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Superplastic formability of Ti-6Al-4V butt-welded plate by laser beam welding

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Abstract: The superplasticity of Ti-6Al-4V butt-welded plates by laser beam welding (LBW) was studied in virtue of hot tensile tests and superplastic bulging tests. Furthermore, microstructural evolution of weld metal upon superplastic forming was systematically analyzed via metallographical tests and scanning electron microscope (SEM). The relation between the microstructure of weld metal and its superplastic ability was discussed. The experimental results show that Ti-6Al-4V butt-welded plates by LBW possess superplasticity. The maximum elongation is up to 154% and the maximum bulge height can be up to 1.81 times the internal radius of the female die. There is an optimum value of the bulge height for bulging gas pressure.

Key words: superplastic forming; Ti-6Al-4V; laser beam welding

1 Introduction

Ti-6Al-4V alloy is a dual phase alloys consisting of α and β phases. It has good mechanical properties, excellent corrosion resistance, outstanding specific strength and good superplastic ability. Thus it is widely used in the fields of aerospace, chemical engineering and navigation[1−2]. The superplastic forming (SPF) of plate has been utilized widely.

In some cases, such as manufacturing expansion bellows made of titanium alloy and large diameter thin-walled structure, the butt-welded plates and tube blanks are needed for superplastic forming[3−5]. High energy beam welding methods has been developed due to their finer weld metal microstructure and better plasticity[6−7].

Laser beam welding (LBW) is especially suitable to weld titanium alloy due to its excellent protection. The microstructure and mechanical properties for weld metal of Ti-6Al-4V by LBW have been studied[8−10]. However, few attentions focus on their superplastic formability[11−13].

In this work, the superplasticity of Ti-6Al-4V butt-welded plate by LBW was investigated by hot tensile tests and superplastic bulging tests.

2 Experimental

2.1 Experimental materials

Two kinds of mill-annealed Ti-6Al-4V plates were used as the experimental materials for hot tensile test and bulging test. The thickness of samples is 0.8 mm and 1.0 mm, respectively. The original microstructures are $\alpha+\beta$ equaled grain.

2.2 Experimental method

Pairs of mill-annealed plates with 130 mm×20 mm×0.8 mm and 125 mm×62.5 mm×1.0 mm were welded. The welding specimens were machined and thoroughly cleaned with a wire brush and emery paper, and then degreased with acetone prior to LBW. The welding parameters are shown in Table 1. The welding direction was perpendicular to rolling direction. All welded specimens were visually inspected and tested with dye penetrant for surface defects. They were also radiographed for internal soundness. As a result, superplastic forming specimens were prepared.

In order to investigate yield strength and elongation of weld metal, hot tensile tests were performed at 925 ℃ with different strain rates using Ti-6Al-4V butt-welded plate by LBW. The tensile specimens were removed

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Table 1 Welding parameters

Sample type	Frequency/Hz	Power/W	Pulse width/ms	Welding velocity/(mm·min^{-1})	Fusion zone width/mm
Bulging sample	32	1 600	30	120−240	1.51−1.91
Hot tensile sample	−	1 300	−	110	1.80−1.82

from butt-welded plate using a wire cutting machine and edges were polished with emery paper. Tensile tests were performed using a SHIMADZU AG-1 250 kN tester with strain rates of 1.11×10^{-4}, 2.22×10^{-4} and 3.33×10^{-4} s^{-1}. The orientations of the tensile specimens taken from welded test pieces are shown in Fig.1. The specimens were 15 mm in gauge length and 6 mm in width. To measure the strain rate sensitivity index(m) of weld metal, velocity jump tests were performed by sudden increase of crosshead speed, i.e. 1 mm/min to 2 mm/min and then from 2 mm/min to 4 mm/min.

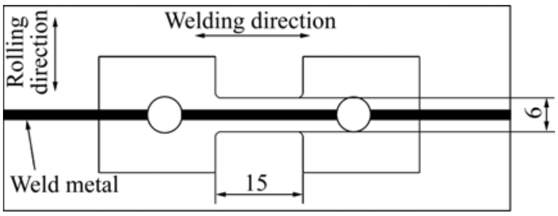

Fig.1 Schematic of sample fabrication (Unit: mm)

Superplastic gas pressure bulging tests were carried out using a 500 kN superplastic forming machine with a 18 kW furnace in Harbin Institute of Technology (HIT). Its schematic diagram is shown in Fig.2. The dies are composed of an air-in plate and a female die. The dimensions of female die are 75 mm in internal diameter and 40 mm in height. The maximum bulge height after rupture was considered the mark for superplastic bulging capacity.

