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ARTICLE

Ultrasonic Vibration-Assisted Thermal Deep Drawing of TC4 Titanium Alloy Cylindrical Parts

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Abstract: To address quality issues such as cracking and earing during the thermal deep drawing of TC4 titanium alloy cylindrical parts, an ultrasonic vibration-assisted forming method was proposed. The effects of ultrasonic vibration on the thermal performance and high-temperature interfacial friction behavior of TC4 titanium alloy were studied by ultrasonic vibration-assisted tensile and sliding friction experiments. By analyzing the drawing force, surface quality, wall thickness distribution, and earing morphology of the fixed-dimension blank under different temperature conditions, the influence of ultrasonic vibration on the forming process and forming quality of TC4 cylindrical part was clarified. Finally, through variable-dimension limit drawing experiments under different temperature conditions, the limit drawing coefficient and the effective height of the TC4 cylindrical part assisted by ultrasonic vibration were obtained. The research findings indicate that applying ultrasonic vibration during the thermal deep drawing of TC4 cylindrical parts can not only effectively reduce the drawing force and earing ratio, but also improve the uniformity of wall thickness distribution, significantly enhancing the limiting drawing ratio and effective height of the drawn specimens.

Key words: TC4; cylindrical parts; deep drawing; ultrasonic vibration; wall thickness distribution; drawing ratio

1 Introduction

Titanium alloy, characterized by low density, high specific strength, thermal stability over a wide temperature range, and excellent corrosion resistance, is regarded as an advanced structural material. It holds an irreplaceable position in high-end manufacturing fields such as aerospace, marine equipment, and chemical processing equipment. In the aerospace field, the application scale of titanium alloys has become one of the important indicators for evaluating the technological advancement of aircraft[1–3]. Deep drawing is one of the typical sheet metal forming processes and also one of the main methods for processing complex sheet metal parts. However, due to the inherent performance of titanium alloys, including high yield strength, low elastic modulus, and restricted plastic deformation capacity, significant anisotropy quality issues such as fracture, wrinkling, and earing easily occur during the deep drawing process, making it difficult to form titanium alloy components with complex shapes[4–7].

To enhance the plastic deformation capability and forming quality of difficult-to-deform titanium alloys, thermal forming is commonly used. In this process, the blank and die are heated to temperatures exceeding 500 °C to exploit the thermal softening behavior of materials, which enhances their formability and forming quality[8-11]. Eva-Lis et al[12] investigated the formability of TC4 titanium alloy for double-curved aero-engine part and thereby identified the optimal forming process parameters. Liu et al[13] achieved high-quality forming of various types of titanium alloy variable diameter tube parts through the thermal tube gas forming technique. Qiao et al[14] prepared complex-shaped titanium alloy aero-engine fairing screens by optimizing the parameters of the thermal deep drawing process. Yang et al[15] optimized the process parameters of the thermal forming process and successfully prepared complex-shaped titanium alloy part. Zhu et al[16] found that TC4 exhibited superior surface forming quality at 650 °C compared with that at 750 °C.

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Ultrasonic vibration-assisted forming is a process that applies ultrasonic vibrations with specific direction, frequency, and energy to the workpiece material (or mold). Its high-frequency vibrational energy facilitates various plastic forming processes. Compared with traditional forming methods, ultrasonic vibration-assisted forming can effectively enhance material formability and forming quality by regulating internal stresses within the workpiece and improving interfacial contact between the mold and the blank[17–20]. Fu et al[21] found that the incorporation of ultrasonic vibration can effectively improve the forming performance of AZ31 magnesium alloy. Huang et al[22] improved the limiting drawing ratio (LDR) of micro-drawing in 304 stainless steel foil by applying ultrasonic vibration. Reza et al[23] introduced ultrasonic vibration to St14 steel during the deep drawing process and found that it can effectively reduce the friction between the material and the die. Xu et al[24] employed ultrasonic vibration forming technique for deep drawing to manufacture the tantalum shell of capacitor, achieving a 22% reduction in adhesive wear of the shell compared to specimens formed without ultrasonic vibration. Rauf et al[25] applied ultrasonic vibration to TC4 during the processing, which effectively improved the surface quality of the formed specimens and reduced the wear of the processing die. Gao et al[26–27] investigated the effect of ultrasonic vibration on the mechanical performance and microstructure of TC4 through uniaxial tensile tests at different temperatures.

To address the restrictions of the traditional thermal deep drawing process for titanium alloys, such as high forming temperature, poor surface quality, and insufficient drawing ratio, an ultrasonic vibration-assisted thermal deep drawing process was proposed. This process aimed to further improve the drawing performance of titanium alloy parts through the volume and surface effects induced by the ultrasonic vibration energy field. Taking the TC4 cylindrical part as the research object, a systematic investigation was conducted to examine the effects of ultrasonic vibration on the mechanical performance, interfacial friction, forming quality defects, and drawing ratios of materials under different temperature conditions during the deep drawing process, and the influence law of ultrasonic vibration on the drawing performance and forming quality of titanium alloy sheet metal parts was determined.

