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ARTICLE

Ultrasonic Vibration-assisted Tensile Process of TC4 Titanium Alloy Sheet Under Thermal Conditions

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Abstract: Based on the poor plasticity and high temperature required for forming of titanium alloy sheet, an ultrasonic vibration-assisted forming method under thermal conditions was proposed, in order to further improve the formability of titanium alloy sheets under thermal conditions. The effects of ultrasonic vibration process parameters on the engineering stress-strain curve, yield strength and elongation of titanium alloy sheet were analyzed by tensile test of TC4 sheet at 200~600 °C. And the microstructure and fractograph of the tensile specimens were analyzed. The results show that superimposing ultrasonic vibration process with appropriate parameters in the thermal tensile process can further reduce the flow stress and yield strength of TC4 sheet and improve the elongation, so as to achieve the purpose of further improving the formability under thermal conditions.

Key words: TC4 titanium alloy sheet; thermal conditions; ultrasonic vibration; tensile test; microstructure

Titanium alloy has excellent performance such as high specific strength, good corrosion resistance, and high heat resistance. Since its first use in aircraft fuselage in the 1950s, titanium alloy has become one of the leading materials for aircraft, aerospace airframe and their engine components, marine and power generation components, and as the application rate of titanium alloy increases year by year, it has become one of the leading indicators to evaluate the advanced nature of aircraft[1-3]. For sheet metal parts of titanium alloys, the rolled sheet is used and processed by a metal-plastic forming method, such as bulging, drawing, flanging, etc. However, compared with conventional metal materials, titanium alloys have low elongation, poor plasticity, and are easily fractured during forming. Moreover, the titanium alloys have low elastic modulus and high yield strength, and the springback angle of the molded part at room temperature is large. At present, for sheet metal parts of titanium alloys, a thermoforming method is mainly used to heats the sheet and the mold to a specific temperature, and the heating can not only reduce the yield strength of titanium alloy, but also improve the elongation and formability of the material. At the same time, it can effectively control the amount of springback and improve the forming accuracy[4-6]. Nevertheless, in the heating process, it is necessary to consider the quality of the parts, such as the changes in microstructure and properties, wall thickness and oxide scale. It also needs to consider the cost and environmental issues, because overheating can result in higher energy consumption, leading to a more severe environmental pollution [7-9].

Ultrasonic vibration-assisted forming is based on a traditional forming process, applying a certain frequency and amplitude of vibration to mold or forming part to improve the formability of the material[10-13]. As early as 1955, Blaha et al[14] applied ultrasonic vibration to the tensile process of single crystal zinc specimens, and a remarkable decrease in flow stress was observed, called softening effect (Blaha effect). That is the first time to reveal the impact of ultrasonic vibration on the metal-plastic forming process. After that, many scholars researched ultrasonic vibration-assisted forming process. In terms of tensile test, Wen et al[15] studied the plastic forming

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properties of AZ31 magnesium alloy under ultrasonic vibration during the tensile process at room temperature. They found that ultrasonic vibration has a significant effect on reducing the flow resistance and improving the formability of AZ31. Jiang et al[16] investigated the effect of ultrasonic vibration on the tensile properties of pure titanium foil. The results show that the application of ultrasonic vibration during the tensile process can not only reduce the strength of pure titanium foil, but also increase the elongation. Xie et al[17] studied the effect of ultrasonic vibration on the microstructure and properties of tensile specimen of AZ31 magnesium alloy. They pointed out that the true stress is reduced to different extents under various ultrasonic vibration conditions, and the fracture mode, plasticity, and microstructure of AZ31 magnesium alloy are also affected by ultrasonic vibration. Wang et al[18] used a developed device to perform a series of tensile tests on T2 copper foils with different grain sizes. They found that when ultrasonic vibration is applied, the yield stress decreases, and as the ultrasonic vibration increases, the hardening exponent increases. Moreover, in terms of bending, Tsujino et al[19] applied ultrasonic vibration with a frequency of 27 kHz to the bending die at room temperature and performed ultrasonic vibration bending tests on metal sheets of different materials (JISA1100P, JISA5052P, SUS304). It was found that the springback angle decreases as the vibration amplitude of the die increases, and decreases to almost zero when a large amplitude is applied. In terms of deep drawing, Pasierb[20] used a special radial vibration die and attached a blank holder in the deep drawing of the cylindrical part. The deep drawing experiments on aluminum, copper, and zinc sheets show that the load decreases significantly when vibration is applied. Jimma imposed vibration to the JISSPCE sheet metal with a thickness of 0.5 mm to increase the material's maximum drawing ratio from 2.68 to 3.01[21].

