Precise forming of Ti60 alloy by superplastic forming /diffusion bonding

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Abstract. The study investigated the high-temperature tensile behavior of Ti60 alloy at different temperatures (940℃ to 1040℃) and different strain rates ($0.1s^{-1}$ to $0.0005s^{-1}$). Ti60 exhibited superplasticity with the best deformation temperature ranging from 940℃ to 960℃. The elongation of the samples decreased significantly at the temperatures over 980℃ due to the growth of grain size. In addition, the study investigated the influence of diffusion bonding temperature and pressure on the microstructure and mechanical properties of the joint. The results showed that there was no microscopic gaps or cracks at the interface of the diffusion bonding joints performed at 2.5MPa, 920℃ and 2 hours. Thereafter, a four-layer structure of Ti60 alloy was fabricated through the SPF/DB. The component with uniform thickness distribution, high surface quality, high diffusion bonding quality was achieved.

Introduction

Titanium and its alloys have wide applications in various fields such as medicine, power generation, automotive manufacturing, and aviation due to their special properties such as good corrosion resistance, low density, and excellent mechanical properties at high temperatures [1]. Compared with steel and other hard alloys, titanium alloy is widely used in aerospace, chemical industry and automobile fields because of its high specific strength, corrosion resistance and excellent fracture toughness. With the requirements of high temperature resistant materials, a lot of new materials such as IMI834, Ti1100, BT18Y, Ti60 and other near-α high temperature titanium alloys serving at temperatures up to 600℃ have been developed. As a potential candidate material for airfoil blade and wheel, Ti60 alloy has been widely concerned by scholars. Compared with IMI834, more Si elements were added to Ti60 alloy, which improved the creep property. A small amount of Ta and C elements were added to improve the heat resistance and widen the α+β phase field.

Ti60 alloy is a hige temperature alloy with high deformation resistance, making it difficult to use traditional processing methods. However, it has been reported that Ti60 has superplasticity at high temperatures [6]. Therefore, SPF and DB can be used for processing. SPF involves forming metal sheets with fine grain or two-phase microstructure at high temperatures, using gas pressure with tools or molds at lower strain rates [7]. Compared with traditional processing techniques such as forging, casting, and milling, SPF/DB posseses unique advantages, including greater design freedom, lower mold costs, elimination of rebound, and production of complex geometries in a single manufacturing step [8].

Wanjara [9] studied the isothermal hot working flow stress behavior of IMI834 at temperatures of 950℃, and the results showed that the phase exhibited greater flow stress softening at higher strain rates. Biallas and Gerhard [10] investigated the effect of environment on the deformation behavior of high temperature titanium alloy IMI834, cracks were found to initiate at slip bands.

Xiufeng Gao, Shaoping Chen et al. [11] used external current to increase atomic activity and performed diffusion bonding on Ti/Ni, and the results showed that the growth of all phases was enhanced by the application of a direct current. However, there are few investigations on the deformation behavior at high temperatures and diffusion bonding parameters of Ti60 alloy. Thus, the purpose of this paper is to study the high temperature deformation behavior of Ti60 and influence of pressure and temperature on the quality of diffusion bonding joints. Besides, a four-layer hollow structural component without obvious defects was manufactured.

Organization of the Text

Material

The Ti60 plates with the thickness of 2mm are provided by Litai Metal Co. Ltd. Their chemical composition is shown in Table 1. The sufficient α stable element and a certain amount of β stable element make it fully solid solution strengthened, and the isomorphous β element further improves its thermal stability.

Table1 Chemical composion of Ti60 titanium alloy (wt%)

Element	Al	Sn	Zr	Mo	Si	Nb	Ta	C	Ti
wt%	5.7	4	3.5	0.4	0.4	0.4	1.0	0.05	allowance

High temperature tensile test

The high-temperature tensile tests were conducted to investigate the high-temperature deformation behavior of Ti60 alloy. The temperature range was from 940℃ to 1040℃, and the strain rates range was from $10^{-1}s^{-1}$ to $10^{-4}s^{-1}$.

Figure 1 shows the true stress-strain curves of Ti60 alloy at different temperatures and strain rates. The flow stress decreased with the increase of temperature, and the material exhibited flow softening behavior after the peak of flow stress. The flow stress increased with the increase of strain rate (from $10^{-1}s^{-1}$ to $10^{-4}s^{-1}$). All curves in Figure 1 showed similar fluctuation trends which could be roughly divided into three stages. The first stage was the initial deformation stage before the peak stress; the second stage started with the appearance of the peak stress to the occurrence of necking ; the last stage started from the occurrence of necking until fracture, which was more obvious in Figure 1 (a), directly reflecting the fracture of Ti60. When the strain rate was $0.005s^{-1}$, the flow stress approached to a steady state indicating that there were sufficient softening mechanisms to balance the strain hardening, such as the dynamic recovery and dynamic recrystallization.

