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ARTICLE

Effect of Ultrasonic Vibration on Mechanical Properties and Bulging Performance of TA2 Titanium Alloy Sheet

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Abstract: Aiming at the problem of poor formability of titanium alloy sheet, the ultrasonic vibration-assisted forming process was studied, the effects of ultrasonic vibration on the mechanical properties of TA2 titanium alloy sheet and the friction coefficient between the contact surfaces were analyzed. On this basis, the ultrasonic vibration-assisted bulging experiment was carried out on specimens with different width-to-length ratios, and the influence of ultrasonic vibration on the bulging force and limit bulging height of TA2 sheet was analyzed. At the same time, based on the grid strain principle, the forming limit diagram of the TA2 sheet was established by measuring the limit strain of the specimens with different width-to-length ratios. The results show that choosing appropriate process parameters in ultrasonic vibration-assisted forming can not only improve the formability of TA2 sheet, but also reduce the influence of friction on plastic deformation behavior of sheet, thus effectively increasing the forming limit of TA2.

Key words: TA2 titanium alloy sheet; ultrasonic vibration; friction coefficient; bulging; forming limit diagram

Titanium alloy has excellent comprehensive performance, such as high specific strength, good corrosion resistance, and high heat resistance. It has become one of the leading materials for aircrafts, missiles, and spacecrafts. As the application rate of titanium alloy increases year by year, it has become one of the leading indicators to measure the advanced nature of aircrafts. However, compared with traditional metal materials, titanium alloy is a hard-to-deform material because of its high strength and low elongation, and it is prone to crack during plastic deformation[1-5]. Therefore, how to reduce the strength of the titanium alloy, and improve the elongation and formability of titanium alloy is of great significance for reducing the production cost of aircraft and improving its performance. At present, in order to improve the plasticity of the titanium alloy sheet, a thermal forming method is usually performed by increasing the forming temperature of the material to a certain range (generally higher than 500 °C). But the forming process is complicated, the mold manufacturing cost is high, and the microstructure and surface quality of the sheet metal are greatly influenced by the high temperature[6-11].

Ultrasonic vibration-assisted forming is an auxiliary forming method which was proposed in the 1950s, by applying high-frequency vibration to the mold or specimen during forming process. The vibration effect of the material can not only reduce the bulging force of the sheet and the flow stress of the material (volume effect), but also reduce the friction between the sheet and the mold (surface effect), thus effectively improving the plastic formability and surface quality of the sheet[12-19]. Yang et al[20] performed the ultrasonic vibration-assisted tensile test on TA1 titanium alloy sheet, and they found that vibration has a positive effect on reducing the yield strength and deformation load of the material, and also helps to improve its forming performance, forming efficiency and product quality by a proper frequency and power. Wen et al[21] studied the plastic formability of AZ31 magnesium alloy by applying ultrasonic vibration during the tensile process. They pointed out that ultrasonic vibration has a significant impact on the plasticity of AZ31 magnesium alloy, and the

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process with proper ultrasonic vibration parameters can reduce the flow stress, deformation resistance and improve the ductility of material. Jimma Takashi[22] applied ultrasonic vibration to a metal sheet with a thickness of 0.5 mm during deep drawing, and the limit drawing ratio of the material increased from 2.68 to 3.01. Moreover, compared with other auxiliary forming methods, ultrasonic vibration-assisted forming has advantages such as simple device, easy to install and debug, and low cost. It is a promising high-efficiency auxiliary forming process.

Referring to the above research information, it is difficult to form titanium alloy sheet at room temperature, so this research studied the effect of ultrasonic vibration on the mechanical properties and bulging performance of TA2 sheet. Based on the ultrasonic vibration-assisted tensile test, the influence of ultrasonic vibration on the mechanical properties of TA2 sheet was analyzed. According to the ultrasonic vibration-assisted sliding friction experiment, the effects of ultrasonic vibration on the friction force and friction coefficient between the TA2 sheet contact surface were studied. Finally, based on the ultrasonic vibration-assisted bulging experiment of specimens with different width-to-length ratios η (ratio of blank width W to length L), the influences of ultrasonic vibration on the bulging force and forming limit height of TA2 sheet were analyzed. At the same time, the ultrasonic vibration-assisted forming limit diagram of TA2 sheet was obtained based on the grid strain principle.