The above research results show that the formability of the material can be improved by heating or applying ultrasonic vibration. However, if ultrasonic vibration-assisted forming is superimposed to a thermal condition, the advantages of thermal forming and ultrasonic vibration-assisted forming can be fully utilized to further improve the forming properties of the material. In this work, ultrasonic vibration-assisted tensile tests for TC4 titanium alloy sheet under thermal conditions were performed. The effects of forming temperature and ultrasonic vibration-assisted process parameters on the tensile properties and microstructure of titanium alloy sheet were analyzed. The results can provide a reference for the application of ultrasonic vibration-assisted forming and the optimization of process parameters under thermal conditions.

1 Experiment

1.1 Experimental device

The ultrasonic vibration-assisted thermal tensile device is composed of four parts: a tensile machine, a heating device, a water cooling circulation system, and an ultrasonic vibration assisting device, as shown in Fig.1. The maximum force of the tensile machine is 100 kN, and the measurement accuracy of force is 0.01 kN. The heating device consists of the upper, middle, and lower electric heating wires, three independent temperature sensors, and three layers of thermal insulating material which can effectively guarantee the stability of the test temperature. The temperature measurement accuracy is ±0.5 °C. The ultrasonic vibration device is composed of an ultrasonic generator, a transducer, and an ultrasonic amplitude amplifier pole. The ultrasonic vibration with frequencies of 20 and 30 kHz and amplitudes of 10, 12 and 14 μm can be applied. During the experiment, the lower end of the specimen was connected with the ultrasonic amplitude amplifier pole, and ultrasonic vibration was applied along the tensile direction; the upper end of the specimen was connected to the movable beam of the tensile machine, and the tensile speed was 5 mm/min. Each group experiment was repeated six times to reduce the experimental error.

1.2 Experimental materials and solutions

At present, among many grades of titanium alloys, TC4 titanium alloy is considered to be the best titanium alloy for application because of its excellent material properties, wide application range, mature technology, and large usage. However, TC4 sheet is a typical hard-to-deform titanium alloy sheet, which is generally formed under a certain thermal condition. In this experiment, the hot-rolled annealed TC4 sheet was used. Table 1 shows the chemical composition, and the thickness of the experimental TC4

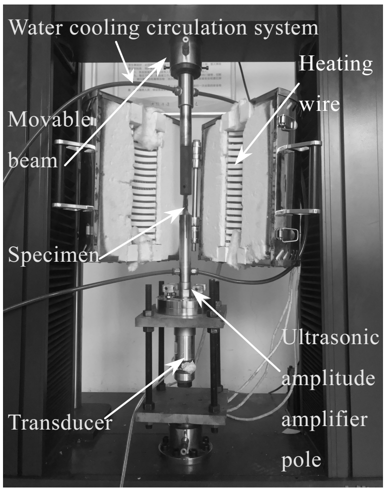

Fig.1 Ultrasonic vibration-assisted tensile test device under thermal conditions

sheet is 1.0 mm; the dimension of the tensile specimen is shown in Fig.2. The tensile specimen has a gauge length of 30 mm, and a width of 5 mm. Holes with the diameter of φ8 mm were machined at both ends to mount it on a tensile test machine. Ultrasonic vibration-assisted tensile tests were carried out at 200, 400, 500, and 600 °C. The temperatures were determined based on the current research results of the TC4 sheet. At the same time, considering the influence of temperature on the microstructure of the sheet, the microstructure and fractograph of the fracture position of TC4 tensile specimens were analyzed by optical microscopy (OM) and scanning electron microscopy (SEM).

