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Geometric precision and microstructure evolution of TA15 alloy by hot shear spinning

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Abstract: To investigate the mechanistic influence of the deviation ratio and heating temperature on the hot shear spinning of TA15 alloy, the geometric precision and microstructure evolution of the hot-spun parts were experimentally investigated under different conditions. The results show that diametrical shrinkage occurs under a negative deviation ratio, and a sudden decrease in heating temperature creates a sharp increase in the shrinkage. A pronounced diametrical enlargement increases from the bottom location to the open end of the workpiece under a positive deviation ratio with a gradual decrease in heating temperature. The hot shear spinning process can lead to a non-uniform microstructure that results from the non-uniform deformation along the thickness direction. The distortion degree of the fiber microstructure formed near the outer surface increases with the decrease in the deviation ratio. A deviation ratio near zero and heating to a temperature within the desired range are beneficial conditions for obtaining spun parts with satisfactory geometric precision and a uniform microstructure.

Key words: titanium alloys; hot shear spinning; geometric precision; microstructure

1 Introduction

Spinning is commonly known as a process that transforms flat sheet metal blanks into hollow shaped parts via the action of one or more rollers that contacts the blank and progressively induces a change in its shape and wall thickness according to the profile of the mandrel and the track of the roller. Because the roller is applied locally to the workpiece, the total formation forces can be significantly reduced compared with conventional press forming. The spinning process combines exceptional flexibility with suitability for producing complicated axisymmetric parts that are highly close to the net shape, thus enabling engineers to optimize designs and reduce the weight and cost of parts. Consequently, the spinning process has been increasingly utilized in aviation, aerospace, weapon and automotive industries [1]. The TA15 alloy represents a type of advanced material that provides the properties of high strength, excellent corrosion resistance, good weldability and high temperature performance as well as light weight compared with steels and Ni-based alloys, thus serving as an important structural material in the aviation and aerospace industries [2]. However, high deformation resistance and low ductility limit its spinnability under the conventional cold spinning process. The specific use of temperature reveals the potential to achieve a significant reduction in the force and/or pressure required for forming [3]. Therefore, the development of a hot-spinning technology for production of TA15 products is of significant importance. However, due to the difficulty of achieving temperature gradients suitable for forming [4], the complex deformation characteristics (such as the expansion caused by heat, the shrinkage caused by cooling [5] and the interactions of expansion, shrinkage and springback after the spinning process) and the low elastic modulus of titanium alloys [6], it is difficult to control the geometric precision and the microstructure of hot-spun parts of the TA15 alloy.

At present, research works that address the characteristics of stress and strain, forming defects and the influence of the process parameters on the hot flow forming and hot shear spinning processes were carried out using the finite element method (FEM) and experimental methods. For hot flow forming, SHAN et al

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[7−9] analyzed the microstructure evolution, the mechanical properties, and the correlations of the microstructure and texture with the deformation history in the hot backward flow spinning process of the BT20 tube using FEA and experimental methods. The results show an obvious through-thickness inhomogeneity in the deformation, the microstructure and the texture. The inhomogeneity of the as-spun microstructure can be strongly reduced using multi-pass and large-deformation tube spinning. At the same time, the tensile strength increased, and the elongation decreased not only in the axial direction but also in the circumferential direction, which means that a tubular workpiece of titanium alloy can be strengthened bi-directionally via spinning. HUANG et al [10] numerically investigated the influence of the coefficient of friction, the roller translation speeds and the roller radius on the neck-spinning process for a JISG3141 steel tube at elevated temperatures. They also compared the experimental and simulated results with respect to the thickness distribution and the outer contour of the spun tubes. Based on these studies, they concluded that spun tubes with acceptable properties could be produced by hot flow forming techniques. On the topic of hot shear spinning, MORI et al [11] developed a hot shear spinning process for cast aluminum alloy parts that can eliminate casting defects and produce a desired distribution in the wall thickness and reported that dendrites and shrinkage cavities in the cast aluminum alloys might be successfully eliminated by hot shear spinning without the occurrence of fracture. LI et al [12] established a three-dimensional (3D) elastic-plastic FE model coupled with the thermal-mechanical effect for hot shear spinning of a TA15 thin-walled cone. Using this model, ZHAN et al [13] investigated the distribution and variation features of the temperature field and the stress and strain fields as well as the influence of the process parameters on the process; they also found that the effect of the contact heat exchange and the friction heat can cause a large temperature gradient along the thickness direction of the deformation zone, which can result in remarkable inhomogeneous deformation. The thermal stress has a significant influence on the magnitude and distribution of the stress. And they also investigated significant factors that influence the differences in wall thickness, the fittability of the workpiece with the mandrel and the trend of wrinkle. These results may provide a theoretical guide for the determination and optimization of the forming parameters for the hot spinning process of TA15 thin-walled cones. However, the FEM analysis of the geometric precision and the microstructure evolution in hot spinning process will encounter severe difficulties. These issues include complex boundary conditions, spatially clustered non-uniform arrangements of complex-shaped grains, strong microstructural sensitivity to processing [14], and the complex deformation characteristics mentioned previously. Although the experiments are expensive to conduct, the experimental results are accurate and reliable and can be used directly to solve the practical problems in production. As a result, it is necessary to use experimental methods to research the geometric precision and the microstructure evolution of a hot-spun part.