2 Experiment

2.1 Deep drawing process and main quality problems of cylindrical parts

During the deep drawing process of cylindrical parts, the blank can be divided into four distinct zones based on the deformation characteristics, including the primary deformation zone, the force transmission zone, the minor deformation zone, and the transition zone (Fig.1). The primary deformation zone is located in the flange region of the blank. Insufficient blank holder force (F_t) provided by the blank holder during deep drawing can cause thickness-directional instability and wrinkling in the flange region. The force transmission zone is situated in the straight wall section of the blank. Excessive punch drawing force (F_p) during deep drawing or a blank drawing ratio exceeding LDR will induce cracking, which is generally initiated at the punch radius. The minor deformation zone is located at the bottom of the cylindrical part. Due to the effects of the punch radius and friction, the material in this region is subjected to relatively low stress and minimal deformation. The transition zone is mainly located in the radius regions of the die and punch. Under the combined action of bending forces and drawing loads, cracking or wrinkling may occur. Additionally, the blanks used for deep drawing are mostly rolled sheets with significant anisotropy, which causes non-uniform material flow during deep drawing, resulting in uneven earing along the edge of the blank. These defects adversely affect the service performance of the deep-drawn part and the material utilization efficiency.

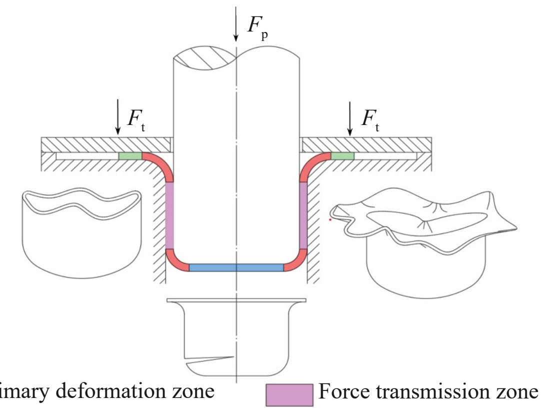

Fig.1 Schematic diagram of four distinct deformation zones and major defects in a deep-drawn cylindrical part

The maximum drawing force $F_{p\text{-}max}$ during drawing can be determined by Eq. (1)[28]:

$$F_{p\text{-}max}=\pi dt\sigma_b \ln k \cdot e^{\frac{\pi}{2}\mu} \tag{1}$$

where t is the sheet thickness (mm); σ_b is the ultimate strength of sheet material (MPa); μ is the coefficient of friction; d is the punching diameter (mm); k is the drawing ratio.

The drawing typically uses the earing ratio (Z) to describe the earing condition of cylindrical part, with Z determined by Eq. (2)[29]:

$$Z=\left[\frac{\sum_{i=1}^{N}\left(\frac{h_{i\text{-}max}-h_{i\text{-}min}}{h_{i\text{-}min}}\right)}{N}\right]\times 100\% \tag{2}$$

where $h_{i\text{-}min}$ is the height of the i-th ear valley (mm); $h_{i\text{-}max}$ is the height of the i-th ear peak (mm); N is the number of ears.

The drawing ratio k corresponding to different blanks is determined by Eq. (3)[30]:

$$k=\frac{D}{d} \tag{3}$$

where D is the initial blank diameter (mm).

2.2 Experimental device and materials

Fig. 2 shows the principle of ultrasonic vibration-assisted thermal deep drawing for the cylindrical part. The system

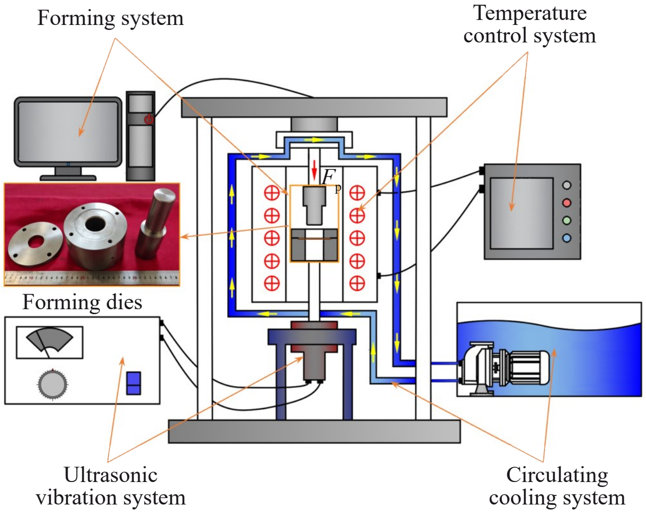

Fig.2 Schematic diagram of principle of ultrasonic vibration-assisted thermal deep drawing for cylindrical parts

mainly consists of four parts: a forming system, a temperature control system, an ultrasonic vibration system, and a circulating cooling system. Temperature control was performed using a GW-1200 electric furnace controller, with a temperature control accuracy of ±5 °C and a heating rate of 40 °C/min. Meanwhile, ultrasonic vibration was applied to the die via an ultrasonic transducer, with a frequency of 20 kHz, an amplitude of 10 μm, and a power of 1.0 kW. By replacing the dies or tooling, this device can also be used to conduct mechanical performance tests of sheet metal, as well as bending and bulging experiments.