2 Results and Discussion

Fig.3 shows the engineering stress-strain curves of ultrasonic vibration-assisted tensile tests of TC4 sheets under different conditions. In the case without ultrasonic vibration, the yield strength of TC4 sheet at 200, 400, 500, and 600 °C is 905.2, 718.2, 678.7, and 582.3 MPa, respectively. Under the same temperature condition, after superimposing the ultrasonic vibration, the TC4 sheet yields into the plastic deformation state in advance, and the flow stress also decreases to some extent. The stress-strain curve decreases as a whole, and the phenomenon of "softening effect" appears[15]. This phenomenon becomes more and more obvious as the amplitude or the frequency of the ultrasonic vibration increases. For example, when the ultrasonic vibration with a 20 kHz/14 μm parameter is applied during the tensile process, the yield strength of the corresponding TC4 sheets at 200, 400, 500, and 600 °C is 825.9, 627.1, 587.2, and 442.4 MPa, respectively, and the reductions are 8.76%, 12.68%, 13.48%, and 24.03%, respectively, as compared to the case without ultrasonic vibration (as shown in Fig.4). The reason is that, on the one hand, after the input of the ultrasonic vibration energy, ultrasonic vibration causes the activation energy inside the material to increase, so the dynamic deformation resistance of the material is continuously decreased; on the other hand, when the ultrasonic vibration energy is superimposed, the macroscopic force acting on the tensile test specimen is lowered, resulting in a decrease in the yield strength of the material.

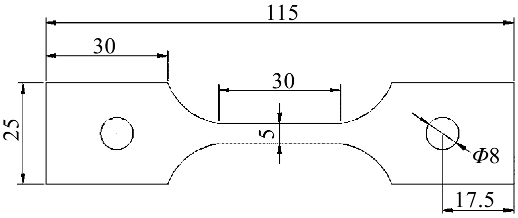

Fig.2 Shape and size of the tensile specimen

Table 1 Chemical composition of TC4 sheet (wt%)

Fe	Si	C	N	O	Al	V	Ti
0.3	0.15	0.1	0.05	0.2	5.6~6.8	3.5~4.5	Bal.

It can also be seen from Fig.3 that the elongation of TC4 sheets at 200, 400, 500 and 600 °C without ultrasonic vibration is 10.57%, 11.23%, 12.09% and 23.83%, respectively, and the elongation of the tensile specimen gradually increases with the increase of temperature. Under the same temperature conditions, after the ultrasonic vibration is superimposed, the elongation of the TC4 sheet has two cases. One is to increase the elongation of tensile specimen after applying ultrasonic vibration. When the 20 kHz/10 μm ultrasonic vibration is applied during the tensile process, the elongation of the TC4 sheet is 11.04%, 12.04%, 14.09%, and 28.30%, at 200, 400, 500, and 600 °C, respectively. Compared with no ultrasonic vibration-assisted tensile, the elongation of TC4 sheet increases by 4.26%, 7.21%, 9.22% and 17.62% (as shown in Fig.5). With the increase of temperature, the elongation increases continuously, this can effectively increase the formability of the material. The other is that the elongation of the tensile specimen is reduced after the ultrasonic vibration is applied. When 20 kHz/14 μm ultrasonic vibration is applied during the tensile process, the elongation of the TC4 sheet is 9.99%, 10.27%, 11.59% and 16.79%, reduced by 5.49%, 8.54%, 10.16% and 29.54%, respectively, compared to the case without ultrasonic vibration.

The reasons for these phenomena are that, on the one hand, the ultrasonic vibration during the tensile process causes a "softening effect" of the material, thereby reducing the yield strength and flow stress of the material, and increasing the elongation of the tensile specimen; on the other hand, ultrasonic oscillation induced by ultrasonic vibration tends to cause stress concentration in the local region of the material and generates fatigue cracks, which lead to premature fracture of the material during the tensile process, and the elongation of tensile specimen is lowered. That is to say, the ultrasonic vibration-assisted forming process has the best process parameters, which can reduce the yield strength and increase the elongation of the material.

3 Microstructure Observation

3.1 Impact on metallographic organization

Considering the temperature characteristics of the TC4 sheet, the microstructures of specimens are observed at only 400 and 600 °C. The microstructures of the TC4 tensile specimens after stretching at 400 and 600 °C with or without ultrasonic vibration are shown in Fig.6~8. There is no new phase formed at these temperatures because the temperature has not reached the recrystallization temperature of TC4 sheet. The content of β-structure between the crystals before and after the application of ultrasonic vibration has a little increase, which can be manifested by the fact that the β phase gradually changes from a finely dispersed distribution to a staggered banded β phase.

