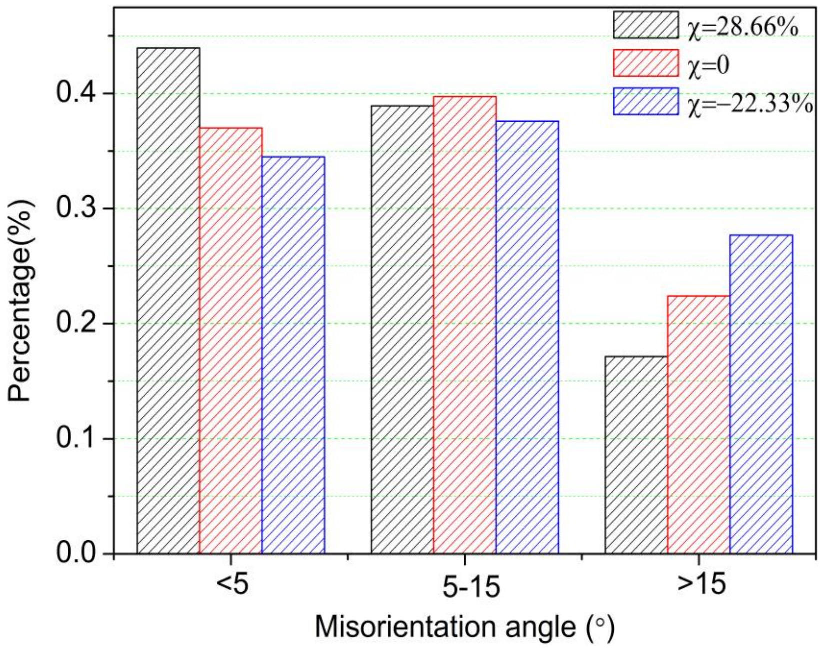

Fig. 8 Distribution of misorientation angle under different deviation ratios

To observe the characteristics of microstructure clearly in R-N plane of spun part, the microstructure under higher magnification is obtained at α=30° and χ=-22.33%, as shown in Fig. 9. It can be seen that the microstructure is unevenly distributed along the thickness direction. There is an area near the middle plane of sheet thickness, which is slightly shifted towards to the inner surface (the surface contacting with mandrel); an interesting observation is that the microstructure is distributed symmetrically about this area, as shown in Fig. 9. The area is defined as the neutral zone in this study, and the width of the neutral zone is approximately 150μm. This phenomenon indicates that the degree of material deformation gradually decreases from sheet outer surface (the surface contacting with rollers) to inner surface. The deformation occurred in inner surface due to the friction between mandrel and blank is also important and should not be ignored in investigating grain refinement. Grains seem to be fragmented by many tiny strips, as clearly seen in Fig. 9.

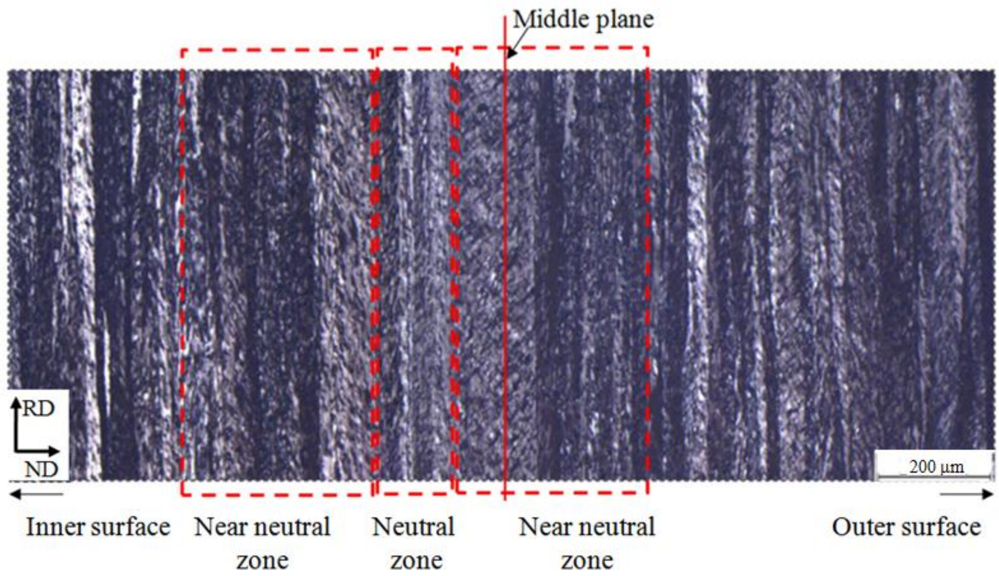

Fig. 9 Microstructure in the near middle section of sheet thickness obtained at α=30° and χ= - 22.33%

