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Superplastic bulging capability of Ti-6Al-4V buttcover plate^①

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[Abstract] The investigation on the superplastic bulging capability of 1.5 mm mill annealed Ti-6Al-4V buttcover plate by means of manual gas tungsten arc welding (M-GTAW) and fusion type plasma arc welding (F-PAW) have been evaluated respectively. The result shows that untreated Ti-6Al-4V buttcover plate by M-GTAW exhibits no superplasticity, while the same untreated plate by F-PAW, shows good superplastic ability because of extremely fine acicular martensite microstructure of weld metal. To the buttcover plate by M-GTAW, the microstructure of weld metal changed into streaky α structure which exhibits good superplasticity from the original β structure under the condition of the constant temperature of 940 °C with the deformation degree of 45%, and changed into the fine equiaxed grain which possesses excellent superplastic ability under the condition of the constant temperature of 800 °C with the deformation degree of 40%.

[Key words] superplastic forming; Ti-6Al-4V alloy; isothermal hot-compression; buttcover plate

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1 INTRODUCTION

Ti-6Al-4V alloy is a dual phase alloys consisting α and β phases. It exhibits not only good mechanical properties but also excellent corrosion resistance and outstanding specific strength. Thus it's widely used in the fields of aerospace, chemical engineering and navigation. This alloy also shows good superplastic ability and the method on the superplastic forming (SPF) of plate have been utilized widely. But the research on its buttcover plate has only been limited on the general mechanical properties by now, while little on its superplasticity^[1~7]. But in some cases, some parts such as thinwalled tube structure and bellows expansion joint use bigger diameter welded pipe as the blank of SPF. So it is necessary to study the superplastic performance of Ti-6Al-4V buttcover plate. In this paper, superplastic capability of Ti-6Al-4V buttcover plate and processing technology on improving superplasticity were investigated.

It is well known, the as-welded microstructure of α + β titanium alloy is cast-structure with poor plasticity. It's necessary to refine grains in order to get the superplastic ability. Generally speaking, the following methods can be used to improve plasticity of weld metal: 1) Adopting solution heat-treatment and aging to refine grains. The resulting plasticity could be improved to the half level of the base metal^[2, 8~11]. 2) Heating and cooling repeatedly (more than 20 times) to refine the microstructure of weld metal^[12]. But it is difficult because of great energy consumption and high cost. 3) Using high energy-density welding method such as plasma arc welding, electron beam welding or laser welding to increase

cooling rate, so much more and finer acicular martensite structure which possesses good plasticity should be obtained. 4) Performing thermomechanical processing and recrystallization annealing to weld metal^[13~17]. The latter two methods were investigated in this paper. Taking into consideration of the economical and practical factors, manual gas tungsten arc welding (M-GTAW) and fusion type plasma arc welding (F-PAW) were selected for the experiments.

2 EXPERIMENTAL

Four groups of samples were tested in the experiment, and their processing routes are as follows, respectively.

Sample A: M-GTAW $\rightarrow$ SPF

Sample B: F-PAW $\rightarrow$ SPF

Sample C: M-GTAW $\rightarrow$ hot-compressing at 940 °C with 45% reduction $\rightarrow$ SPF

Sample D: M-GTAW $\rightarrow$ hot-compressing at 800 °C with 40% reduction $\rightarrow$ SPF.

2.1 Welding

1.5 mm thick mill-annealed Ti-6Al-4V (mass fraction, %) plate was used as the experimental material. Both M-GTAW and F-PAW were performed. Welding was carried on pairs of 125 mm $\times$ 62.5 mm $\times$ 1.5 mm Ti-6Al-4V mill-annealed plate. The gap between two plates was 0.3 mm. Specimens were thoroughly cleaned with a wire brush and emery paper, pickled in solution of H₂O+HNO₃+HF (76%:20%:4%, volume fraction), and then degreased with acetone prior to welding. For M-GTAW, double-faced metal-plate welding was carried out in order to ensure welding quality and subsequent greater

strain. The total thickness of weld metal was 3.0 mm. Strips of 1.5 mm × 1.5 mm × 200 mm were cut from the Ti-6Al-4V plate and used as filler metal. Smaller welding heat input was adopted in order to obtain more much acicular supersaturation martensite. The height of weld metal by F-PAW was the same as that of base metal. Both M-GTAW and F-PAW welding parameters were tabulated in Table 1.