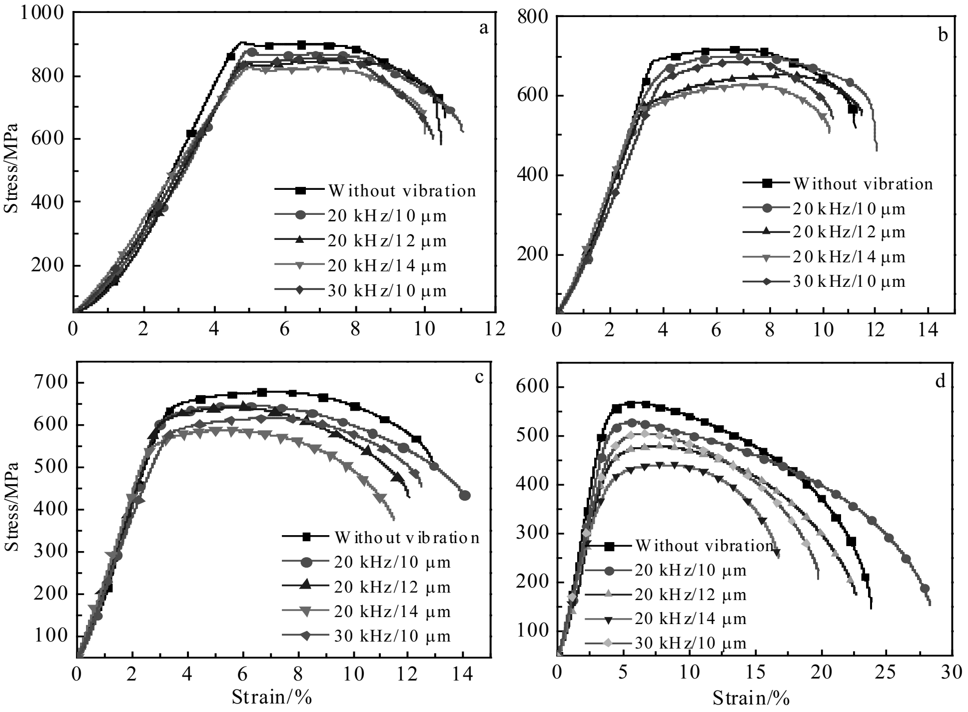

Fig.3 Engineering stress-strain curves of TC4 tensile specimens loaded with ultrasonic vibration at different temperatures: (a) 200 °C, (b) 400 °C, (c) 500 °C, and (d) 600 °C

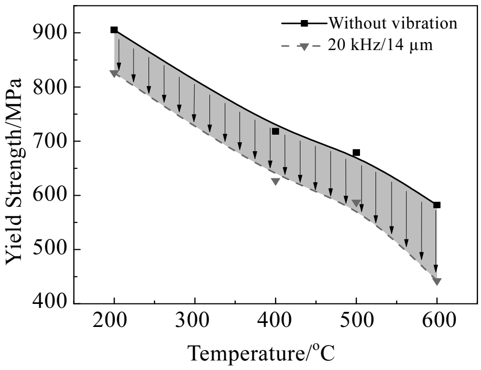

Fig.4 Effect of ultrasonic vibration and temperature on the yield strength of the TC4 sheet

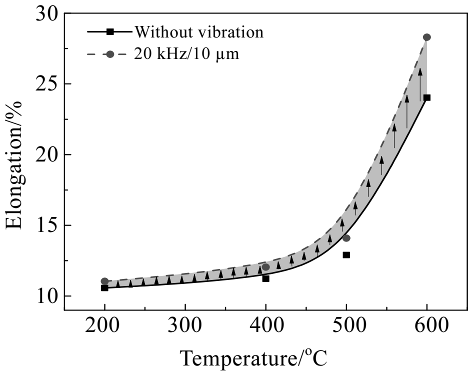

Fig.5 Effect of ultrasonic vibration and temperature on the elongation of the TC4 sheet

3.2 Changes in the tensile fractograph of the samples

The fractographs of the TC4 tensile specimens after stretching at 400 and 600 °C with or without ultrasonic vibration are shown in Fig.9~11. It can be seen from comparison between Fig.9 and Fig.10 that the fracture mode of the TC4 sheet belongs to the transgranular dimple fracture with uniform equiaxed dimple, and as the temperature increases, the dimple size gradually becomes larger and deeper. In comparison, when 20 kHz/10 μm ultrasonic vibration is applied, the dimple size is larger, and the formability is better. Due to the presence of the β phase, small dimples are evenly distributed in the large dimple. It can be seen from Fig.11 that after the application of 20 kHz/14 μm ultrasonic vibration, the fracture surface changes from a dimple fracture to a mixed mode of dimple fracture and cleavage patterns, and with the increase of temperature, the trend of this change becomes more and more obvious, which leads to the deterioration of the formability of TC4 sheet. Since the inputted ultrasonic vibration energy is different, the stress state of the specimen