Fig. 10 shows the microstructure in neutral zone under various deviation ratios. It can be seen that grains have very little refinement in the neutral zone but fragmented in both sides of sheet surfaces under positive and zero deviation ratios, as shown in Figs. 10(a) and 10(b), respectively. However, under a negative deviation ratio, through-thickness refinement occurs (Figs. 9 and 10(c)). These results indicate that grains can be refined differently when subjected to different degrees of deformation under different deviation ratios in shear spinning. The reasons for these observations are that under positive and zero deviation ratios, the speed of material flow gradually decreases from the outer surface to the inner surface of sheet due to the effect of rollers; on the other hand, friction between mandrel and blank could also lead to material flow at some degrees in inner surface. There is no doubt that the degree of deformation in the outer surface is greater than that in inner surface. However, the amount of deformation in inner surface is relatively small under positive and zero deviation ratios. Thus there is an undeformed zone or small deformation zone which deviates from the middle plane of the sheet thickness (Zone Ⅰ in

Figs. 10(a) and (b)), the grains from the surfaces to the neutral zone are clearly refined. When under a negative deviation ratio, the material in middle section of the thickness can also flow because of large deformation and the friction between blank surfaces and mandrel as well as rollers. Thus the microstructure can be refined through the whole thickness of the spun sheet.

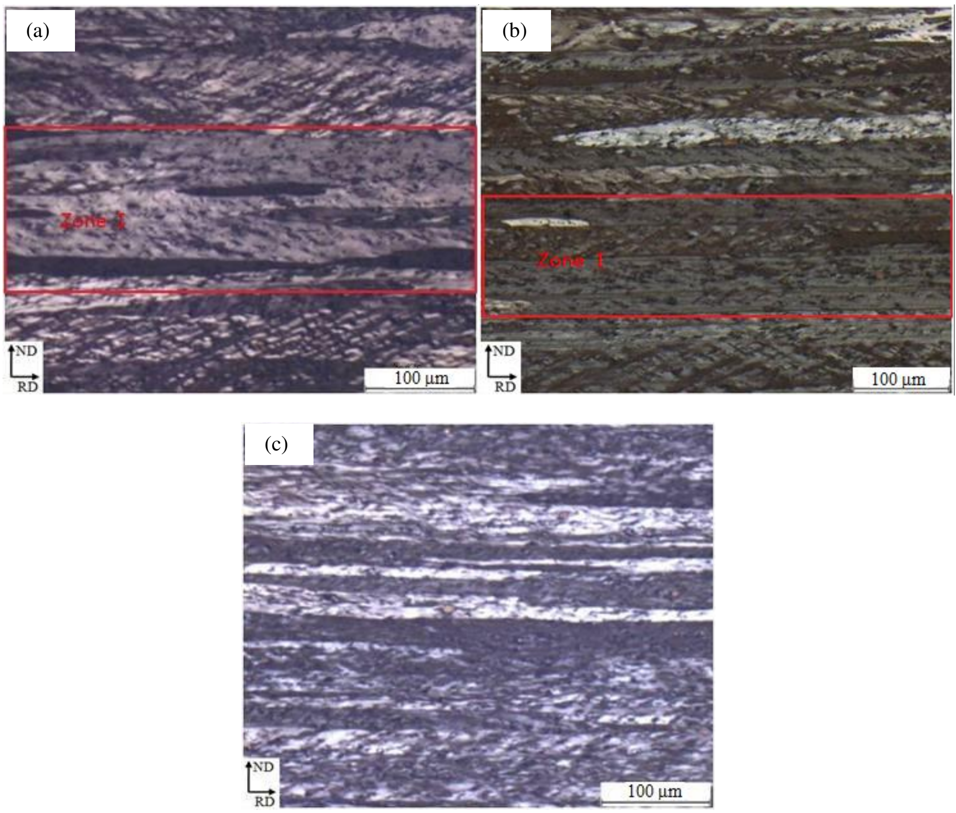

Fig. 10 Microstructure in the neutral zone of sheet thickness obtained at α=30° under (a) χ=28.66% , (b) χ=0 and (c) χ= - 22.33%