The experimental material was TC4 with a thickness of 0.5 mm, and its chemical composition is listed in Table 1. The experimental temperatures were set at 500, 550, 600, and 650 °C. The die used in the experiments had an inner diameter of 35 mm and a fillet radius of 4 mm, while the punch had an outer diameter of 34 mm and a fillet radius of 2 mm. The die material was SUS304 stainless steel. Meanwhile, a fixed-gap blank holder method was adopted during the deep drawing process. A groove (0.5 mm) was machined on the die, and the die was assembled with the blank holder via four uniformly distributed M8 threads to ensure a constant blank holder gap throughout the deep drawing process and minimize the influence of blank holder force on the deep drawing of the blank. Additionally, it was considered in this study that the deep drawing performance of cylindrical part was related not only to temperature but also to the material's deformability and friction behavior with the die. Consequently, prior to deep drawing, a preliminary study was conducted to investigate the effects of ultrasonic vibration on the thermal performance and friction behavior of TC4.

Table 1 Chemical composition of TC4 sheet (wt%)

Al	V	Fe	Si	C	O	Ti
5.6–6.8	3.5–4.5	≤0.3	≤0.15	≤0.1	≤0.2	Bal.

3 Results and Discussion

3.1 Effect of ultrasonic vibration on thermal performance

The volume effect is macroscopically characterized by reduced material tensile strength and improved elongation (EL), which is a typical feature of ultrasonic vibration-assisted forming processes. Anisotropy is a typical characteristic formed during the rolling process of metal sheets, which affects material flow and deformation behavior. In this study, to systematically evaluate the influence of ultrasonic vibration on the mechanical performance and anisotropy of TC4 sheets under different temperature conditions, tensile specimens were cut at angles of 0°, 45°, and 90° relative to the rolling direction (Fig.3). The tensile specimens have a gauge length of 30 mm, a width of 5.0 mm, a thickness of 0.5 mm, and a tensile rate of 5 mm/min.

Fig. 4 shows the stress-strain curves of TC4 at different temperatures with and without ultrasonic vibration. Without ultrasonic vibration (0 kW), the tensile strength of the material gradually decreases with the increase in temperature, and the magnitude of the reduction increases with rising temperature, showing an obvious high-temperature softening effect. After applying ultrasonic vibration (1.0 kW), the tensile strength of TC4 further decreases. This result indicates that the input of ultrasonic vibration not only further enhances the high-