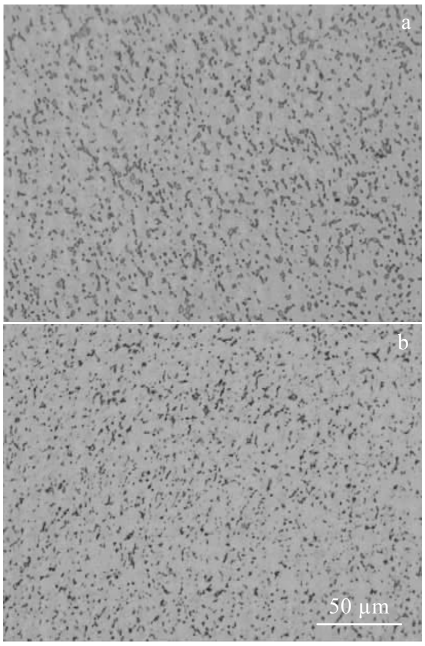

Fig.6 Metallographic structures of TC4 tensile specimens without ultrasonic vibration at 400 °C (a) and 600 °C (b)

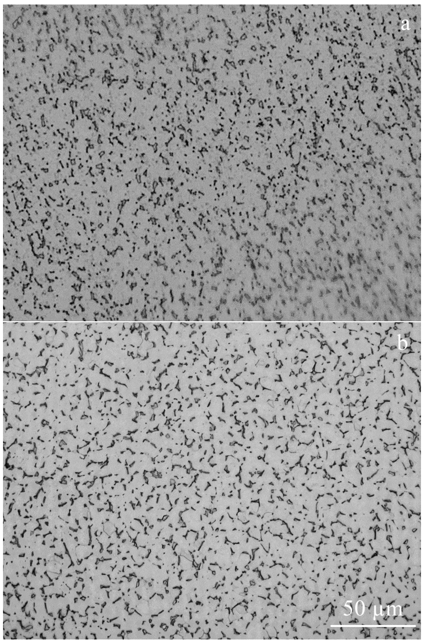

Fig.8 Metallographic structures of TC4 tensile specimens with 20 kHz/14 μm ultrasonic vibration at 400 °C (a) and 600 °C (b)

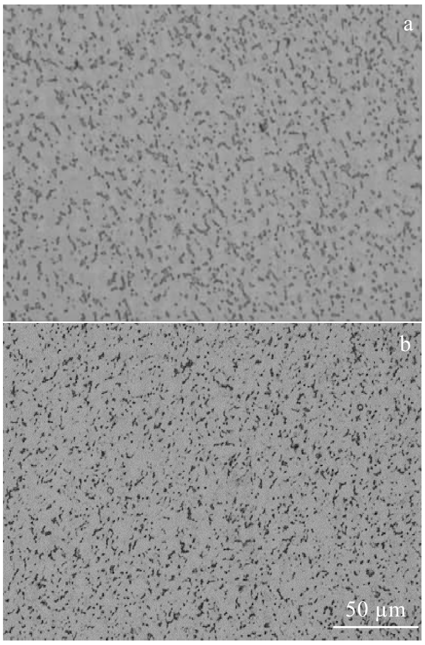

Fig.7 Metallographic structures of TC4 tensile specimens with 20 kHz/10 μm ultrasonic vibration at 400 °C (a) and 600 °C (b)

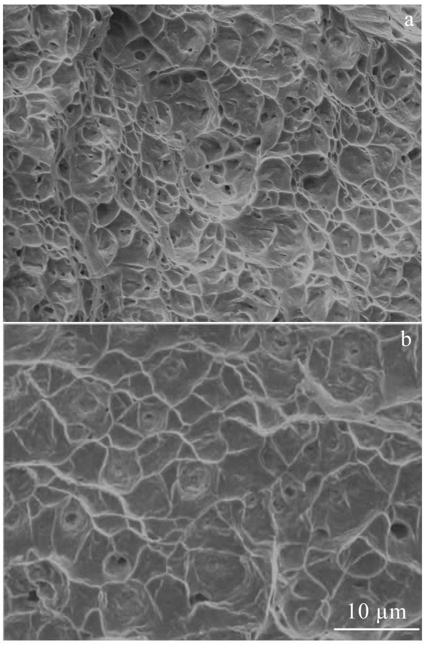

Fig.9 Fractographs of TC4 tensile specimens without ultrasonic vibration at 400 °C (a) and 600 °C (b)