Fig. 11 shows the microstructure near the neutral zone of sheet thickness obtained at α=30° under various deviation ratios. It illustrates that under a positive deviation ratio, grains are refined by the crossed strips with an angle near 135°; when the deviation ratio is zero, grains are fragmented by a number of parallel tiny strips with an angle of near 35° to rolling direction; while under a negative deviation ratio, angles of the crossed strips are near 90°. These are related to the mechanism of microstructure refinement and will be explained in the following section.

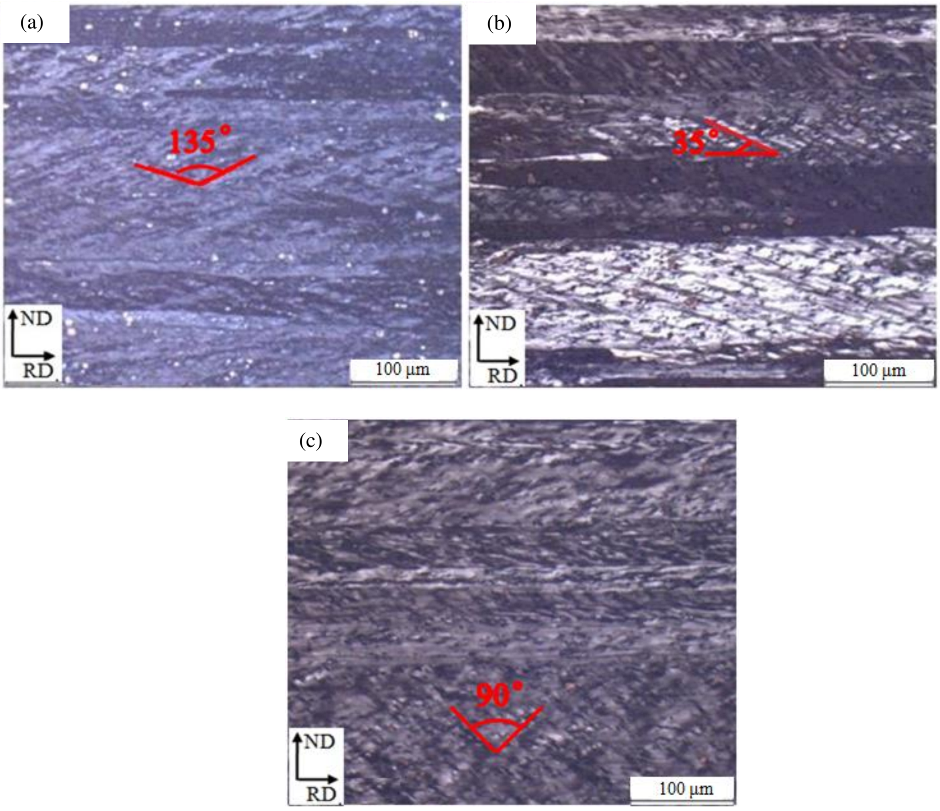

Fig. 11 Microstructure near the neutral zone of sheet thickness obtained at α=30° under (a) χ=28.66% , (b) χ=0 and (c) χ= - 22.33%