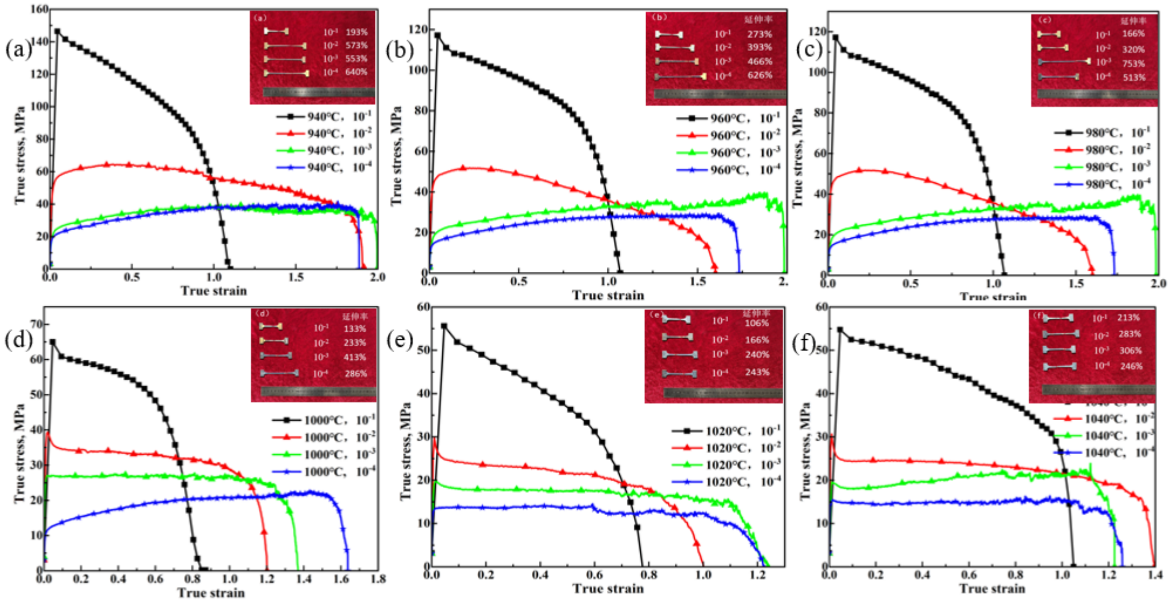

Fig. 1 Real stress-strain curves at different strain rates
(a)940℃ (b) 960℃ (c) 980℃ (d) 1000℃ (e) 1020℃ (f) 1040℃.

The dynamic recovery and dynamic recrystallization are the main softening mechanisms for Ti60 alloy at high temperature deformation[14,15]. The degree of softening depends on the the variation of temperaturses which changes the microstructure, such as grain sizes or dislocation densit. Figures 2 shows the trends of elongation and tensile strength at different temperatures. When the temperature is 980°C and the strain rate is $10^{-4}s^{-1}$, the elongation of the material is the highest (780%). The elongation of the materials generally decreases with the decrease of temperature. When the temperature is 980°C and 1000°C, the elongation of the material increases when the strain rate decreases.

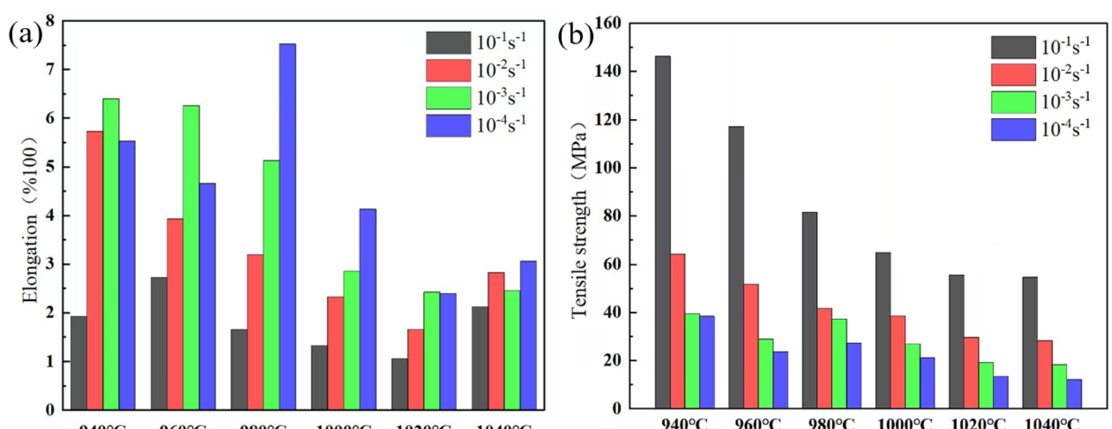

Fig. 2 (a) The variation trend of elongation at different temperatures after fracture (b) The trend of tensile strength with temperature.