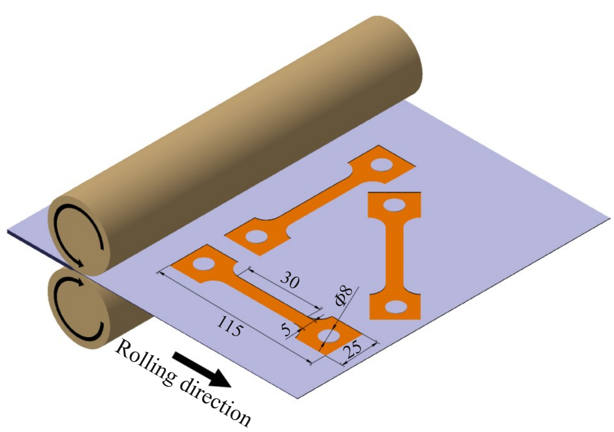

Fig.3 Schematic diagram of dimensions and sampling method of tensile specimens

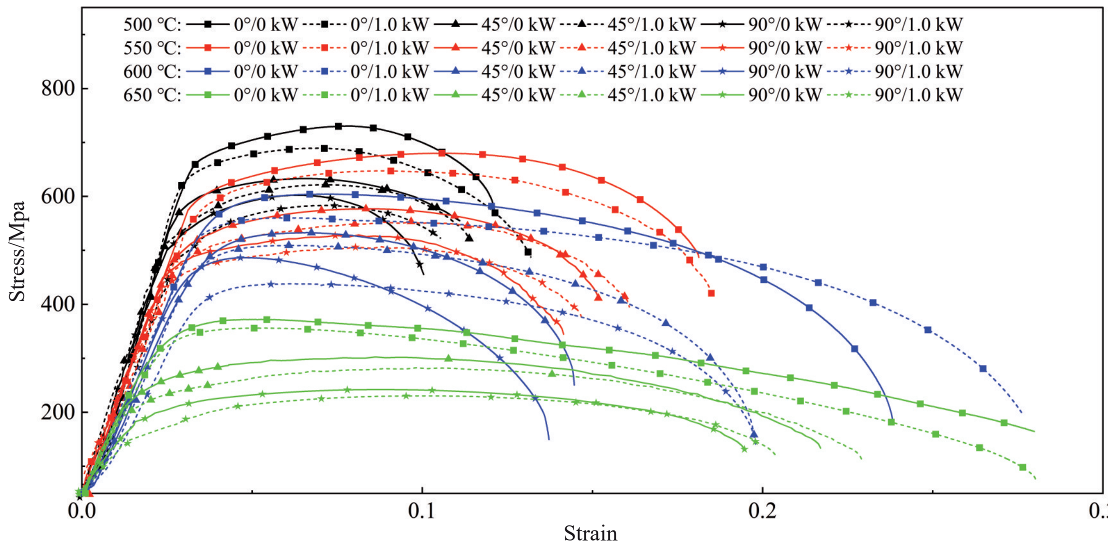

Fig.4 Stress-strain curves of TC4 under different temperatures and ultrasonic vibration conditions

temperature softening effect, but also effectively reduces the resistance to dislocation motion, thereby promoting the activation of more slip systems[26–27]. Fig.5 shows the effect of ultrasonic vibration on EL of TC4 at different temperatures. At 500 °C, the post-fracture EL of the 0°, 45°, and 90° specimens without ultrasonic vibration is 12.21%, 11.09%, and 10.07%, respectively. After applying ultrasonic vibration, these values increase to 13.19%, 11.38%, and 10.53%, respectively. When the temperature increases to 600 °C, EL at break of the 0°, 45°, and 90° specimens without ultrasonic vibration is 23.82%, 14.46%, and 13.72%, respectively; after ultrasonic vibration treatment, EL at break of the 0°, 45°, and 90° specimens significantly increases to 27.63%, 20.10%, and 20.06%, respectively. EL improvement of the 45° and 90° specimens is more pronounced, leading to a marked reduction in anisotropy induced by the rolling process.

3.2 Effect of ultrasonic vibration on friction performance

During deep drawing, friction occurs between the blank and the die surface under contact pressure due to microscale irregularities. This not only causes scratches on the surface of the blank or die, but also may even lead to part scrappage. The surface effect is another characteristic of ultrasonic vibration-assisted forming. Generally, at room temperature, ultrasonic vibration improves the contact between the die and the blank, thereby reducing the friction coefficient (μ); however, research under high temperature conditions remains restricted. To address this gap, high-temperature friction performance experiments between TC4 and the die material SUS304 under ultrasonic vibration were conducted based on sliding friction tests. During the experiments, TC4 friction specimens were placed between two SUS304 surfaces, a clamping force of F_N=1.0 kN was applied, and the corresponding friction coefficient (μ) was determined by measuring the friction force (F_f) under different temperatures and ultrasonic vibration conditions. The friction coefficient μ satisfies the following relationship with the friction force and clamping force (F_N) :

$$\mu = \frac{F_f}{2F_N} \tag{4}$$

Fig. 6 shows the relationship between friction force and sliding distance for the TC4/SUS304 contact pair under different temperatures and ultrasonic vibration conditions. Fig. 7 presents the friction coefficient μ of the TC4/SUS304 contact pair at various temperatures, which were calculated using Eq. (4) to account for the effects of ultrasonic vibration. As shown in Fig.6, at 500, 550, 600, and 650 °C, the friction

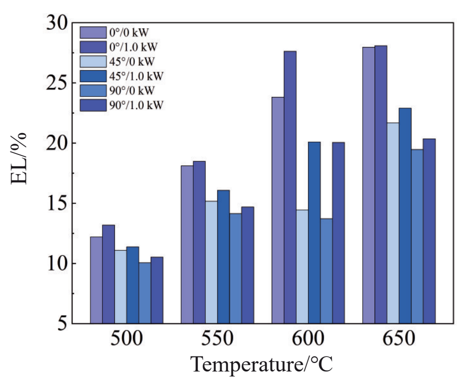

Fig.5 Effect of ultrasonic vibration on EL of TC4 at different temperatures

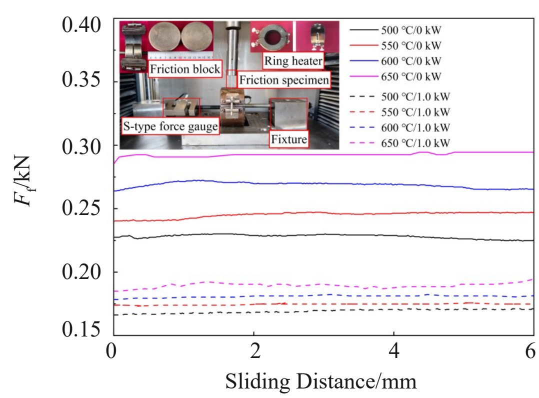

Fig.6 Relationship between friction force and sliding distance of TC4/SUS304 contact pair under different temperatures and ultrasonic vibration conditions