In shear spinning, the deviation condition of the gap between mandrel and roller deviating from Sine law ($t=t_0\sin\alpha_0$, t is the final wall thickness, t_0 is the initial blank thickness, and α_0 is the half-cone angle of the mandrel) is an important influence factor to forming quality. This deviation condition is called as deviation ratio from Sine law, and is simplified as deviation ratio. In terms of spinning theory, negative deviation can improve the spinning feasibility of material and the fittability of the spun part with the mandrel but will increase the spinning force. Conversely, positive deviation can decrease the spinning force at some degree. With respect to the process parameters, ZHAN et al [15] found that the deviation ratio is one of the most important factors that affect the product precision, and CHEN et al [16] also demonstrated that a negative deviation ratio may improve the shape and size precision of cold-spun parts. However, to date, few studies have been conducted on the deviation ratio in the hot shear spinning process. Furthermore, XU et al [8] demonstrated that the spinning temperature has a distinct influence on the forming properties of spun workpieces. Therefore, in this study, the heating temperature was selected as the other decisive parameter. The results of experiments on the hot shear spinning of conical TA15 alloy workpieces were presented under different deviation ratios and heating temperatures. The geometric precision of the hot spun parts was examined and the microstructure evolution was observed. Finally, the findings concerning the mechanistic effects of the deviation ratio and heating temperature on the geometric precision and microstructure evolution of TA15 material were discussed. The results may provide a significant guide to practical control of the geometric precision and microstructure for the hot shear spinning of TA15 alloy.

2 Experimental

2.1 Materials

The TA15 alloy chosen as the experimental material was produced by Baoji Non-ferrous Metal Works in the form of an as-hot-rolled sheet with a nominal thickness of 5 mm. The chemical composition of the blank is listed in Table 1.

Table 1 Chemical composition of TA15 blank (mass fraction, %)

Position	Al	V	Mo	Zr	Si	Fe
Upper layer	6.7	1.3	1.2	2.0	0.02	0.04
Under layer	6.6	1.4	1.2	1.0	2.0	0.02
Position	C	N	H	O	Ti	
Upper layer	0.01	0.01	0.003	0.008	Bal.	
Under layer	0.04	0.01	0.01	0.10	Bal.	

Figure 1 shows the initial microstructures of the TA15 blank. The initial microstructure consists mainly of α phase (bright areas) with a small amount of β phase (dark areas). The grains appear as bar-shaped under the action of rolling deformation, but the microstructure in cross-section is distributed more randomly than that in the axial section.

Fig. 1 Initial microstructures of TA15 blank: (a) Axial section; (b) Cross-section

2.2 Conditions

Negative, zero and positive deviation ratios were employed to examine the effects of the deviation ratio and the heating temperature on the hot shear spinning of TA15 alloy. The blank was heated by two hand-held oxyacetylene flames located in front of the rollers in an attempt to maintain a temperature in the range of 500−600 °C, as monitored by an infrared thermometer. Because this temperature is rather low, no phase transformation will occur in the deformation. Figure 2 shows the temperature recorded during the spinning process. As observed in Fig. 2, the temperature was variable and did not remain in the desired range due to the difficulty of controlling the temperature of the blank via the flame heating in addition to the complicated heat exchange under different deviation ratios. From Fig. 2, it can be observed that except for a gradual decrease in temperature at the final stage, the temperature under a zero deviation fluctuates slightly regardless of the deviation ratio, the temperature under a negative deviation also fluctuates slightly except for a sharp decrease in the middle stage and the temperature under a positive deviation decreases while the spinning process going on. The other main parameters are a roller feed rate of 1.0 mm/r and a mandrel revolution rate of 60 r/min. The mandrel and rollers used in the hot shear spinning experiment are illustrated in Fig. 3, and the definitions of the directions on a spun part are shown in Fig. 4.

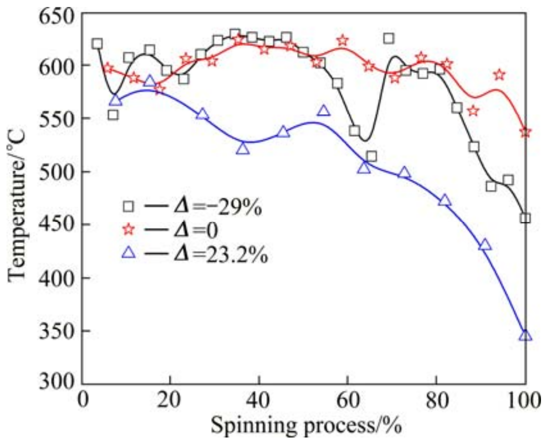

Fig. 2 Experimental conditions for hot shear spinning (Δ: Deviation ratio)

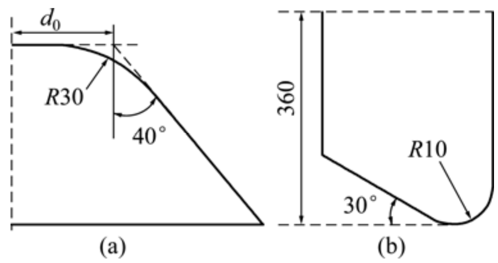

Fig. 3 Dimensions of mandrel (a) and roller (b) (Unit: mm)

Additionally, the microstructure evolution in the wall region of the spun part was observed in both tangential and circumferential sections (Fig. 4) along the thickness direction. The specimens for optical metallography were etched with a solution consisting of 13%HF+7%HNO_3+80%H_2O.

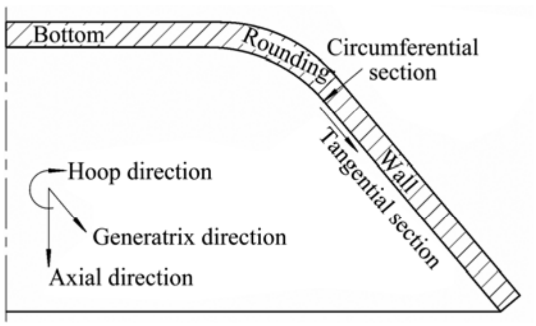

Fig. 4 Definition of directions and sections of spun part

2.3 Indices for geometric precision

In this section, the shape and size characteristics for the geometric precision of the spun cone walls were described. These indices include the inner diameter deviation, the wall thickness deviation, the wall thickness difference, the hemi-cone angle deviation and the relative inner diameter difference. The first three indices were used in this work as the indices of size precision, and the latter two were used as the indices of shape precision.