Fig. 2 (b) shows the tensile strength of samples at different temperatures. It can be seen that the tensile strength decreases with the increase of temperature at the same strain rate, and the tensile strength increases with increasing of strain rates at the same temperature. Therefore, for the deformation behavior of Ti60, the temperature and strain rate are important parameters. The maximum tensile strength (148.4Mpa) is achieved at 940°C and $0.001s^{-1}$.

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Diffusion bonding

This experiment aimed to investigate the influence of several experimental parameters on the joint performance by using different temperatures and pressures to obtain optimal joint quality. Prior to the experiment, the contact surfaces of the Ti60 alloy were polished by 180# sandpaper, the plate surface was also cleaned by ultrasonic to remove oil stains.

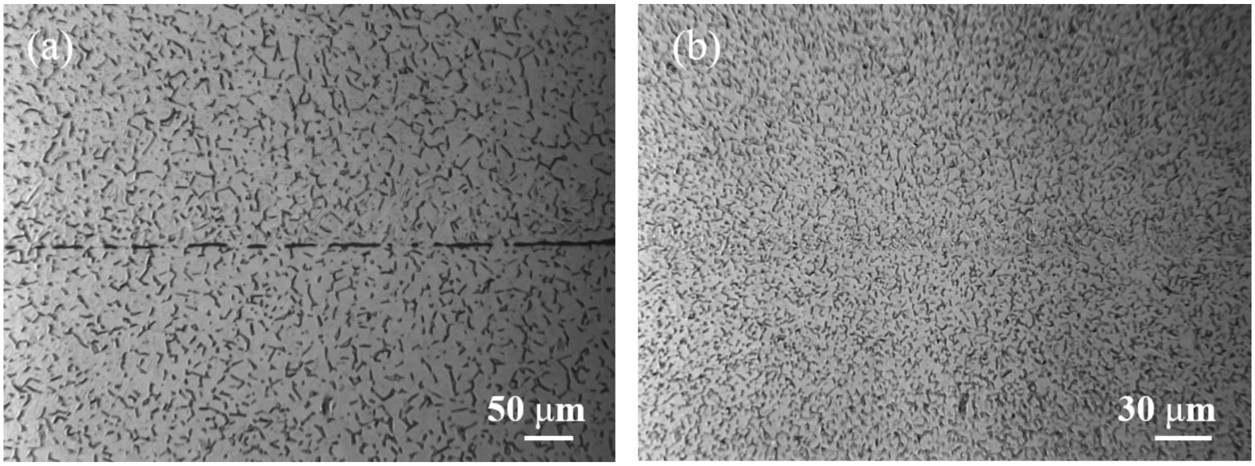

Fig. 3 microstructure of the diffusion-bonded joint at (a) 900℃, 2.5Mpa,1.5h. (b) 920℃, 2.5Mpa,2h.

In Figure 3 (a), due to the insufficient diffusion temperature and holding time, there were several unconnected areas at the diffusion-bonded joints. With the increase of temperature and the extension of holding time, the atomic diffusion of the sample became more sufficient and the joint ratio could reach over 90%. However, if the temperature is too high, the grains size of the Ti60 will increase, resulting in embrittlement of the material.

At 920°C, 2.5 MPa for 2 hours, the surface of the joint was smooth. Due to the high pressure of the diffusion bonding, the material underwent large plastic deformation at the interface, which ensured the tight connection of the joint. The interface of the joints almost disappeared, and there were no pores or cracks in the connection interface.

Four-storey structure

The lightweight four-layer structure with high toughness saves materials and maks it highly valuable in the aerospace industry. Based on the above experimental results, the optimal temperature for DB was 920°C. Therefore, Ti60 sheets were diffusion-bonded at 920°C and 2.5 MPa for about 2 hours. Subsequently, SPF was performed at 980°C with a strain rate of $10^{-4}s^{-1}$.