3.3 Mechanism of grain refinement in shear spinning

To investigate the mechanism of grain refinement in shear spinning, EBSD technology at higher magnification is adopted to obtain the grain orientations of the microstructure in a localised area, as circled in Fig. 12(a) and shown in Fig. 12(b), under a zero deviation ratio. It can be seen that, the observation area is obviously made up by three colours of parallel bands, that is to say, there are three types of orientation in grains, <110>, <111> and <101>, respectively. There are narrow bands with small misorientations about the neighbouring bands, as shown by the narrow yellow regions in the EBSD orientation image (Fig. 12(b)). These parallel bands are changed from one to another, as shown in Fig. 12(b). In green bands, there are some black lines with an angle near 35° to rolling direction. The grain characteristics in this localised area are similar to features of deformation bands (DBs), which subdivide grains, particularly coarse-grains, into regions of different orientations during deformation, which are often observed on a macroscopic scale in aluminium and its alloys [13, 23-26]. In Al-1% Mg alloy [13], such DBs were characteristic of several black and white bands in optical image. In AA1060 aluminum plate processed by snake rolling [25] and in Al-Si-Cu alloys after tensile testing [26], the similar DBs to those in this study, which were characteristic of many bands with different colors in EBSD orientation image, were also generated. Meanwhile, orientation differences between neighbouring DBs are accommodated in transition bands whose width is reduced to only one or two units but the large orientation change is retained [27]. The macroscopic subdivision of grains into DBs and transition bands superimposes on microscopic break-up into cell blocks, which are bounded by longer, aligned boundaries termed as geometrically necessary boundaries (GNBs), including dense dislocation walls (DDWs) and microbands (MBs) [13, 20]. It is reported that GNBs are aligned approximately with an angle of 25°~ 40° to the rolling direction. Generally, one or two sets of GNBs can be observed in DBs. These phenomena are similar to the characteristics of optical images and EBSD orientation images after shear spinning obtained in this study. These indicate that in shear spinning, the formation of DBs is the major mechanism of microstructure refinement. And in DBs, grains are micro subdivided by GNBs, namely some tiny strips observed in above optical images and substructures observed in EBSD images. As for the formation of DBs, one theory is that, different regions of a grain may experience different strains if the work done within the bands is less than that required for homogeneous deformation and if the bands can be arranged so that the net strain matches to the overall deformation [28]. Thus different regions of a deforming grain gradually rotating to different orientations lead to grain subdivision. This theory was examined by Lee et al.

[29] in the model of rolling texture development. Their result showed theoretically that only two independent slip systems may suffice to accommodate the shape change when DBs occurs. Another theory is associated with the selection of operative slip system ambiguously. Imposed strains can be accommodated by more than one set of slip system and DBs are formed due to the slip systems rotations in different senses [28]. In shear spinning process, the formation of DBs is more likely to result from the sequences described in the first theory above because the complex stress state and initial coarse grain easily cause to different regions of a grain undergoing different strain in this process.

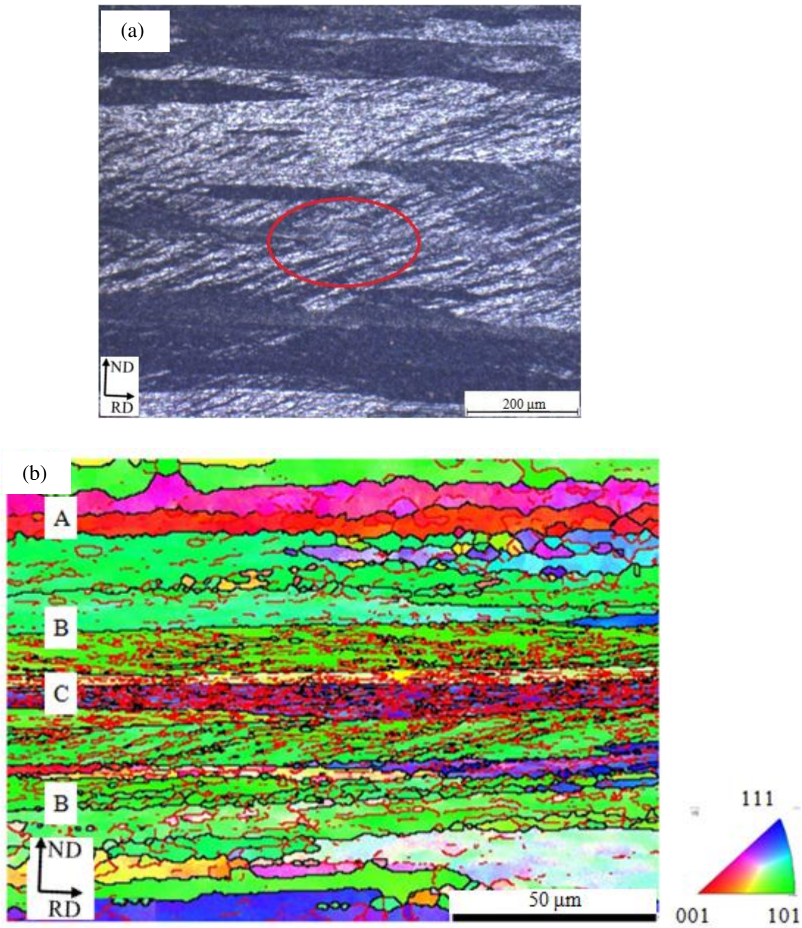

Fig. 12 Microstructure of the workpiece obtained at α=30° and χ=0 : (a) Optical microstructure and (b) EBSD orientation image in a localised area of (a)