Table 1 Welding parameters

Welding method	Arc current / A	Arc voltage / V	Travel speed / (m·min ⁻¹)	Inert gas flow / (L·min ⁻¹)
M-GTAW	35	18	0.1	20
F-PAW	40	20	0.3	25

2. 2 Isothermal hot-compression deformation of weld metal by M-GTAW

The purposes of hot-compression deformation are as follows. On one hand, severe deformation degree of hot-compression results in intense weld metal deformation and a highly distorted grain boundary and strongly distorted space lattice, thus increasing nuclear rate of recrystallization as well, and furthermore finer equiaxed grains are obtained in the weld microstructure. On the other hand, through hot-compression deformation the thickness of weld metal is close to that of base metal, so the difference of flow stress between base metal and weld metal can be decreased, and the deformation of samples should become more uniform as well. These above-mentioned are very important to perform SPF successfully.

In the experiment, samples A, B of Ti-6Al-4V weld joint by M-GTAW and F-PAW were compressed in the range of $\alpha + \beta$ at forging temperature of 750 °C ~ 940 °C. Samples C and D were compressed at 940 °C, the upper limit forging temperature, and at 800 °C, 50 °C above the lower limit forging temperature, respectively.

All welded samples were visually inspected and tested with dye penetrant for surface defects. They were also radiographed for internal soundness. From the radiographically sound samples, hot-compressing samples were prepared. Samples were brushed high temperature antioxidant before heating.

During hot-compression, sample C was applied to pressure of 40~ 70 MPa at 940 °C and sample D was of 50~ 80 MPa at 800 °C, both of the duration time were 30 min. After hot-compression, the thickness and deformation degree of weld metal of sample C were about 1.66 mm and 45%, and those of sample D were about 1.8 mm and 40%, respectively.

2. 3 Superplastic gas free bulging

The method used in the experiment was superplastic gas free bulging. Its forming schematic diagram is shown in Fig. 1. The die used comprised of an air-in plate and a female die. The design dimension

of female die is 75 mm in internal diameter and 40 mm in height.

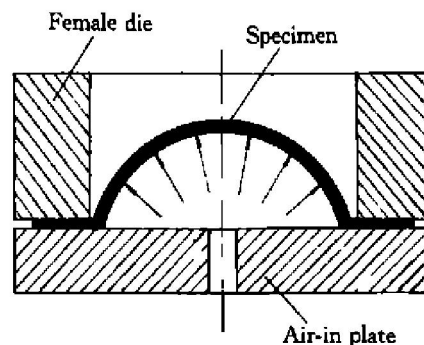


Fig. 1 Schematic diagram of SPF

The main purpose of this experiment is to study how to improve the superplasticity of weld microstructure through hot-compressing deformation, the flag of superplasticity is the maximum bulge height after rupture, so all of the samples will be bulged until rupture. SPF testing was carried out using 1 MN superplastic forming machine with an 18 kW furnace in Harbin Institute of Technology.

Firstly, sample was heated up to 180 °C and held for 10 min, and was taken from furnace to paint high temperature antioxidant. And then the sample was put into dies and removed into furnace to heat up to 925 °C, the superplastic forming temperature for Ti-6Al-4V alloy. Later on loaded for seal and held for 30 min. Finally, inflated argon into sample to bulge until burst.