1 Experiment

The ultrasonic vibration-assisted stretching device is shown in Fig.1. A set of ultrasonic vibration device was installed to the tensile machine. One end of the tensile specimen was connected with the ultrasonic vibration device, and the other end was connected with the stretching fixture. In the experiment, the tensile force was monitored by the tensile machine, and the ultrasonic vibration was applied by the ultrasonic vibration device. Ultrasonic vibration-assisted sliding friction experimental device is shown in Fig.2. Based on the ultrasonic vibration-assisted tensile test device, a set of sliding friction experimental device was installed. The device mainly consists of two pressing blocks, S-type force sensor device, and pre-tightening bolts. The material of the pressing block was 45# steel, with a surface roughness of 1.0 μm. During the experiment, the force (F_n) was applied to the specimen between the two pressing blocks by the pre-tightening bolt. Then the tensile force (F_f) was applied by the tensile machine with a constant tensile speed during sliding friction. The friction force (F_μ) was equal to the tensile force (F_f), and the direction was opposite. The friction coefficient (μ) between the pressing blocks and the specimen during the experiment was determined by Eq.(1) according to Coulomb's law.

$$\mu = -\frac{1}{2} \cdot \frac{F_f}{F_n} \tag{1}$$

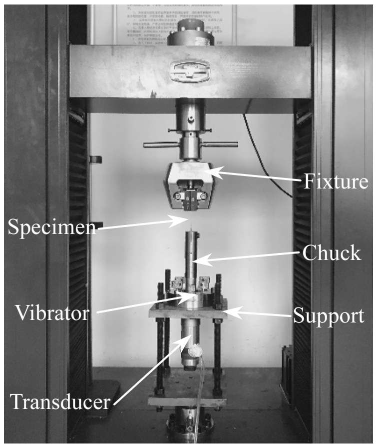

Fig.1 Ultrasonic vibration-assisted stretching device

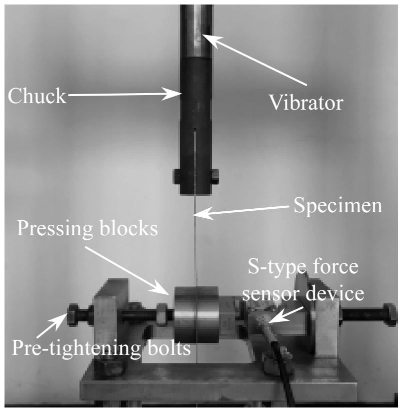

Fig.2 Ultrasonic vibration-assisted sliding friction experimental device

The principle of ultrasonic vibration-assisted bulging is shown in Fig.3. In addition to the formability of the sheet, the bulging performance is also related to the friction between the punch and the specimen. Therefore, the material and surface roughness of the punch were the same as those of the material for the ultrasonic vibration sliding friction test. The thickness

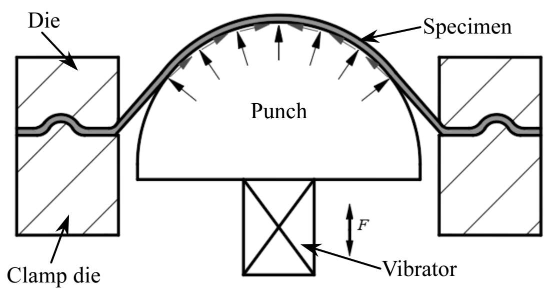

Fig.3 Principle of ultrasonic vibration-assisted bulging test

of the TA2 sheet for the experiment was 0.5 mm, the inner diameter of the die was Φ21 mm, and the diameter of the punch was Φ20 mm. In order to obtain the forming limit of the sheet under different deformation paths, the specimens with width-to-length ratio η of 1.0, 0.8, 0.6, 0.4 and 0.2 were used during bulging, and the length L of the specimens was constant at 40 mm (as shown in Fig.4). At the same time, in order to obtain the strain distribution of the bulged specimens, circular grids with a diameter (d_0) of 2.0 mm were printed on the surface of the specimens before bulging. Because of the different width-to-length ratios of the specimens, the circles will become elliptical at the end of the test, as shown in Fig.5. In the research process, the major axis of the deformed ellipse was d_1 and the minor axis was d_2. The major engineering strain (e_1) and minor engineering strain (e_2) of the bulging specimens can be calculated by Eq.(2) and Eq.(3), respectively.