Complicated stress states under various deviation ratios in shear spinning result in the different patterns of DBs, such as DBs with parallel GNBs under a zero deviation ratio and DBs with crossed GNBs under positive and negative deviation ratios, as shown in Fig. 11.

The mechanism of deformation in ideal shear spinning is pure shear stress state [30]. There are axial shear stress τ_0 generated by the compressive stress of the rollers in deformation area and circumferential shear stress τ_θ generated by the transmission of torsional moment when the blank rotates with the mandrel, as shown in Fig. 13. In shear spinning, due to the initial coarse grains of 3A21 aluminium alloy and inhomogeneous stress, it is easy to subdivide a grain into different regions undergoing different strain, which results in the different orientations in the grain. With the increase of deformation, misorientations between areas are increased and then the high angle boundaries are formed, which leads to the formation of DBs. Meanwhile, in DBs, parallel GNBs with an angle of near 35° to the rolling direction are generated under the effect of the shear deformation. Under a further deformation, the non-uniform strain in the interior of DBs increasing the misorientation of GNBs may bring about the formation of secondary DBs even tertiary DBs [24] and a greater refinement. For example, the black lines in green bands shown in Fig. 12 indicate that grain boundaries are generated along GNBs in DBs. Therefore, under a zero deviation ratio, grains are subdivided by DBs where the shear deformation is the main deformation mode. Wonsiewicz and Chin [31] have also been found the good agreement between a location-dependent shear strain and a macroscopic break-up of the grains.

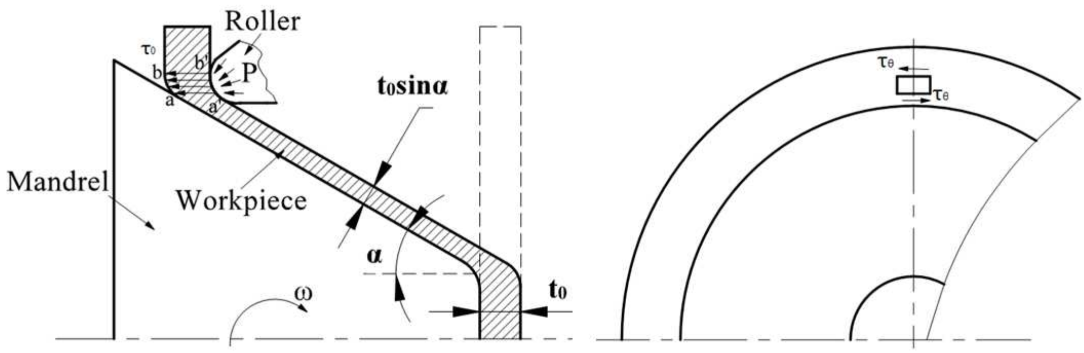

Fig. 13 Schematic description of the stress state in shear spinning

When the thickness of the spun part deviates from the Sine Law, there is additional stress in deformation area. Under a positive deviation ratio, the gap between mandrel and roller, t_1, exceeds the gap calculated by Sine Law, t_f. According to the volume constant condition, the material in the deformed area is supplied with the material in the flange area. Thus, the inner diameter of flange area R decreases by ΔR, which results in additional circumferential compressive stress σ_r and radial tensile stress σ_θ in flange area, as shown in Fig. 14(a). This implies that the material undergoes a combination of shear and tensile stress in deformation area under a positive deviation ratio. Since the complicated stress state under a positive deviation ratio, it is possible to form the two sets of GNBs in grains. Due to the effect of tensile stress, the angle of the GNBs is not 110°, the angle of GNBs crossed under zero deviation ratios, but larger than it. Therefore, the formation of DBs with crossed GNBs results in grain subdivision by a combination of shear and tensile deformation under a positive deviation ratio. When the deviation ratio is negative, however, the excessive material is squeezed into the flange area, which causes the inner diameter of flange area R increases by ΔR. Thus there are additional circumferential tensile stress σ_r and radial compressive stress σ_θ in flange area, as shown in Fig. 14(b). Similarly, formation of DBs with crossed GNBs by a combination of shear and compressive stress in deformation area lead to grain fragmentation under a negative deviation ratio. And the angle between the crossed GNBs is decreased under the influence of compression deformation when the deviation ratio is negative.