2. 4 Microscopic observation

The microstructures of samples were examined using an optical microscope BH2UMA. Specimens were cut from the undeformed edge of weld line were ground, polished and etched using etchants with following chemical composition: 50% HNO₃ + 40% HF + 10% H₂O (volume fraction). Specimens were cut from the undeformed edge of weld line.

3 RESULTS AND DISCUSSION

3. 1 Bulge forming of postwelded samples

3. 1. 1 Bulge forming of buttcover plate by M-GTAW

Welded sample A, which carried out no any pre-treatment but only ground its weld metal to the thickness of base metal, was bulged directly. Firstly, it was heated up to 925 °C for 30 min; and then increased pressure to 4 MPa until rupture after compressing about 1 h. It could be observed that the amount of deformation of sample A was extremely small. The maximum height of bulge is less than 10 mm and inhomogeneous. There is hardly any deformation within weld joint, and only slightly bulge near weld line, thus further deformation is restrained.

The optical metallograph of weld microstructure

by M-GTAW (Fig. 2), shows that the weld microstructures are comprised of acicular martensite and retained β phase, which is similar to fast cooling cast structure, and coarse β grain boundary can be seen clearly. Compared with the ideal grain size ($2 \sim 3 \mu\text{m}$) of superplastic deformation of Ti-6Al-4V titanium alloy, such coarse grain is too large to superplastic forming.



Fig. 2 Micrograph of weld metal by M-GTAW

3.1.2 Bulge forming of buttcover plate by F-PAW

Sample B, performed the same pretreatment procedure as sample A, was heated up to 925°C and held for 30 min, and then increased pressure to 5 MPa until burst. The crack located on the base metal, and the maximum height of bulge is 38 mm as shown in Fig. 3(a). The weld line length is 75 mm prior to bulging and is 114 mm after bulging, the average thickness of deformed weld metal is 1.32 mm.

Fig. 4, the optical metallograph of weld microstructure by F-PAW, shows that the weld microstructure is almost entirely ultra fine acicular martensite α' , which possesses good plasticity. Its better superplasticity during SPF may be attributed to that the finer and thinner α' phase could be easily cut by shear force, and result in more much nucleating sites and globular α phase during recrystallization. So the weld microstructure is improved and possesses superplasticity.

3.2 Bulge forming of samples after hot compression

After sample C was bulged, its maximum bulge height is 30 mm (Fig. 3(b)). The average thickness and length are 1.66 and 75 mm before bulging, respectively; and are 1.35 and 105 mm after bulging, respectively. The weld line appears uniform thickness and smooth surface. The thickness of base metal reduces from 1.5 to 1.0 mm; the amount of deformation of weld metal is less than that of base metal. The location of crack is on the weld line near female die.

The reason why in sample C bulging was burst on the weld joint near female die is that weld microstructure has lower plasticity and toughness, in