The definitions of the indices are shown as follows.

1) The inner diameter deviation δ_{D} includes the maximum inner diameter deviation of $\delta_{\mathrm{d},i}^{\max}=D_i^{\max}-D_i$ and the minimum inner diameter deviation of $\delta_{\mathrm{d},i}^{\min}=D_i^{\min}-D_i$, where $D_i^{\max}$ and $D_i^{\min}$ are the maximum and minimum values of the actual inner diameter of a spun part at the cross-section i, respectively, and D_i is the corresponding diameter of the mandrel at the cross-section i, as shown in Fig. 5. δ_{D} represents the fittability of the spun part with the mandrel, and a δ_{D} value near zero indicates a good fittability of the spun part. δ_{D} also represents the diametrical enlargement or shrinkage of the spun part. The difference between $\delta_{\mathrm{d},i}^{\max}$ and $\delta_{\mathrm{d},i}^{\min}$ indicates the fittability distribution at the cross-section i. A small value of this difference indicates a uniform fittability in a hoop.

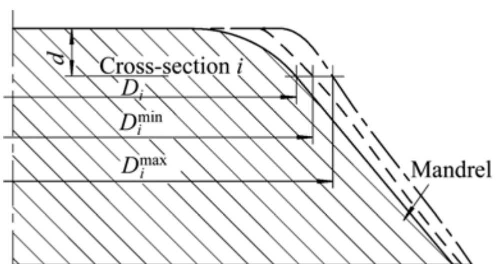

Fig. 5 Measurement of inner diameter

2) The wall thickness deviation δ_{t} is defined as $\delta_{\mathrm{t},i}=t_i-t$. In this equation, t_i is the average wall thickness at the cross-section i of a spun part, and t is the ideal wall thickness of the part. A small value of δ_{t} represents a high precision of the wall thickness distribution.

3) The wall thickness difference is defined as $\Delta t=t_{\max}-t_{\min}$. In this equation, $t_{\max}$ and $t_{\min}$ are the maximum and minimum values of the wall thickness in the wall zone of the spun part, respectively. Δt indicates the uniformity of the wall thickness distribution. A small value of Δt indicates an even wall thickness distribution.

4) The hemi-cone angle deviation δ_α includes the maximum hemi-cone angle deviation $\delta_{\alpha,i}^{\max}=\alpha_i^{\max}-\alpha$ and the minimum hemi-cone angle deviation $\delta_{\alpha,i}^{\min}=\alpha_i^{\min}-\alpha$. In these equations, $\alpha_i^{\max}$ and $\alpha_i^{\min}$ are the maximum and minimum values, respectively, of the actual hemi-cone angle at each tested point on the cross-section of spun part, and α is the ideal hemi-cone angle. A near-zero value of δ_α reflects a satisfactory shape fixability. The difference between $\alpha_i^{\max}$ and $\alpha_i^{\min}$ indicates the shape fixability distribution in a hoop.

5) The relative inner diameter difference is defined as $\Delta D_i=(D_i^{\max}-D_i^{\min})/(D_i-d_0)\times 100\%$. The meaning of d_0 is shown in Fig. 3(a). In this study, the value of d_0 is 180 mm. ΔD_i represents the roundness of the spun part. As the value of ΔD_i decreases, the roundness of the spun cone improves.

A 3D laser scanning system and graphical software were adopted to assess the dimensional accuracy of the inner diameter. The detailed steps were conducted as follows: 1) Scan the inner surface of a spun part with a VxScan laser scanning system; 2) Import the scanned results into the UG software; 3) Intercept selected cross-sections on the spun part using the planes parallel to the bottom plane with a certain distance d from the bottom plane of the spun part (Fig. 5); 4) Measure the diameter of the part at each cross-section. Additionally, the wall thickness of the spun part was measured four times for each section using a PX−7 ultrasonic thickness instrument with a precision of 0.01 mm. In this study, all data were obtained after the spun parts were removed from the tools and cooled.

3 Results and discussion

The results of the geometric precision of the size and shape of TA15 spun-cone parts were first presented under different deviation ratios and varied temperatures along with analysis of the variation rules of the geometric precision indices and the influencing mechanism of the deformation conditions. Next, the circumferential and tangential microstructures of spun parts were presented under different deviation ratios by an analysis of the observed differences and an explanation was presented in terms of non-uniform deformation and temperature difference, etc.

3.1 Geometric precision

Figure 6 shows the influence of the deviation ratio Δ on the inner diameter deviation δ_D. It can be observed that under the same deviation ratio, $\delta_{d,i}^{max}$ and $\delta_{d,i}^{min}$ vary similarly with the axial distance to the bottom d, but under different deviation ratios, there is an obvious difference in the variation of δ_D with increasing d.

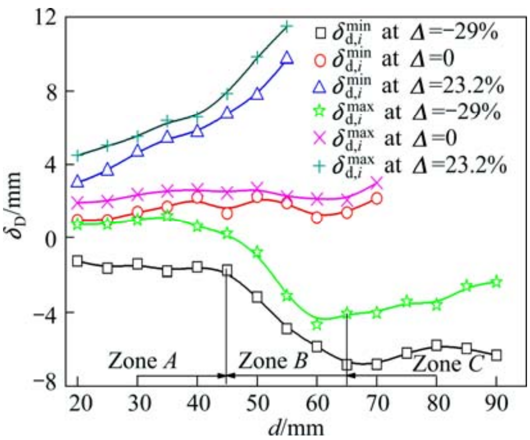

Fig. 6 Influence of deviation ratio on inner diameter deviation

As shown in Fig. 6, if the deviation ratio is negative, the values of δ_D are almost negative. The absolute values of δ_D vary somewhat when d is less than 45 mm, then increase gradually with increasing d and are observed to fluctuate after d becomes larger than 65 mm. According to the variation characteristics of δ_D, the wall zone can be partitioned into three zones, referred to as zone A (the zone near the bottom), zone B (the middle of the wall zone) and zone C (the zone near the open end), as shown in Fig. 6. The above results indicate that a certain amount of diametrical shrinkage occurs in the wall zone. The shrinkage in zone A is small, and the shrinkage in zone B increases sharply, while the shrinkage rate slows when d extends into zone C.