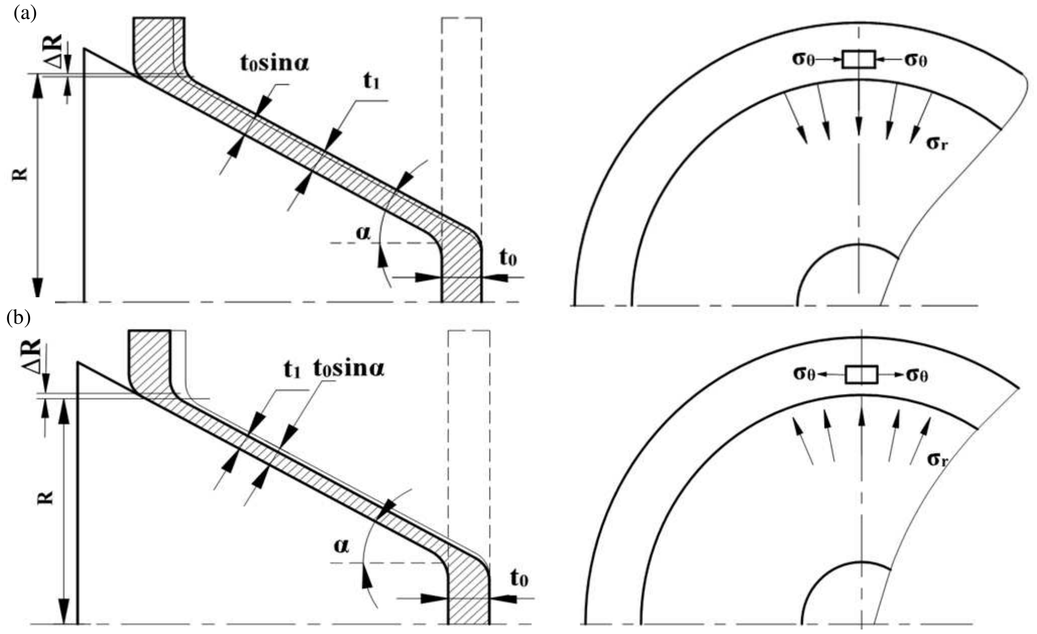

Fig. 14 Schematic of the stress state in flange area in shear spinning under (a) a positive deviation ratio and (b) a negative deviation ratio

Therefore, grain refinement of 3A21-O aluminium alloy in shear spinning could be regarded as the grain subdivision by DBs. Firstly, different regions of a grain may experience different amounts of strain, and with an increased deformation, the misorientation between the two bands increases. Then the different patterns of DBs and transition bands are formed under complicated stress states. Finally, under a further plastic deformation, a relatively high cumulative misorientation between GNBs in the interior of DBs leads to the formation of secondary DBs even tertiary DBs, which may bring about a greater degree of macroscopic break-up of grains.

3.4 Effects of grain refinement on micro hardness

To investigate the effect of grain refinement on mechanical properties of shear spun parts, micro hardness is measured to examine the variations of mechanical properties. The initial average micro hardness of 3A21-O alloy sheet is about 62.5 HV. Average relative standard deviation is approximately 1.41% and the maximum relative standard deviation of the point near surface can reach to 4.81%. Micro hardness distributions and standard deviation of spun parts from inner surface to outer surface are obtained, as shown in Fig. 15.