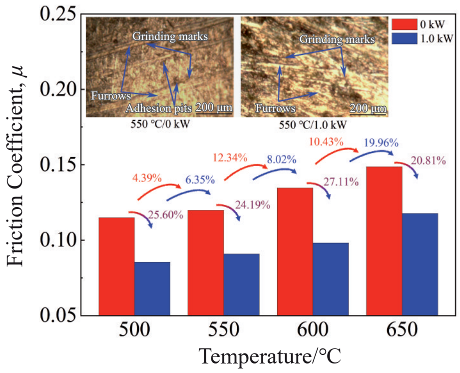

Fig.7 Effect of ultrasonic vibration on friction coefficient of TC4/SUS304 contact pair at different temperatures

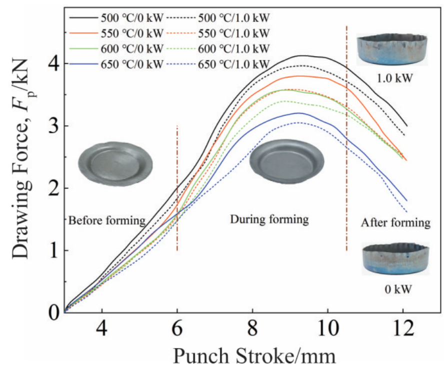

Fig.8 Relationship curves between F_p and punch stroke under different temperatures and ultrasonic vibration conditions

forces F_f are 0.230, 0.241, 0.269, and 0.294 kN, respectively, with the corresponding friction coefficient μ of 0.115, 0.120, 0.135, and 0.149, respectively. Both the friction force and the friction coefficient μ gradually increase with the increase in temperature. This trend can be attributed to the reduction in strength and stiffness of the metal at elevated temperatures, which intensifies adhesive wear between the contact surfaces of the titanium alloy and the die, thereby increasing the friction force. Under the same temperature condition, after applying ultrasonic vibration, the corresponding F_f is 0.170, 0.175, 0.181, and 0.189 kN, with the corresponding friction coefficient μ of 0.085, 0.091, 0.098, and 0.118, respectively. Both the friction force and the friction coefficient μ decrease to varying degrees, with the maximum reduction of 35.90% and 27.11%, respectively. This phenomenon is attributed to the continuous variation in the direction of the friction force vector at the interface between the blank and the die under ultrasonic vibration, which results in mild wear on the specimen surface, with shallow grinding marks and furrows, as well as a large number of original surfaces. In contrast, the specimen surface under the condition without ultrasonic vibration exhibits severe grinding marks, accompanied by deep furrows and adhesion pits.

3.3 Effect of ultrasonic vibration on thermal deep drawing force

Blanks with a diameter of 50 mm were selected to systematically compare the effects of ultrasonic vibration on the drawing force, wall thickness (T) distribution, and earing of cylindrical part under different temperature conditions. On this basis, by gradually increasing the initial diameter of the blank until the critical fracture condition was reached during forming, LDR and effective height h of the cylindrical part were further evaluated.

Drawing force refers to the total pressure that needs to be applied to the punch during deep drawing, generally including the deformation resistance and the force required to overcome various resistances. The magnitude of the drawing force can comprehensively reflect the deformation resistance and the formability of materials. Fig.8 presents the relationship curves between punch stroke and drawing force (F_p) under different temperatures and ultrasonic vibration conditions during the deep drawing process. When the punch stroke is less than 6 mm, the effect of ultrasonic vibration on the drawing force is insignificant due to the small deformation. When the punch stroke is between 6 and 12 mm, the application of ultrasonic vibration significantly reduces the drawing force during the process, which increases to a maximum at a punch stroke of 9 mm and then decreases continuously. At temperatures of 500, 550, 600, and 650 °C, the corresponding maximum drawing forces ($F_{p\text{-max}}$) are 4.12, 3.81, 3.58, and 3.22 kN, respectively, showing a gradual decrease with the increase in temperature; the $F_{p\text{-max}}$ after applying ultrasonic vibration is 3.95, 3.57, 3.41, and 3.02 kN, respectively, representing reductions of 4.13%, 6.30%, 4.75%, and 6.21% compared with the non-ultrasonic vibration condition (Fig. 9). From Eq. (1), it is evident that during the ultrasonic vibration-assisted thermal deep drawing process, on the one hand, the ultimate strength σ_b of the blank is reduced under the action of ultrasonic vibration; on the other hand, ultrasonic vibration improves the interfacial friction between the sheet and the die, leading to a significant reduction in friction coefficient μ. This consequently results in a continuous decrease in $F_{p\text{-max}}$. Meanwhile, the reduction in both deep drawing force and friction coefficient effectively suppresses adhesive wear and scratching caused by high temperature during the deep drawing process of the formed parts, thereby improving the surface quality of the specimens (as indicated by the surfaces of the 0 kW and 1.0 kW