changes. On the one hand, a proper ultrasonic vibration process parameter can enhance the formability of TC4 sheet, resulting in a larger dimple size in the ductile fracture. On the other hand, the improper ultrasonic vibration process parameters lead to premature fracture of the specimen and worse plasticity, which causes the fracture mode to change from ductile fracture to brittle fracture, thereby forming a mixed mode of dimple fracture and cleavage patterns (region marked by arrows in Fig.11).

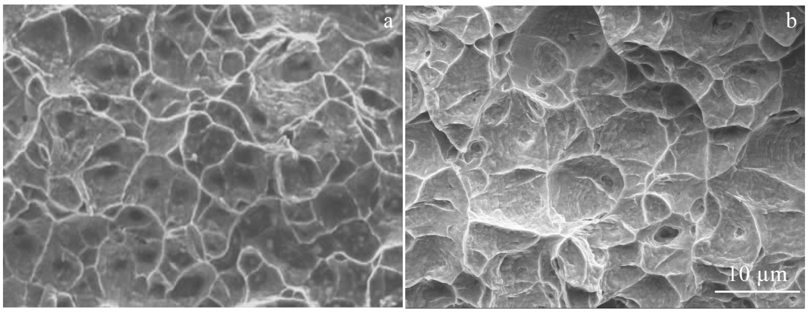

Fig.10 Fractographs of TC4 tensile specimens with 20 kHz/10 μm ultrasonic vibration at 400 °C (a) and 600 °C (b)

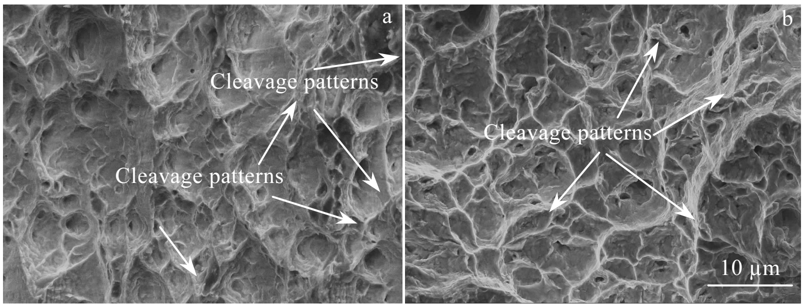

Fig.11 Fractographs of TC4 tensile specimens with 20 kHz/14 μm ultrasonic vibration at 400 °C (a) and 600 °C (b)

4 Conclusions

1) When superimposing ultrasonic vibration with appropriate frequency and amplitude during the thermal tensile process of TC4 sheet, the flow stress of the material decreases, and the stress-strain curve moves down as a whole. The "softening effect" of the material is discovered.

2) Ultrasonic vibration-assisted thermal tensile process of TC4 sheet has the optimal ultrasonic vibration process parameters. Thereby, the formability of the TC4 sheet can be improved under thermal conditions.

3) Ultrasonic vibration-assisted thermal tensile process of TC4 sheet needs to select appropriate ultrasonic vibration process parameters to prevent premature fracture of the material.

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温热条件下 TC4 钛合金板材的超声振动辅助拉伸工艺

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摘　要：针对钛合金板材塑性变形能力差、成形温度高的问题，提出了温热条件下超声振动辅助成形方法，希望在温热环境条件下进一步提高钛合金板材的成形性能。通过 200~600 ℃条件下的 TC4 板材超声振动辅助拉伸试验，分析了超声振动工艺参数对钛合金板材拉伸过程当中的工程应力-应变曲线、屈服强度、延伸率等性能指标的影响规律，并对拉伸试件显微组织及断口形貌进行分析。结果表明，温热拉伸过程施加合适的超声振动工艺参数，可以使 TC4 板材流动应力、屈服强度进一步降低，延伸率进一步提高，从而实现在温热条件下进一步提高成形性能的目的。

关键词：TC4钛合金；温热条件；超声振动；拉伸试验；微观组织

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