It can be seen that, after shear spinning, micro hardness is obviously improved compared to that of the initial blank, micro hardness values increase when the deviation ratio is decreased. The average improvements in micro hardness under various deviation ratios are shown in Table 3. It can be seen that under a negative deviation ratio, the average micro hardness is increased by 16.04% from the initial value. However, micro hardness values fluctuate along thickness direction and the fluctuation is increased with the deviation ratios increasing. Under positive and zero deviation ratios, the values near surfaces seem to be smaller than the values near neutral zone. The reasons for these observations are that, the micro hardness of surfaces is influenced by grain refinement and work hardening on one hand. Meanwhile, severe deformation in surfaces leads to serious distortion of grains, therefore the stability of compression resistance is reduced, which result in a decreased micro hardness. Thus, when the deformation is relatively small, micro hardness near surfaces may be lower than that near neutral zone. On the other hand, the fluctuation of micro hardness near surface may be resulted from the experiment error. It is also observed that the micro hardness values of the neutral zone are lower than the values of the areas near the neutral zone under positive and zero deviation ratios. The reason is that, the thickness reduction is small in these cases, and the degree of deformation is so small in the neutral zone that grains have very little refinements in neutral zone, which results in smaller micro hardness of the neutral zone. Under a negative deviation ratio, the micro hardness value gradually increases from the inner surface to the outer surface, as shown in Fig. 15. This is due to large deformation along thickness direction resulting in uniform refinement of grains. This corresponds to the characteristics of grain refinement under this condition as explained above.

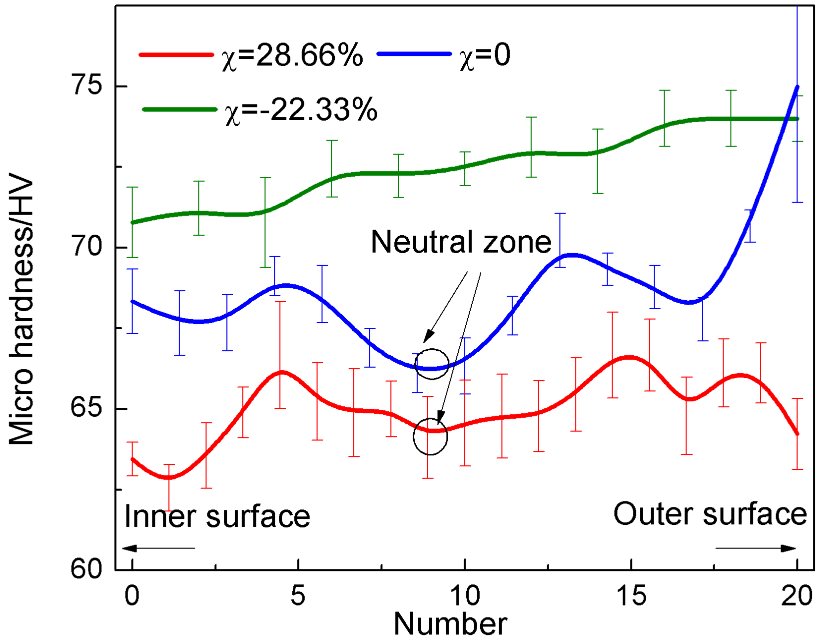

Fig. 15 Micro hardness of workpiece under different deviation ratios obtained at α=30°

Table 3 Improvement of micro hardness under various deviation conditions

Deviation ratios	χ=28.66%	χ=0	χ=-22.33%
Average improvement (%)	3.95	10.13	16.04

4. Conclusions

The microstructure of 3A21-O aluminium alloy in shear spinning under various deviation ratios is studied and the grain refinement mechanism is analysed. The main conclusions are as follows:

(1) After shear spinning, significant grain refinement can be found under various deviation ratios. However, the distributions of grain refinement along the thickness direction are different. Under positive and zero deviation ratios, grains in the neutral zone are little refined; while a through-thickness refinement can be achieved under a negative deviation ratio.

(2) The mechanism of grain refinement in shear spinning of 3A21 aluminium is due to the

formation of deformation bands (DBs). These DBs are generated by the formation of the high angle boundaries, which are resulting from the increase in misorientations among the different regions of a grain due to the initial coarse grain and inhomogeneous deformation. In addition, in these DBs, there are parallel geometrically necessary boundaries (GNBs) formed by a zero deviation ratio and crossed GNBs formed by positive and negative deviation ratios due to the different stress states induced by various deviation ratios.

(3) The non-uniform grain refinement leads to different improvements in micro hardness along thickness direction after shear spinning. The average value of micro hardness is increased with the deviation ratio decreased. Under a negative deviation ratio, the average value of micro hardness can be increased by about 16% compared with the initial value.

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