$$e_1 = \frac{d_1 - d_0}{d_0} \times 100\% \tag{2}$$

$$e_2 = \frac{d_2 - d_0}{d_0} \times 100\% \tag{3}$$

2 Results and Discussion

2.1 Ultrasonic vibration-assisted tensile test

The engineering stress-strain curves of the TA2 sheet under different ultrasonic vibration process parameters are shown in Fig.6. It can be seen from the figure that the yield strength and tensile strength of the TA2 sheet are 272.0 and 316.2 MPa in the case without ultrasonic vibration, and the elongation is 30.1%. After applying ultrasonic vibration with a frequency of 20 kHz and amplitudes of 10, 12 and 14 μm, the yield strength and tensile strength of the TA2 sheet decrease accordingly, because of the “softening effect” induced by ultrasonic vibration. However, compared to the case without ultrasonic vibration, the elongation of the specimen improves by applying ultrasonic vibration with an amplitude of 10 μm, and the elongation of specimen reaches to 34.0%, but it decreases with the increase of the amplitude because the TA2 sheet has a significant material “hardening effect”. After applying ultrasonic vibration with a frequency of 25 kHz and an amplitude of 10 μm, the strength of the TA2 sheet decreases, and its elongation decreases sharply, because “hardening effect” becomes dominant compared with “softening effect”, which restrains the plastic deformation performance of the sheet metal.

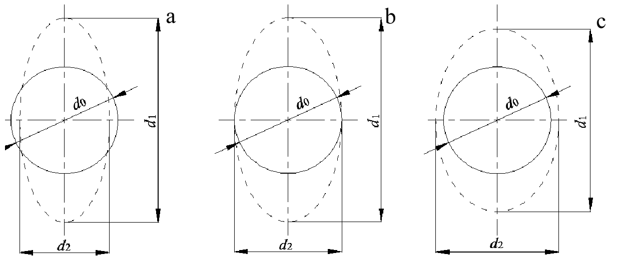

Fig.5 Changes of circular grids after deformation: (a) $d_1>d_0$, $d_2<d_0$; (b) $d_1>d_0$, $d_2=d_0$; (c) $d_1>d_0$, $d_2>d_0$

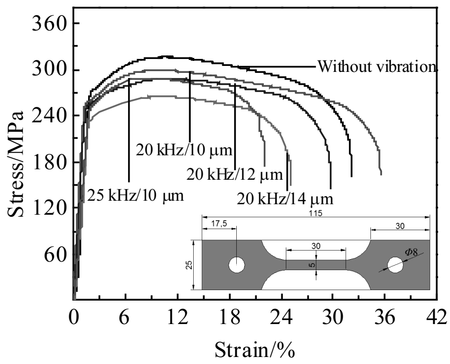

Fig.6 Engineering stress-strain curves under different vibration process parameters

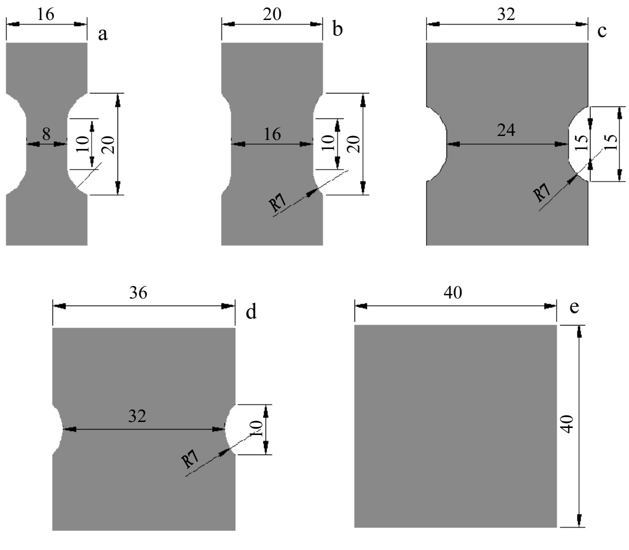

Fig.4 Shapes and dimensions of specimens for bulging experiments: (a) η=0.2, (b) η=0.4, (c) η=0.6, (d) η=0.8, and (e) η=1.0