After spinning under the large negative deviation, the surface temperature of the deformed region decreases quickly due to the thin wall, and thus the deformed area contracts distinctly to grasp the mandrel during the spinning. In addition, the expansion in diameter resulting from the springback is small due to a large deformation under large negative deviation ratios, while the reduction in diameter resulting from the cooling is large due to the high spinning temperature of approximately 600 °C. This combination causes the diameter of the deformed area to contract further, and thus δ_D is negative. The sharp increase in shrinkage in zone B is mainly due to a sudden decrease in the heating temperature during the spinning process at that stage, as shown in Fig. 2. The sudden decrease in the heating temperature can drive an increase in the expansion in diameter resulting from the springback and an increase of the reduction in diameter resulting from the cooling. Moreover, the sudden decrease in the heating temperature increases the temperature difference and creates uneven deformation along the wall thickness direction in the deformation zone. Additionally, there is a strong restriction effect from the flange. The combined effects lead to a sharp increase of the shrinkage in zone B. The reduction of shrinkage in zone C is mainly due to the decrease in the heating temperature at the final stage (Fig. 2) and the decreasing restriction from the flange.

As shown in Fig. 6, when the deviation ratio is positive, the values of δ_D are positive and increase as d increases with a maximum δ_D of approximately 12 mm. An increasingly pronounced diametrical enlargement appears along the axial direction from the bottom location to the open end, indicating a declining fittability of the part wall with the mandrel along the axial direction. The reasons for the poor fittability may be ascribed as follows: 1) a poor fittability of the deforming area with the mandrel during the spinning process under a large positive deviation; 2) the springback resulting from the increasing elastic deformation with decreasing heating temperature (Fig. 2); 3) the decreased diametrical contraction resulting from the cooling with the decrease in the heating temperature (Fig. 2).

As shown in Fig. 6, when the deviation ratio is zero, the values of δ_D are positive and increase slightly with d with the variation of δ_D in the range of 2.5 mm. The small fluctuation implies a better fittability of the spun part under the zero deviation than that produced under the positive and negative deviations from the Sine law. This is due to a minor variation in the heating temperature during the process under the zero deviation, as shown in Fig. 2.

As shown in Fig. 6, the difference between $\delta_{d,i}^{max}$ and $\delta_{d,i}^{min}$ under the negative deviation ratio is obviously larger than that under the positive or zero deviation ratio, which indicates that the diametrical enlargement/shrinkage along the hoop direction of the former is more obvious than that of the latter two. This may be attributed to the fast thermal diffusion resulting from the thin workpiece under the negative deviation ratio.

Figure 7 shows the influence of the deviation ratio Δ on the wall thickness deviation δ_t and the wall thickness difference Δt of the spun parts. From Fig. 7(a), it can be observed that regardless of the deviation ratio, the values of δ_t increase as d increases, the degree of deviation of the wall thickness from the Sine law under the zero deviation ratio is the smallest, and the values of δ_t are positive under a positive deviation ratio and negative under the negative deviation ratio. These observations are connected with the variation of the wall thickness

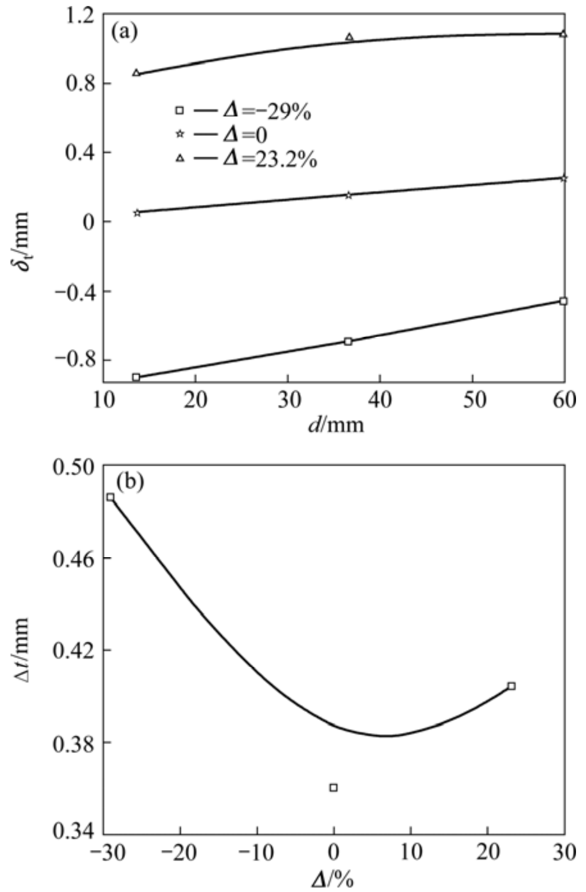

Fig. 7 Influence of deviation ratio on wall thickness distribution: (a) Wall thickness deviation; (b) Wall thickness difference of wall

under different deviation ratios with increasing d. The values of the wall thickness of all the workpieces spun under the different deviation ratios are observed to increase from the bottom location to the open end, the wall thickness formed under the positive deviation ratio is the thickest, and the wall thickness formed under the negative deviation ratio is the thinnest. At the early stage of the spinning process, the small effect from the deformed area and the large restriction from flange cause the rollers to shear the blank according to the Sine law. Therefore, it is the deviation ratio that determines the variation of wall thickness at this stage. As the spinning process progresses, the flange of the spun part decreases with the increasing d, and the tensile stress provided for thinning of the deformed area in the tangential direction decreases. The springback caused by residual stress and the shrinkage caused by the decreasing heating temperature together may lead to the increase of the wall thickness as d increases.