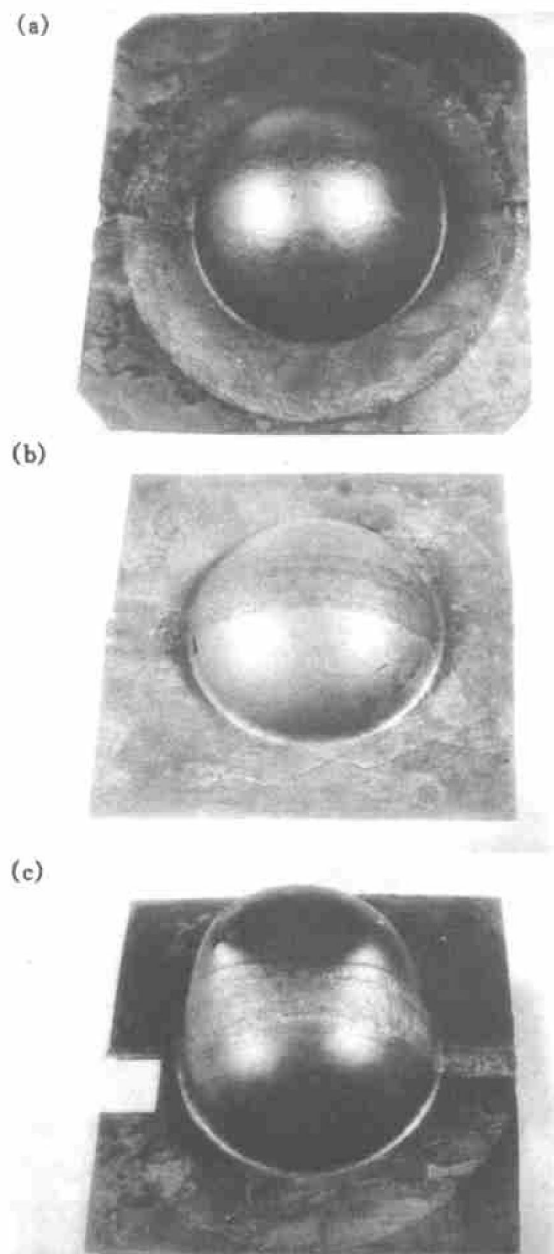


Fig. 3 Photographs of samples after bulging
(a) —Sample B; (b) —Sample C; (c) —Sample D



Fig. 4 Micrograph of weld metal by F-PAW

addition, inhomogeneous deformation between weld metal and base metal leads to large stress concentra-

tion at grain boundary, when stress concentration reaches a critical value, the surface of weld metal appears crack, and the sample bulging is burst from the location of crack.

Isothermal hot-compression with enough deformation degree carried out below the β transus temperature is finished at $\alpha + \beta$ two phase temperature. In the weld microstructure, β boundary divided by acicular martensite is partly broken, thus cause no full and no clear configuration of β grain boundary and distorted streaky α phase which is distributed by mixture of α and β phase (Fig. 5(a)), the mechanical properties of this microstructure possesses better plasticity and impact ductility, higher temperature lasting and creep property comparing with Widmanstatten structure. It can be transformed into equiaxed $\alpha + \beta$ microstructure which possesses definite superplasticity during SPF.

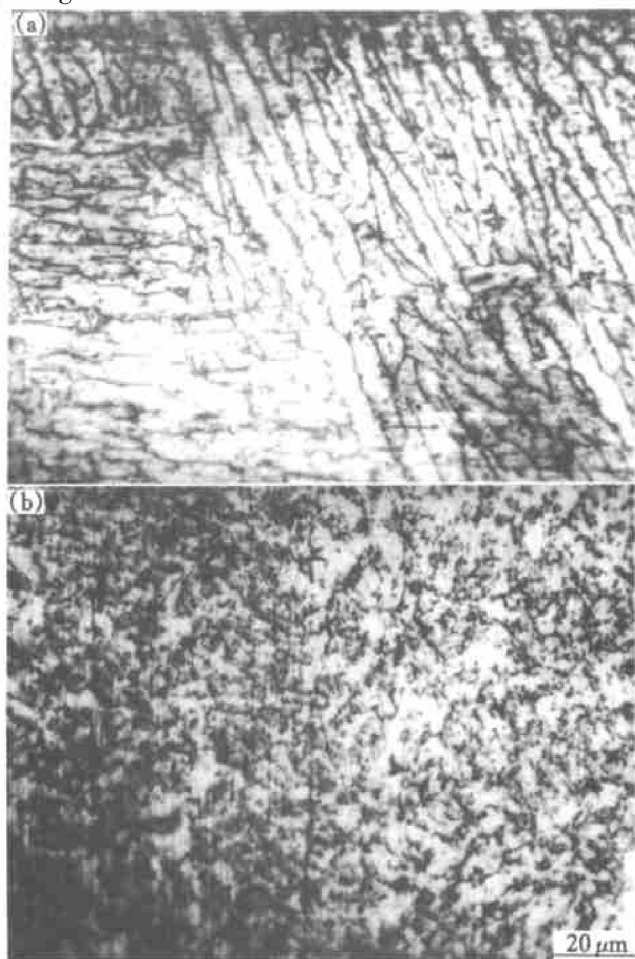


Fig. 5 Micrographs of weld metal after isothermal hot-compression
(a) $-940\text{ }^{\circ}\text{C}$ with reduction of 45%;
(b) $-800\text{ }^{\circ}\text{C}$ with reduction of 40%