2.2 Ultrasonic vibration-assisted sliding friction test

The force F_n applied to the TA2 sheet by pressing blocks was 2.0 kN during sliding friction test, the friction force (F_μ) between TA2/45# steel under different ultrasonic vibration parameters is shown in Fig.7, and the friction coefficients are shown in Fig.8. In the case without ultrasonic vibration, with the increase of sliding distance, the friction between TA2/45# steel has little change, the F_μ between TA2/45# steel is 0.578 kN, and the friction coefficient is 0.145.

After applying ultrasonic vibration, the friction between TA2/45# steels fluctuates slightly with the change of sliding distance. The fluctuation amplitude increases with the increase of vibration, and the frequency increases with the increase of ultrasonic frequency. When ultrasonic vibration with the

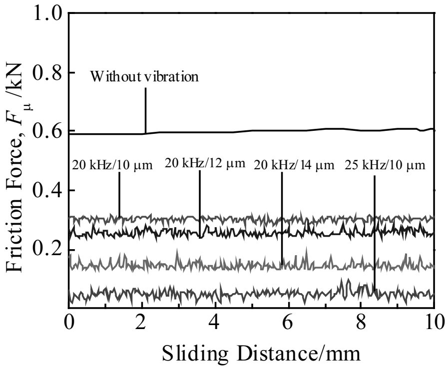

Fig.7 Friction force curves between TA2/45# steel under different ultrasonic vibration parameters

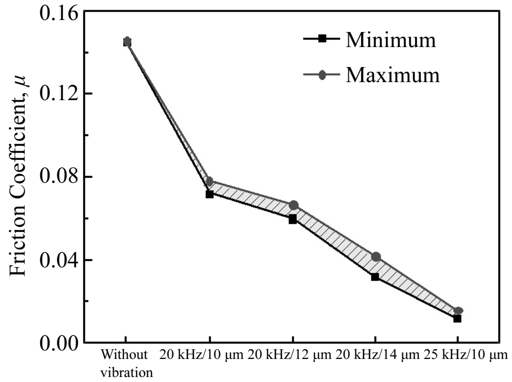

Fig.8 Friction coefficients under different ultrasonic vibration process parameters

parameter of 20 kHz/10 μm, 20 kHz/12 μm, and 20 kHz/14 μm is applied, the F_μ is 0.289~0.313, 0.238~0.268, and 0.128~0.168 kN, and the corresponding friction coefficient is 0.072~0.078, 0.060~0.067, and 0.032~0.042, respectively. When ultrasonic vibration with a parameter of 25 kHz/10 μm is applied, the F_μ between TA2/45# steel is 0.048~0.064 kN, and the friction coefficient is 0.012~0.016.

It can be seen from the comparison that after applying ultrasonic vibration, the friction force and friction coefficient between TA2/45# steel decrease significantly with the increase of ultrasonic amplitude and frequency. This is because after applying the ultrasonic vibration, direction of friction vector rapidly changes, leading to a large instantaneous kinetic energy, and to some extent, "smoothing" the peaks of the surface and reducing the sliding resistance. At the same time, the ultrasonic vibration energy is converted into thermal energy on the local surface, and produces a local thermal effect, thereby reducing the occurrence of the sticking welding phenomenon.