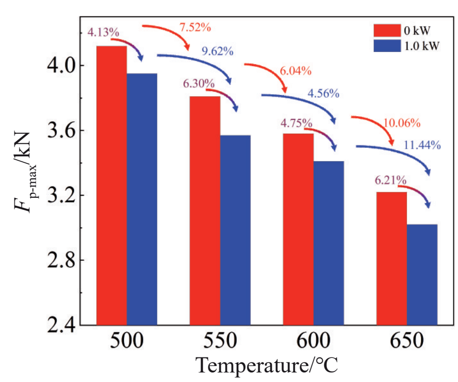

Fig.9 Effect of ultrasonic vibration on $F_{p\text{-max}}$ of TC4 cylindrical parts at different temperatures

specimens in Fig.8).

3.4 Effect of ultrasonic vibration on wall thickness distribution of thermal deep drawing parts

During the deep drawing process of cylindrical parts, significant changes occur in the wall thickness (T) distribution due to different stress states in various deformation zones. Excessive thinning or thickening of the wall will affect the service performance of the parts. Therefore, to investigate the effect of ultrasonic vibration on the wall thickness distribution of cylindrical part, the wall thickness T at typical locations of the specimens was measured using a sectioning method.

Fig. 10 shows the wall thickness distribution of TC4 cylindrical parts under different temperatures and ultrasonic vibration conditions. The wall thickness in the base region of the specimens shows minimal variation, with only slight thinning observed. The wall thickness in the fillet region changes more significantly, mainly characterized by thinning. The wall thickness in the cylindrical wall region gradually increases with the increase in specimen height. Meanwhile, the extent of wall thickness variation gradually decreases with the increase in temperature. For example, when the temperature increases from 500 °C to 650 °C, the corresponding minimum wall thickness (T_{min}) increases from 0.465 mm to 0.476 mm, and the corresponding thinning rate decreases from 7.00% to 4.80%; the maximum wall thickness (T_{max}) decreases from 0.579 mm to 0.553 mm with the increase in temperature, and the corresponding thickening rate decreases from 15.80% to 10.60%. Under the same temperature condition, the uniformity of wall thickness in all deformation zones is improved to varying degrees after applying ultrasonic vibration (Fig. 11). This indicates that the effect of ultrasonic vibration on the deep drawing process of TC4 cylindrical parts results from the combined action of the mechanical performance, interfacial friction, and the corresponding deformation mechanisms of the materials. On the one hand, when ultrasonic vibration is applied under specific temperature conditions, the high-temperature softening effect of the material is enhanced, leading to a decrease in tensile strength and an increase in EL (Fig. 4 – Fig. 5); on the other hand, ultrasonic vibration also reduces the friction between the blank and the die (Fig.6–Fig.7),

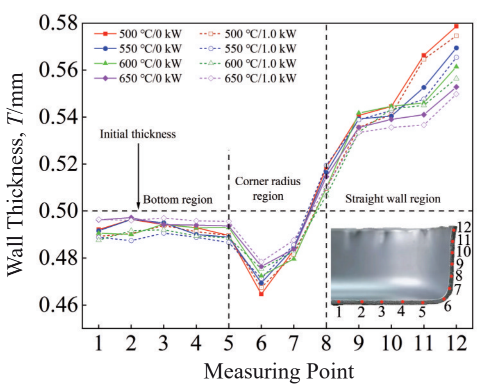

Fig.10 Thickness distribution of TC4 cylindrical part under different temperatures and ultrasonic vibration conditions

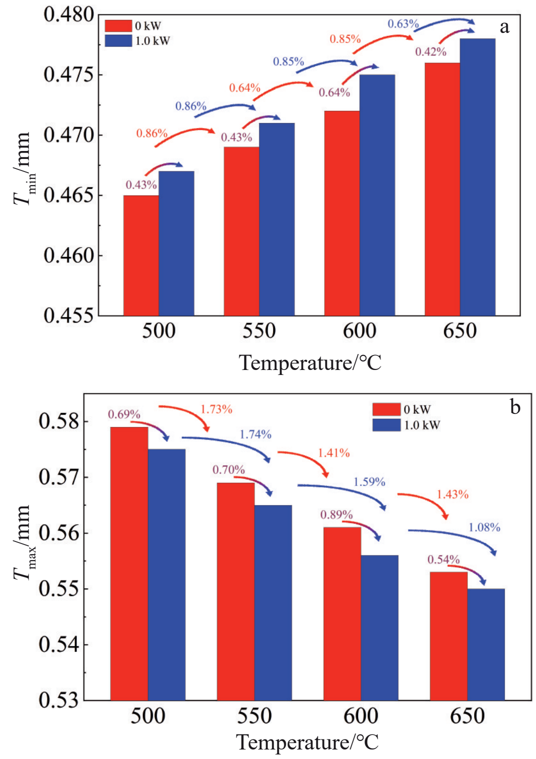

Fig.11 Effect of ultrasonic vibration on T_{min} (a) and T_{max} (b) of TC4 cylindrical part at different temperatures

thereby facilitating the flow of the blank in the flange region toward the deformation zone and ultimately improving the drawing performance.