As shown in Fig. 7(b), the wall thickness difference Δt first decreases and subsequently increases as the deviation ratio increases from negative to positive. The small value of Δt can be attributed to the reasonable deviation ratio and the small variation of the heating temperature during the process.

Figure 8 shows the influence of the deviation ratio $\varDelta$ on the hemi-cone angle deviation δ_α and the relative inner diameter difference ΔD_i. As shown in Fig. 8(a), under the positive deviation ratio, the values of δ_α are positive and larger than those under the zero deviation ratio (which are also positive), and the values of δ_α are negative under the negative deviation ratio, except for the $\delta_{\alpha,i}^{\max}$ near zone A. The low shape fixability is caused by the springback and the shrinkage in the unloading and cooling process. The mechanism of the effects is similar to the analysis of the influence of the deviation ratio and temperature on δ_{D}.

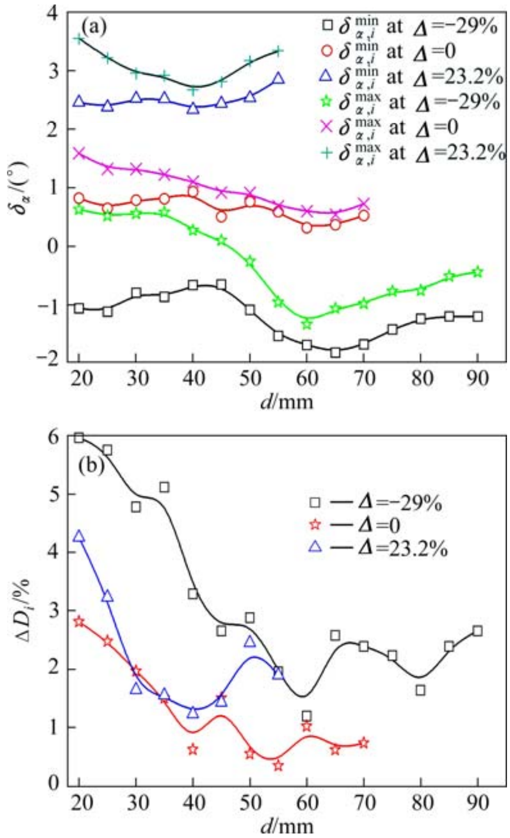

Fig. 8 Influence of deviation ratio on shape precision: (a) Hemi-cone angle deviation; (b) Relative inner diameter difference

From Fig. 8(b), it can be observed that along the axial direction of the workpiece, the relative inner diameter difference ΔD_i decreases gradually and subsequently fluctuates in a small range. With a small variation of the value of δ_{D} ($\delta_{\mathrm{d},i}^{\max}-\delta_{\mathrm{d},i}^{\min}$) (see Fig. 6) and the increase of D_i, ΔD_i decreases. The detailed variation of ΔD_i is closely related to the variation of the difference between $\delta_{\mathrm{d},i}^{\max}$ and $\delta_{\mathrm{d},i}^{\min}$ shown in Fig. 6. The combined effects are similar to the analysis of the influence of the deviation ratio and temperature on the difference between $\delta_{\mathrm{d},i}^{\max}$ and $\delta_{\mathrm{d},i}^{\min}$.

3.2 Microstructure

Figures 9 and 10 present images of the circumferential and tangential microstructures, respectively, under −29% of deviation ratio along the thickness direction. As shown in Figs. 9 and 10, a fiber microstructure forms near the outer surface along the circumferential direction and the tangential direction with refined grains smaller than those in the initial state. From the near inner surface to the near outer surface, the microstructure change from coarse to fine and the process of fiber microstructure changes from flat to distorted can be observed.

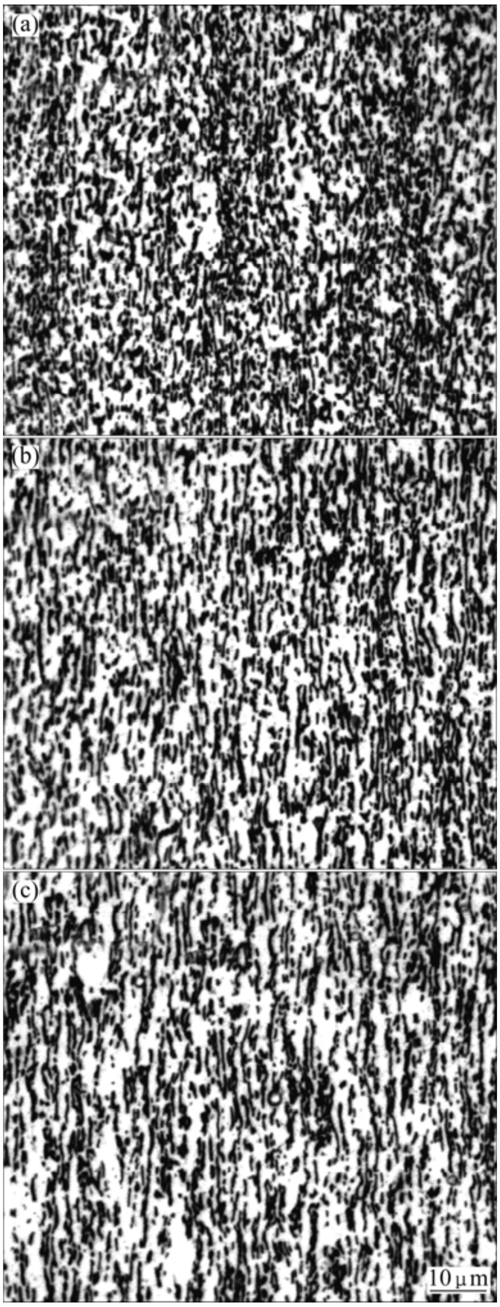

Fig. 9 Circumferential microstructure under −29% of deviation ratio along thickness direction: (a) Near outer surface; (b) Middle; (c) Near inner surface