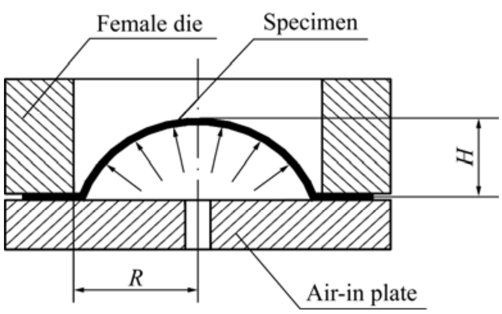

Fig.2 Schematic diagram of superplastic bulging test

Firstly, specimens were heated up to 180 ℃ and held for 10 min, and taken from furnace to paint high temperature antioxidant. And then specimens were put into dies and removed into furnace to heat up to 925 ℃, which is the optimum superplastic forming temperature for Ti-6Al-4V alloy. The furnace was sealed by load and held for 30 min. Finally, the inflated argon was input into specimens to bulge until burst.

The microscopic specimens of weld metal were cut from post-weld line, undeformed weld metal and deformed weld metal with different thinning rates. Specimens were ground, polished and etched using etchants with following chemical composition: 10%HNO_3+2%HF+88%H_2O (volume fraction). The microscopic specimens were examined using an optical microscope BH2UMA.

3 Results and discussion

3.1 Test results

The hot tensile experimental results show that the elongations of weld metal are between 101% and 154% and their yield strengths are between 21.5 and 34.4 MPa. Fig.3 depicts the effect of strain rate on the elongation of weld metal. It represents that the elongation increases with the decrease of strain rate. When the strain rate decreased to one third of the original one, the elongation increased by about 50% and the yield strength decreased by about 35%.

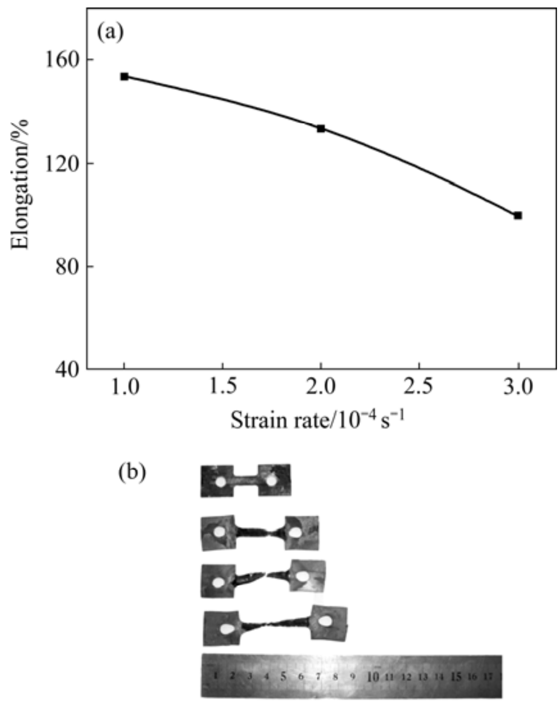

Fig.3 Effect of strain rate on elongation: (a) Relationship between strain rate and elongation; (b) Tensile samples

Fig.4 shows the results of velocity jump test. The strain rate sensitivity (m) derived from velocity jump test is equal to about 0.37.

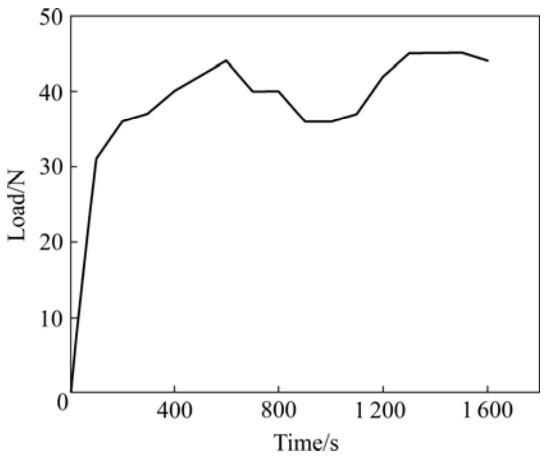

Fig.4 Result of velocity jump test

Fig.5 shows the female die and as-formed part. Fig.6 depicts the relation between welding velocity and bulge height. Fig.7 depicts the relation between gas pressure and bulge height. The results prove that butt-welded plate by LBW made of Ti-6Al-4V has excellent superplastic bulging capability. Their bulge heights are between 60 and 68 mm and the relative bulge heights (which is the ratio of the bulge height to internal radius of female die) are between 1.6 and 1.81. The faster