3.5 Effect of ultrasonic vibration on earing of thermal deep drawing part

For most metals, the rolling process imparts significant anisotropy to the sheet material, leading to irregular edges of the deep-drawn cylindrical part. This phenomenon, known as "earing", requires an additional trimming process after deep drawing to ensure the wall height (h) of the cylindrical part. Therefore, the Z and h are also key indicators for evaluating the deep drawing performance of cylindrical part.

To determine the variation in the edge h of cylindrical parts, corresponding h measurements were taken at interval of 15°. As shown in Fig.12, the variation pattern of h is dependent on temperature and ultrasonic vibration conditions. It can be seen that all specimens have four ears with relatively stable positions. As the temperature increases from 500 °C to 650 °C, the improved material flowability and enhanced deformation uniformity result in an increase in effective h (defined as the depth of the ear trough) from 9.46 mm to 10.01 mm, while the Z calculated from Eq. (2) decreases from 11.87% to 4.86%. After the application of ultrasonic vibration at 500 and 650°C, due to the reduced anisotropy of the blank (Fig. 4), the Z decreases from 11.87% and 4.86% to 11.45% and 4.14%, respectively, while the effective wall height of the cylinder wall increases to 9.52 and 10.09 mm, respectively. The aforementioned research results indicate that during the thermal deep drawing process of titanium alloy cylindrical

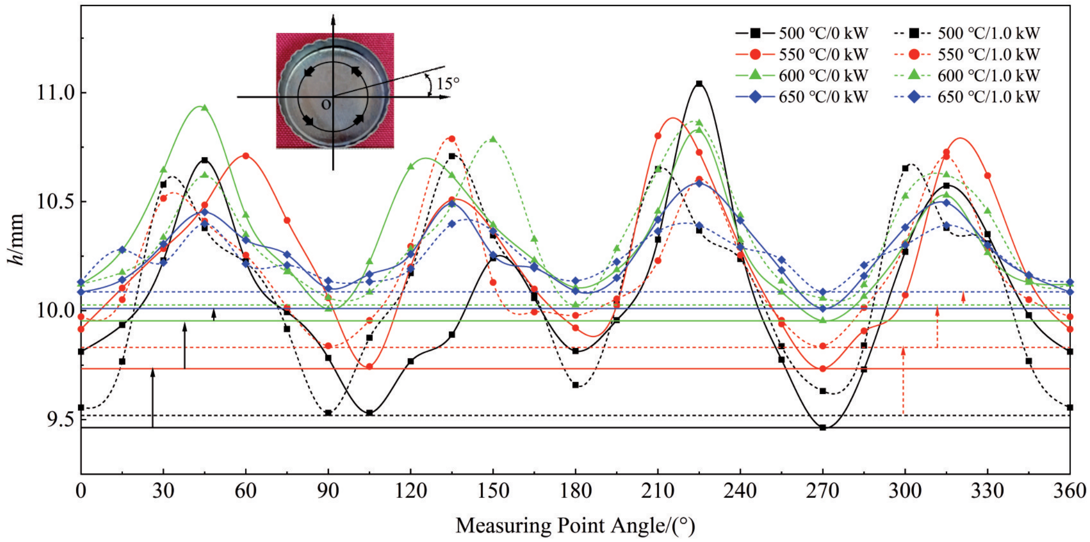

Fig.12 Variation law of *h* of TC4 cylindrical parts under different temperatures and ultrasonic vibration conditions

parts, the application of ultrasonic vibration further enhances the material flow properties. This not only suppresses the formation of ears during the deep drawing process, but also effectively increases the drawing *h* of the cylindrical parts.

3.6 Effect of ultrasonic vibration on LDR

LDR is one of the most critical process parameters in sheet metal forming. It reflects the maximum variation in blank diameter before and after deep drawing, thus serving as a key indicator for evaluating the forming limit of sheet metal. During the deep drawing process, an excessively high drawing ratio can lead to fracture in the bottom fillet region of the specimen, while an excessively low ratio results in low production efficiency. Therefore, investigating LDR is of great significance. In this study, the blank diameter was set to 50 mm as the baseline. The blank diameter was gradually increased by 0.5 mm each time until fracture occurred, thereby determining LDR under different temperatures and ultrasonic vibration conditions.