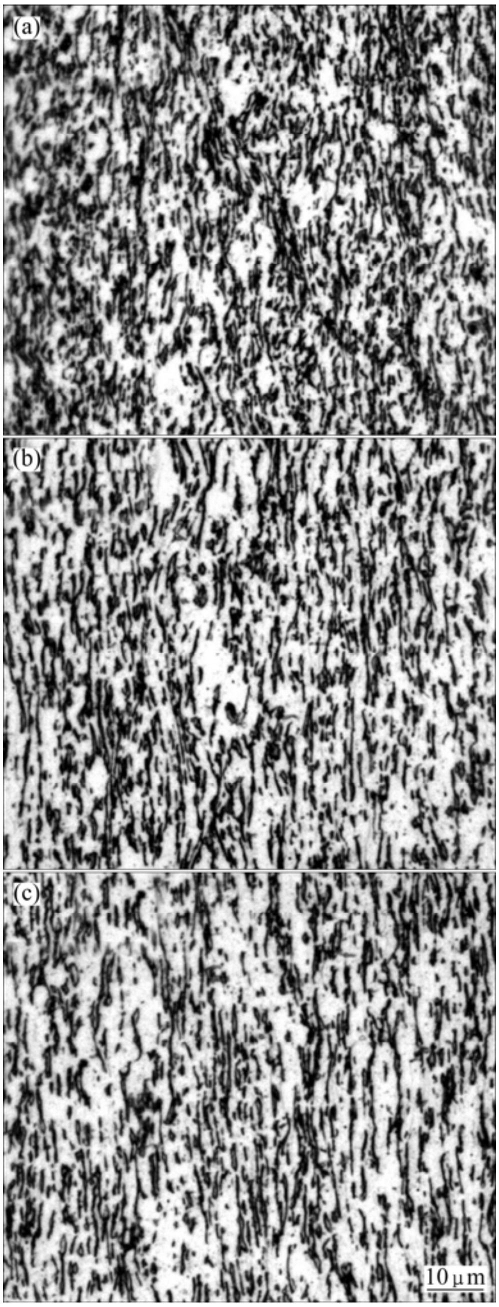

Fig. 10 Tangential microstructure under −29% of deviation ratio along thickness direction: (a) Near outer surface; (b) Middle; (c) Near inner surface

The non-uniform deformation along the thickness direction causes the difference in the microstructure on the near outer and inner surfaces. The reasons for this non-uniform deformation may relate to three aspects.

The first is the difference in friction among the workpiece, the mandrel and the rollers. The material is subjected to a large force moment produced by the shearing force, which produces the shear deformation in both the tangential and circumferential directions. The direction of the friction between the rollers and outer surface of the blank is the same as that of the metal flow, thus causing the material to flow forward. Meanwhile, the friction between the mandrel and the inner surface of the blank hinders the material from flowing, thus preventing the expansion of the deformation. All of these factors lead to the formation of a velocity gradient and a non-uniform deformation in the wall thickness direction. When the velocity gradient between the outer surface and the inner surface becomes sufficiently large, the distortion of the fiber microstructure forms near the outer surface.

The second reason for the non-uniform deformation lies in the difference in the deformation along the thickness direction. As the blank deforms under the action of the rollers from the outer surface and expands along the thickness direction during the process, the deforming area under the action of the rollers gradually increases from the outside to the inside along the thickness direction. This means that the absolute values of stress and strain will decrease gradually from the outer surface to the inner surface along the thickness direction.

The third reason is the temperature difference along the thickness direction. In the hot spinning process, the outer surface of the blank loses heat through radiation, air convection, and heat conduction and receives heat through the flame at the same time. However, the inner surface transfers heat to the dies mainly via conduction. As a result, the temperature of the outer surface may be much higher than that of the inner surface. Additionally, the low thermal conductivity of the TA15 alloy means that it is difficult for heat to spread, and thus, the heat may concentrate in the region under the action of the rollers. All of these factors lead to an uneven temperature distribution along the thickness direction of the workpiece and varying levels of plasticity of the inner and outer surfaces of the conical workpiece. Therefore, the material on the outer surface at a high temperature flows easily, and the deformation is large, while the material near the inner surface at a low temperature is less deformed and the grain size is larger.

Figures 11 and 12 show the circumferential and tangential microstructures, respectively, along the thickness direction under 23.2% of deviation ratio. It can be observed that the grain size is also smaller than the initial grain size, indicating that the hot spinning process can refine the grains of the conical workpiece in the both tangential and circumferential directions. However, the distortion of the fiber microstructure is not as obvious as that produced under the negative deviation ratio. This implies that the degree of fiber microstructure closely correlates with the deviation ratio. A smaller thickness reduction and smaller tensile force will exist in the tangential direction, resulting from the more serious accumulation of material around the rollers under the positive deviation ratio compared with that under the negative deviation ratio.