2.3 Ultrasonic vibration-assisted bulging test

The relationship between the bulging force and the punch stroke of the TA2 sheet with the width-to-length ratio η=1.0 is shown in Fig.9. The limit bulging height under different ultrasonic vibration parameters is shown in Fig.10. It can be seen that the maximum bulging force of the TA2 sheet during the bulging process is 16.73 kN in the case without ultrasonic vibration. When ultrasonic vibration with the parameter of 20 kHz/10 μm, 20 kHz/12 μm, 20 kHz/14 μm, and 25 kHz/10 μm is applied, the maximum bulging force is 5.43, 4.6, 3.62, and 4.27 kN, respectively. Compared to the case without ultrasonic vibration, the maximum bulging force decreases by 67.4%, 72.5%, 78.4% and 74.5%, respectively. The limit bulging height of the specimen is 9.55 mm in the case without ultrasonic vibration, and when ultrasonic vibration with the parameter of 20 kHz/10 μm, 20 kHz/12 μm, 20 kHz/14 μm, and 25 kHz/10 μm is applied, the limit bulging height of the specimen is 10.02, 9.74, 9.7 and 7.20 mm, respectively. For a comprehensive comparison, the ultrasonic vibration with a frequency of 20 kHz and an amplitude of 10 μm has the most significant effect on the increase of the limit bulging height of the sheet.

The comparison of the maximum bulging forces of the specimens with different width-to-length ratios under different ultrasonic vibration parameters is shown in Fig.11. Fig.12 shows the comparison of the limit bulging heights of specimens with

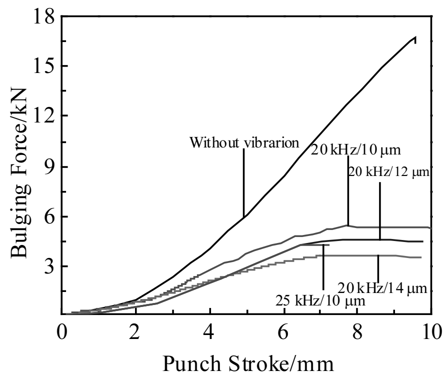

Fig.9 Relationship between bulging force and punch stroke under different ultrasonic vibration process parameters

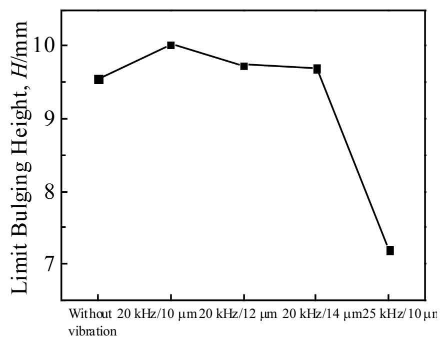

Fig.10 Limit bulging heights under different ultrasonic vibration process parameters

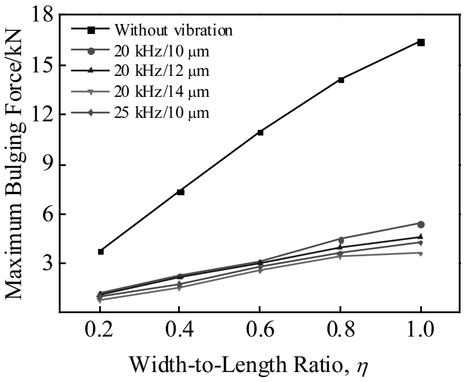

Fig.11 Maximum bulging forces of specimens with different width-to-length ratios

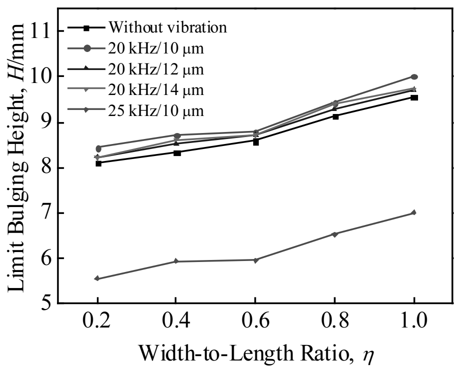

Fig.12 Limit bulging heights of specimens with different width-to-length ratios

different width-to-length ratios under different ultrasonic vibration parameters. It can be seen that the maximum bulging force increases with the increase of the width-to-length ratio of the specimen. The maximum bulging forces of the specimens with different with-to-length ratios decrease significantly after applying ultrasonic vibration, and decrease slightly with the increase of the ultrasonic vibration amplitude. The limit bulging heights of specimens increase slightly with the increase of ultrasonic vibration amplitude. When ultrasonic vibration with a frequency of 25 kHz and an amplitude of 10 μm is applied, the limit bulging height of specimen is significantly reduced. It is indicated that the ultrasonic vibration frequency of 20 kHz is the optimal parameter for the bulging process. When the ultrasonic vibration amplitude is 20 kHz/12 μm, the height of the forming limit diagram is higher than that in the case without vibration, but lower than that in the case of 20 kHz/10 μm. When the amplitude is 14 μm, the height of the forming limit diagram is reduced steeply.