According to the high-temperature tensile and diffusion bonding experimental parameters described above, Ti60 four-layer structure components were processed, as shown in Figure 4. The surface of the component was flat and smooth, with no obvious defects such as burrs, and the dimensional accuracy was high. The vertical ribs structure of the component could be observed at the wire-electrode cutting position, as shown in Figure 4. The quality of the vertical ribs was well, and the joint in the diffusion bonding area of the core sheet was tight.

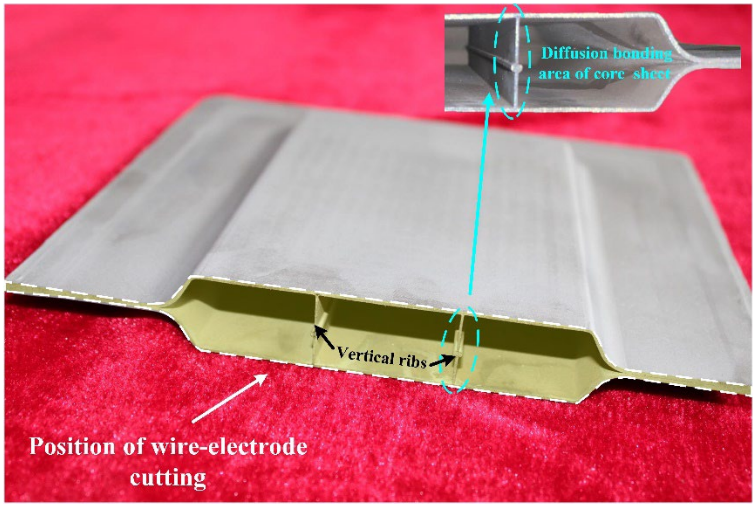

Fig. 4 the position of the wire-electrode cutting on the four-layer structure and the vertical ribs.

Figure 5 shows the defects that occurred during the SPF/DB process. It shows the failure of diffusion bonding due to insufficient holding time of the core sheet, resulting in the disconnection of the core sheet and the Face sheet. And it shows the rupture of the core sheet at the location of excessive thinning during the SPF process, causing insufficient air pressure and failure of the experiment.

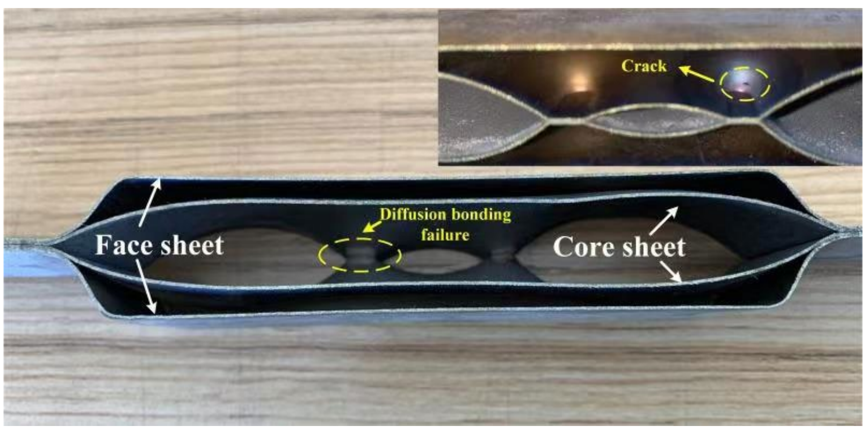

Fig. 5 Defects in four-layer structure components

The outer surface of the four-layer structure was smooth and flat, with no obvious collapse, and the cross-sectional shape was regular without any significant defects. There were no obvious unconnected parts in the diffusion bonding area. The Ti60 four-layer structure produced in this paper ensures a lightweight structure with excellent temperature resistance performance. It ensures the continuous improvement of spacecraft speed and performance.

Summary
The superplasticity of Ti60 alloy was studied in the temperature range from 940°C to 1040°C and the strain rate range from $10^{-1}s^{-1}$ to$10^{-4}s^{-1}$. The diffusion bonding of Ti60 alloy was also studied, and a four-layer structure was fabricated. The following conclusions can be drawn: At 980°C and a strain rate of $1\times10^{-4}s^{-1}$, Ti60 can achieve the maximum elongation rate (780%). The materials tensile strength is inversely proportional to the temperature and directly proportional to the strain rate. A stable joint surface can be obtained by insulation at 920°C and 2.5Mpa for 2 hours. Based on the above experimental parameters, the Ti60 four-layer structure was produced, and with a high surface quality and no significant defects.

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