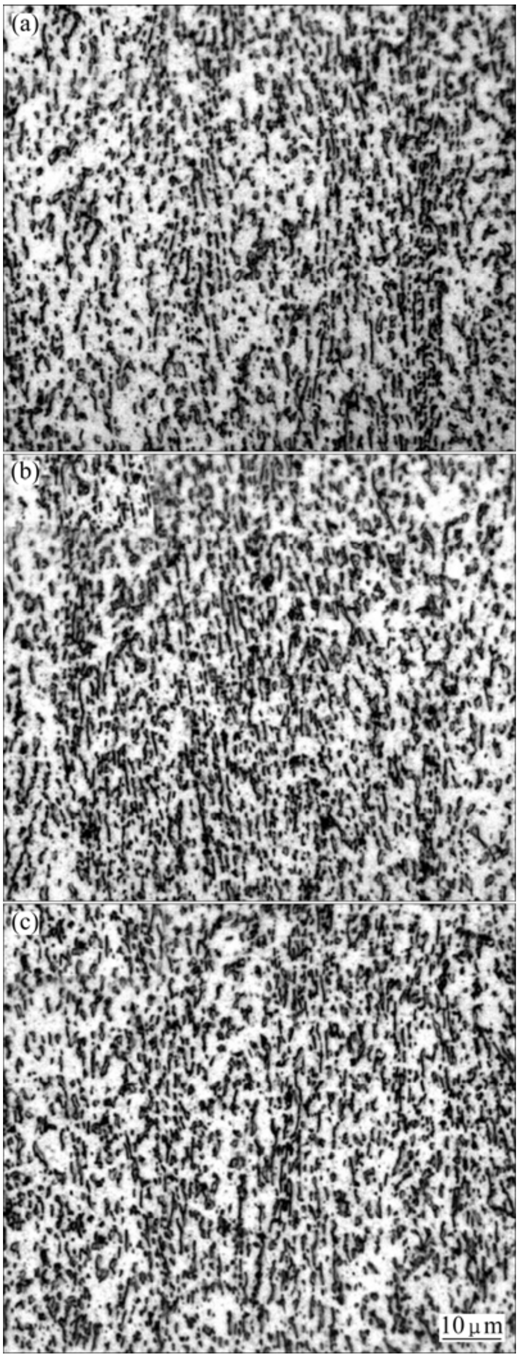

Fig. 11 Circumferential microstructures under 23.2% of deviation ratio along thickness direction: (a) Near outer surface; (b) Middle; (c) Near inner surface

Figures 13 and 14 show the circumferential and tangential microstructures, respectively, under a zero deviation ratio along the thickness direction. These

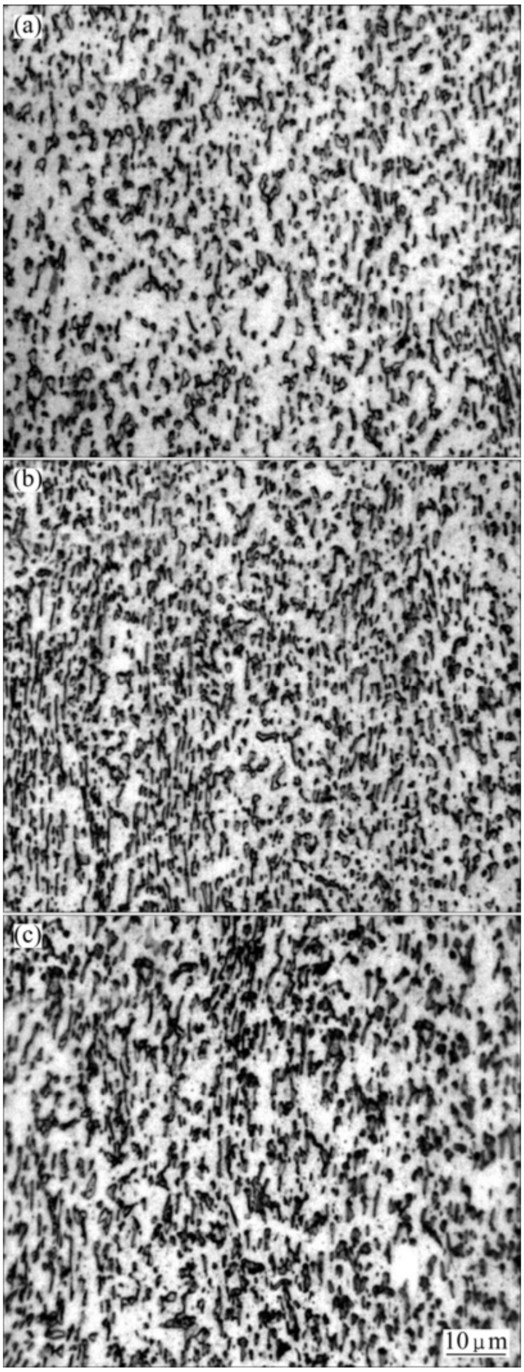

Fig. 12 Tangential microstructures under 23.2% of deviation ratio along thickness direction: (a) Near outer surface; (b) Middle; (c) Near inner surface

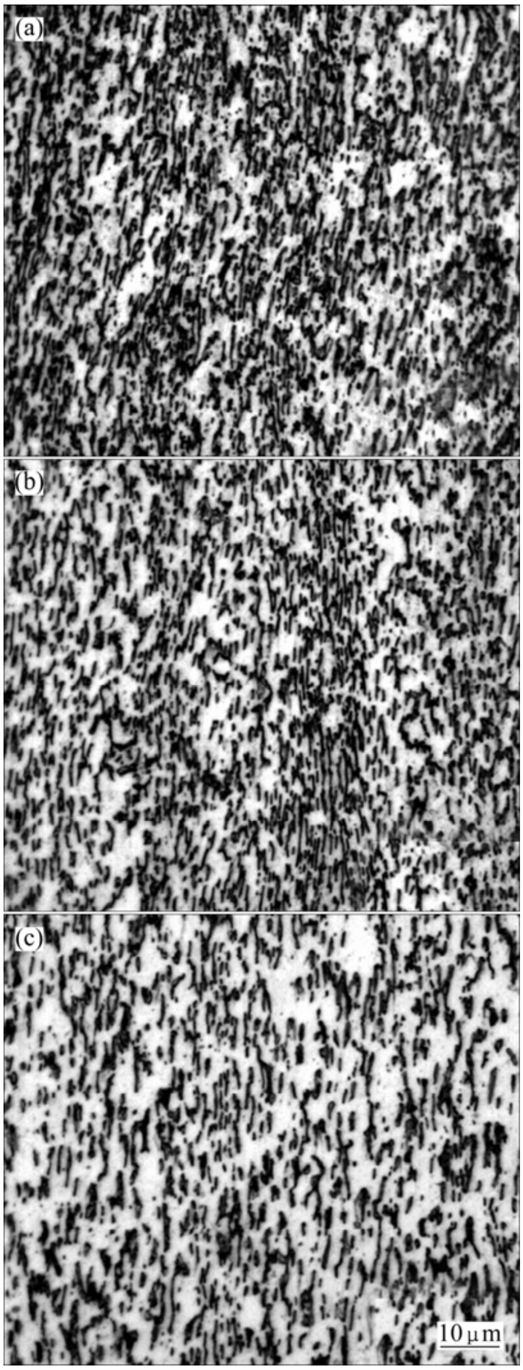

Fig. 13 Circumferential microstructures under zero deviation ratio along thickness direction: (a) Near outer surface; (b) Middle; (c) Near inner surface