Fig.5 Female die and part after bulging

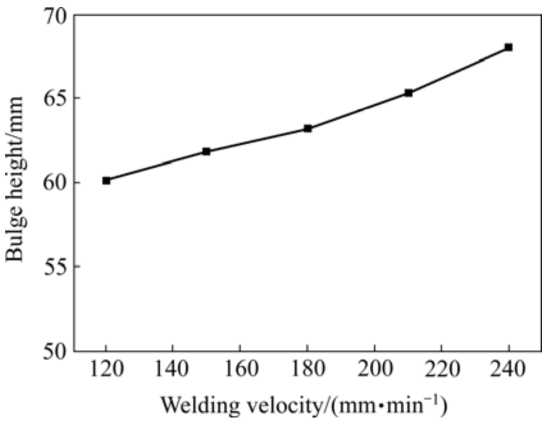

Fig.6 Effect of welding velocity on bulge height

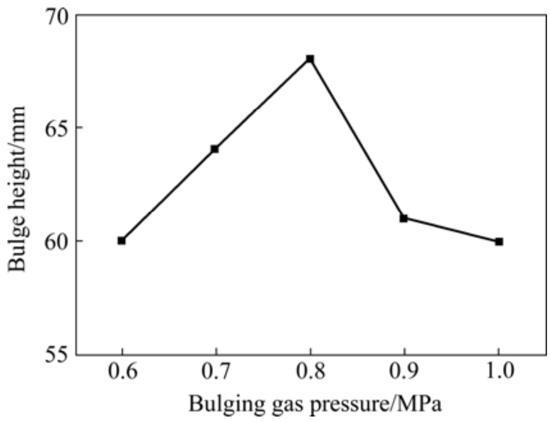

Fig.7 Effect of gas pressure on bulge height

the welding velocity is, the higher the bulge height will be. The gas pressure has an optimum value, but both the welding velocity and gas pressure have a little effect on the bulge height.

3.2 Discussion

The hot tensile tests represent that the strain rate sensitivity (m) of weld metal is equal to about 0.37 while all the elongations of weld metal are more than 100%. As a result, they are greater than criteria of superplasticity. These demonstrate that Ti-6Al-4V butt-welded plate by LBW possesses superplasticity. As shown in Fig.8(a), the fusion zone is composed of fine acicular α' martensite because LBW has extremely rapid cool velocity, for example more than 500 ℃/s[14]. Under such a cool velocity, weld metal is solidified into fine acicular α' phase due to their rapid cool velocity resulting from high power density.

The experimental results suggest that all of butt-welded plates by LBW have good superplastic bulging capability. Among them, the relative bulge height is up to 1.81. The faster the welding velocity is, the higher the bulge height is. As shown in Figs.8 and 9, the microstructural evolutions of weld metal during superplastic forming are as follows. At the outer edge of specimens, no deformation occurs, and weld metal is equivalent to be subjected to a post-weld heat-treatment (see Fig.9(b)). During reheating, the microstructure transforms into weavebasket-like microstructure, which is significantly coarser than original acicular martensite.

The bulge height increases with the increase of welding velocity because the increase of welding velocity results in an increase of cool rate of weld metal, which causes martensite finer. Deformations are distributed to more grains, which improves the plasticity of weld metal and leads to the higher bulge height[15].

The bulging gas pressure has an optimum value. The larger the gas pressure is, the faster the strain rate is. Therefore, unsufficient recrystallization is produced, and