Fig. 13 shows the effects of temperature and ultrasonic vibration on LDR and effective wall height of cylindrical part. As shown in Table 2, the critical blank diameters at fracture at 500, 550, 600, and 650 °C are 51, 54, 57, and 60.5 mm,

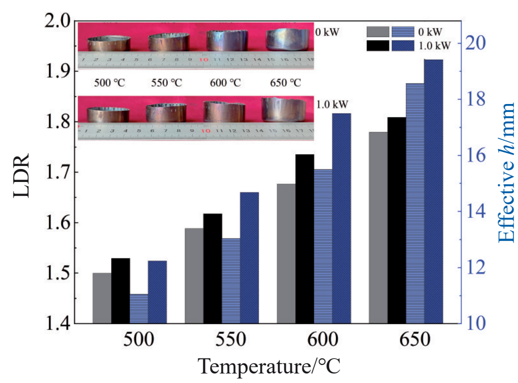

Fig.13 Effect of ultrasonic vibration on LDR and effective wall height of cylindrical part at different temperatures

Table 2 Effect of ultrasonic vibration on the corresponding ultimate blank diameter of cylindrical part at different temperatures

Temperature/°C	Ultrasonic vibration/kW	Blank diameter/mm									Appearance
		51	52	54	55	57	59	60.5	61.5	62	
500	0	√	×	-	-	-	-	-	-	-	
	1.0	√	√	×+	-	-	-	-	-	-	
550	0	√	√	√	×+	-	-	-	-	-	
	1.0	√	√	√	√	×	-	-	-	-	
600	0	√	√	√	√	√	×	-	-	-	-
	1.0	√	√	√	√	√	√	×	-	-	
650	0	√	√	√	√	√	√	√	×+	-	
	1.0	√	√	√	√	√	√	√	√	×	

Note: √ indicates successful deep drawing, while × indicates fracture or wrinkling or both; + indicates that this parameter has a corresponding appearance illustration.

corresponding to LDR of 1.50, 1.59, 1.68, and 1.78, and effective wall height of 11.06, 13.04, 15.5, and 18.57 mm, respectively. After applying ultrasonic vibration, the critical blank diameters at fracture at 500, 550, 600, and 650 °C increase to 52, 55, 59, and 61.5 mm, yielding LDR of 1.53, 1.62, 1.74, and 1.81, respectively; the corresponding effective wall height increases to 12.24, 14.68, 17.50, and 19.42 mm, respectively. Meanwhile, if the blank dimensions are excessively large and exceed LDR, defects such as fracture in the punch fillet region or wrinkling in the flange region of the deep-drawn part usually occur.

4 Conclusions

1) Under specific temperature conditions, applying ultrasonic vibration with a frequency of 20 kHz, an amplitude of 10 μm, and a power of 1.0 kW to TC4 not only improves the plastic deformation capacity, enhances the high-temperature softening effect, and suppresses the anisotropy of the material, but also decreases the interfacial friction between the blank and the die, thus effectively improving the thermal forming performance.

2) During the thermal deep drawing process of TC4 cylindrical parts, applying ultrasonic vibration can effectively reduce the drawing force and improve the surface quality of the specimens. The maximum reduction amplitude of the $F_{p\text{-}max}$ reaches up to 23.54%, and the surface scratches of the specimens are significantly reduced.

3) During the thermal deep drawing process of TC4 cylindrical parts, applying ultrasonic vibration improves the wall thickness distribution uniformity of the deep-drawn specimens and reduces the earing ratio, thereby increasing the effective wall height.

4) Under the same temperature condition, applying ultrasonic vibration not only increases LDR of TC4 cylindrical parts, but also enhances the wall thickness distribution uniformity and the effective wall height of the specimens.

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TC4钛合金圆筒件超声振动辅助热拉深工艺

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摘　要：针对TC4圆筒件在热拉深过程中的破裂和制耳等质量问题，提出了超声振动辅助成形方法。通过超声振动辅助拉伸、滑动摩擦实验，确定超声振动对TC4热性能及界面摩擦性能的影响。通过探究不同温度条件下固定尺寸坯料的拉深力、拉深试件表面质量、壁厚分布和凸耳形态等，确定了超声振动对TC4圆筒件成型过程及质量的影响；最后通过不同温度条件下的变尺寸极限拉深实验，得到了超声振动辅助TC4圆筒件的极限拉深系数及试件有效高度。结果表明，TC4圆筒件热拉深过程，通过施加超声振动辅助，不仅能有效降低试件拉深力，还可以减小试件的制耳率，提高壁厚分布均匀性，有效提高了TC4圆筒件的极限拉深比和拉深试件有效高度。

关键词：TC4；圆筒件；拉深；超声振动；壁厚分布；拉深比

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