figures show that certain differences remain in the microstructure near the outer surface and inner surface, but the grain size is smaller than that observed under the positive deviation ratio and displays a more uniform fiber microstructure than that produced under the negative deviation ratio. This means that a uniform deformation in the wall thickness direction occurs because of the small temperature difference along the wall thickness direction resulting from a small fluctuation of the heating temperature when the deviation ratio is zero (Fig. 2).

Taking into consideration of the influence of the deviation ratio and the temperature on the geometric precision, it is clear that a near-zero deviation ratio and a steady temperature in the desired range are beneficial conditions for obtaining spun parts with good geometric precision and a uniform grain-sized microstructure.

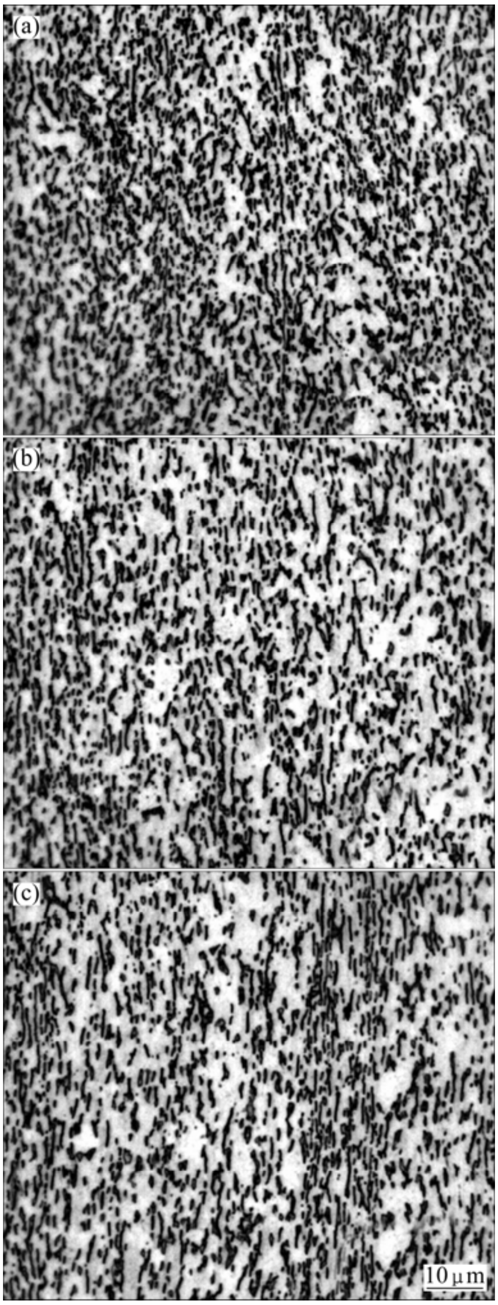

Fig. 14 Tangential microstructures under zero deviation ratio along thickness direction: (a) Near outer surface, (b) Middle; (c) Near inner surface

4 Conclusions

1) Diametrical shrinkage occurs under a negative deviation ratio, and a sudden decrease in the heating temperature will bring about a sharp increase in the shrinkage. An increasingly pronounced diametrical enlargement exists from the bottom location to the open end of the workpiece under a positive deviation ratio and a gradual decrease of the heating temperature.

2) The size precision represented by the wall thickness deviation and the wall thickness difference, and the shape precision represented by the hemi-cone angle deviation and the relative inner diameter difference, are both high in the case of zero deviation ratio, resulting from the reasonable deviation ratio and the small variation of the heating temperature during the process.

3) The hot shear spinning of TA15 alloy can lead to a non-uniform microstructure with decreasing grain size from the inner to the outer surface, which results from the non-uniform deformation along the thickness direction due to the difference in the friction, deformation and temperature along the thickness direction. The fiber microstructure forms near the outer surface, the smaller the deviation ratio, the larger the distortion degree of the fiber microstructure.

4) The grain size under a zero deviation ratio is smaller than that produced under a positive deviation ratio, and a more uniform fiber microstructure exists compared with that produced under a negative deviation ratio. A deviation ratio near zero and heating to a temperature within the desired range are beneficial conditions for obtaining spun parts with satisfactory geometric precision and uniform grain-sized microstructure.

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TA15 钛合金热剪旋件的几何精度与显微组织分析

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摘 要：为了揭示偏离率和加热温度对 TA15 钛合金加热剪切旋压件的影响机制，研究了不同偏离率下热剪旋件的几何精度和微观组织。结果表明：在负偏离下工件会发生径缩，且温度的突然降低会使径缩更严重。在正偏离条件下且加热温度缓慢降低时，沿工件底部到口部有明显扩径。沿热剪旋工件厚向的不均匀变形使工件晶粒细化且近外层晶粒比近内层晶粒细小。在近外层可能形成纤维组织，该纤维组织的扭曲程度随着偏离率的减小而增加。近零偏离和保持加热温度在合理范围时有利于获得几何精度高和微观组织均匀的工件。

关键词：钛合金；热剪切旋压；几何精度；显微组织

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