2.4 Ultrasonic vibration-assisted forming limit diagram

The above research results show that applying ultrasonic vibration with appropriate parameters can effectively improve

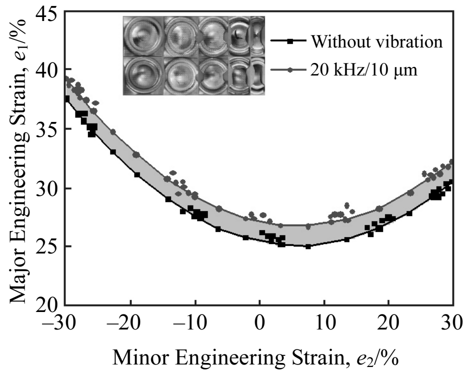

Fig.13 Ultrasonic vibration-assisted forming limit diagram of TA2 sheet

the plastic deformation ability of the sheet. It provides a basis for the feasibility of ultrasonic vibration-assisted forming of titanium alloy sheet, and is good for broadening the application of ultrasonic vibration-assisted forming in the forming process of titanium alloy sheet parts. Based on the ultrasonic vibration-assisted bulging of specimens with different width-to-length ratios, the mesh strain of the rupture zone of the ultimate forming specimen is measured, and the ultrasonic vibration-assisted forming limit diagram is established with major engineering strain (e_1) as the ordinate and minor engineering strain (e_2) as the abscissa (as shown in Fig.13). It can be seen that after applying ultrasonic vibration with a frequency of 20 kHz and an amplitude of 10 μm, the forming limit curve of the TA2 sheet rises as a whole. The deformable area of the material is obviously enlarged, and the increase range is 7.2%~12.6% due to different deformation paths.

3 Conclusions

1) The results of ultrasonic vibration-assisted tensile test show that the yield strength and tensile strength of TA2 sheet decrease with the increase of ultrasonic vibration amplitude or frequency. Compared to the case without ultrasonic vibration, the elongation of TA2 sheet improves by applying ultrasonic vibration with a frequency of 20 kHz and an amplitude of 10 μm, and it shows a downward trend under other ultrasonic vibration parameters.

2) The results of ultrasonic vibration-assisted sliding friction test show that with the increase of ultrasonic vibration amplitude or frequency, both the friction force and the friction coefficient between the contact surface are reduced. Ultrasonic vibration can effectively reduce the influence of friction on the forming process of sheet metal.

3) The results of ultrasonic vibration-assisted bulging test show that under the condition of appropriate ultrasonic vibration process parameters, ultrasonic vibration can not only reduce the bulging force of TA2 sheet, but also increase the

limit bulging height of TA2 sheet, thus enhancing the formability of TA2 sheet.

4) Through the strain measurement results of ultrasonic vibration bulging of specimens with different width-to-length ratios under the limit state, the forming limit diagram of TA2 sheet is established. Compared to the case without ultrasonic vibration, the forming area and the formability of TA2 sheet increase after applying ultrasonic vibration with a frequency of 20 kHz and an amplitude of 10 μm.

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超声振动效应对 TA2 钛合金板材力学及胀形性能的影响

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摘　要：针对钛合金板材塑性变形能力差的问题，进行了超声振动辅助成形工艺的研究，分析超声振动对钛合金 TA2 板材力学性能及与接触面之间摩擦系数的影响。在此基础上进行了不同宽长比坯料的超声振动辅助胀形实验，分析超声振动对 TA2 板材胀形力、极限胀形高度的影响。同时，基于网格应变原理，通过不同宽长比坯料极限应变的测量，建立 TA2 板材的成形极限图。结果表明，选择合适的超声振动辅助成形工艺参数，不仅可以提高 TA2 板材变形能力，还可以减小摩擦对板材成形性能的影响，从而有效提高了 TA2 板材的成形极限。

关键词：TA2 板材；超声振动；摩擦系数；胀形；成形极限图

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