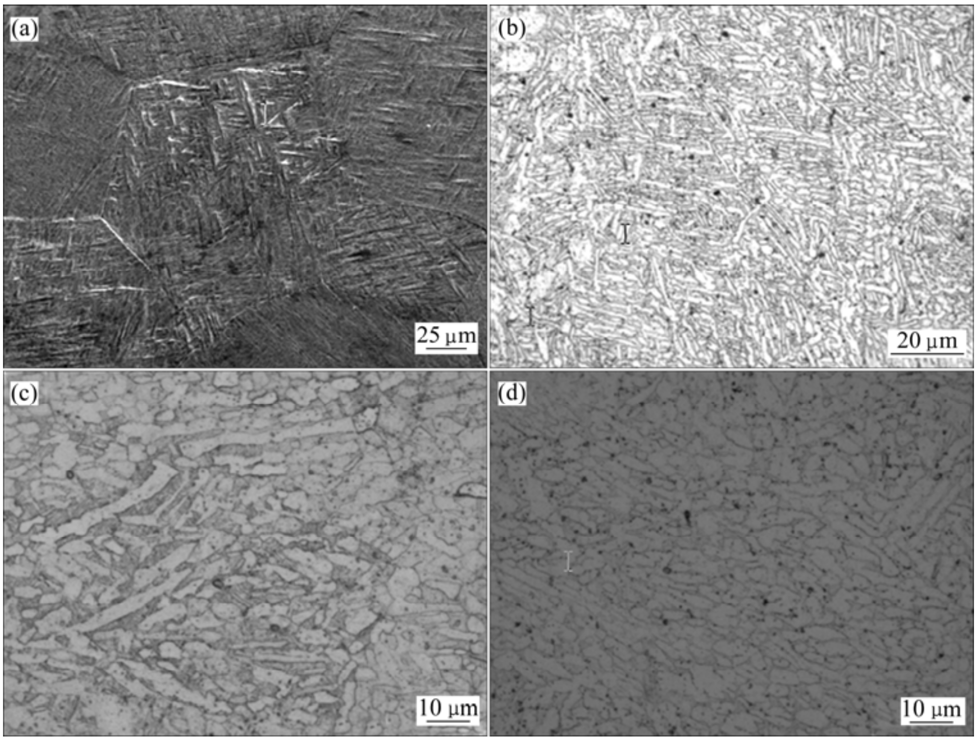

Fig.8 Microstructures of Ti-6Al-4V weld metal with different elongations: (a) Original weld metal; (b) 101% elongation; (c) 123% elongation; (d) 167% elongation

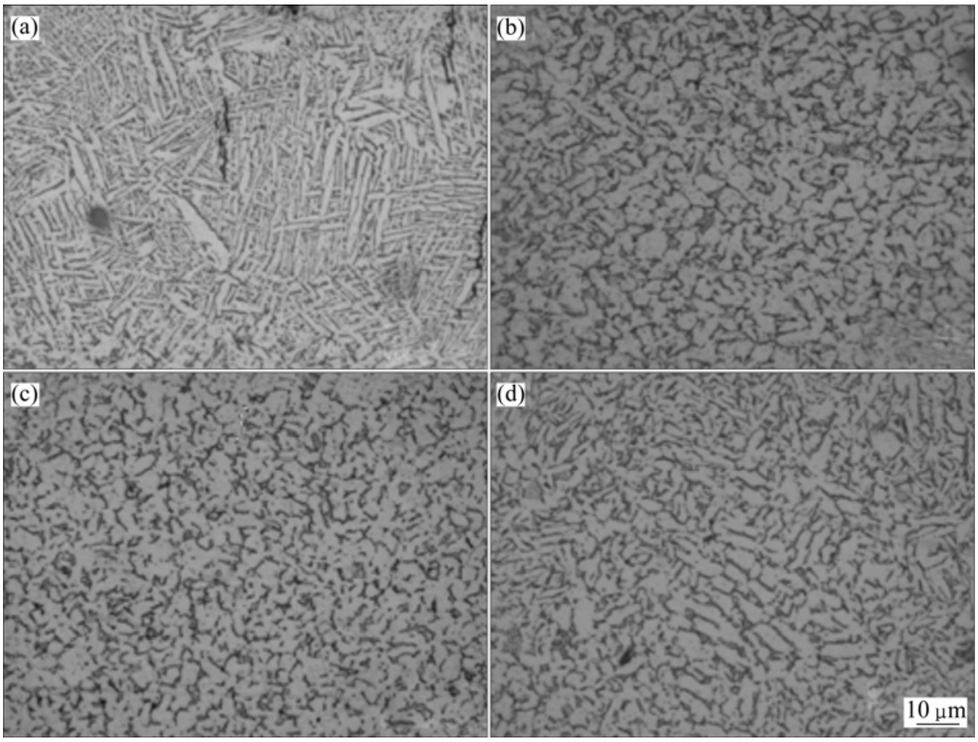

Fig.9 Microstructures of Ti-6Al-4V weld metal with different thinning rates after bulging: (a) After heating; (b) 40.0% thinning rate; (c) 47.3% thinning rate; (d) 56.4% thinning rate

globular α phase is difficult to form. So the plasticity of weld metal can not be sufficiently improved during deformation, which leads to the decrease of bulge height. On the contrary, when smaller gas pressure is applied, the differences of strain rates between base and weld metal are increased due to the differences of flow stress of base and weld metal. Tensile stress is produced between base and weld metal because the amount of deformation of base metal is more than that of weld metal. As a result, the bulge height is decreased with the decrease of plasticity of weld metal.

4 Conclusions

1) Ti-6Al-4V butt-welded plates by LBW have superplasticity, wherein their elongations are between 101% and 154% and their flow stresses are between 21.5 MPa and 34.4 MPa, the strain rate sensitivity (m) of weld metal is about 0.37.

2) The slower the strain rate is, the longer the elongation is, and the faster the welding velocity is, the higher the bulge height is.

3) All of Ti-6Al-4V butt-welded plates by LBW have good superplastic bulging capability. The ratio of bulge height to internal radius of female die is up to 1.81. The maximum bulge height is closely related to corresponding input power density, wherein the faster the welding velocity is, the higher the bulge height will be.

4) The weld microstructure of Ti-6Al-4V butt-welded plates by LBW has the trend to develop into typical superplastic microstructure namely equaled grain. Metallographical analysis shows that the microstructure of Ti-6Al-4V weld metal by LBW is composed of fine acicular martensite. During superplastic deformation, acicular martensite grain is changed into globular α+streaky $\alpha+\beta$ grain.

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