As seen in Fig. 3(c), after SPF testing, the maximum bulge height of sample D is 40 mm, which has come into contact with the bottom plate under female die, and forms a small plane on the bottom plate. The weld line length and the average thickness are 75 and 1.8 mm before bulging, and are 125 and

1.25 mm after bulging, respectively. The shape of as-bulged sample is approaching cap-like, whose maximum bulge height has exceeded the radius of hemisphere. Fig. 5(b) shows that the weld microstructure is extremely similar to the $\alpha + \beta$ equiaxed structure of base metal (Fig. 6) and have only some differences on the homogenization of α and β distribution. This elongated microstructure is formed under lower deformation temperature and smaller plastic strain in the range of $\alpha + \beta$ field. The composition of metastable acicular martensite α' structure generates lamellar $\alpha + \beta$ grains, and then during isothermal hot-compression, this microstructure is broken up into small segments. At the same time, α phase penetrates into β phase, and α and β phases dynamically recrystallize respectively and diffuse and mix each other between them. The transformation changes lamellar $\alpha + \beta$ grains into near-quiaxed structure. As the temperature decreases, β phase precipitates secondary α phase, which grows on the primary α phase and both mix each other, so it is difficult to distinguish them. This near-quiaxed microstructure possesses excellent performance such as good plasticity and toughness, and its superplasticity is also similar to that of base metal because of the similarity of microstructure.

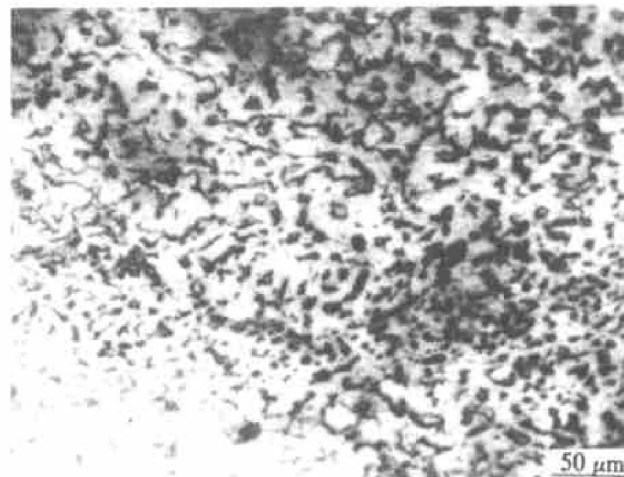


Fig. 6 Micrograph of original base metal

3.3 Effect of isothermal hot-compression conditions on superplasticity of weld metal

The results show that isothermal hot-compression processing is an effectively method to improve microstructure and performance of the weld metal, the effect of deformation temperature and deformation degree on final microstructure is decisive. During hot-compression, the uniform fine globular $\alpha + \beta$ structure is more prone to be obtained from the original α' martensite structure at lower temperature than that at higher temperature. At lower hot-compression temperature, the same strain should need larger deformation stress, but as a result, greater deformation energy be stored during deformation increases nucleation power and rate, therefore uniform fine secondary α

phase can be obtained. And lower temperature is beneficial to forming the nucleation of dynamic and static recrystallization in α phase and to obtain uniform fine equiaxed grains as well. All of these are helpful to improve various performance of weld metal, especially superplasticity.

During hot-compression at higher temperature, on one hand, the volume fraction of β phase was larger than that of α phase because of α/β transformation, thus weld metal possesses better plasticity and needs lower deformation stress; but on the other hand, these result in lower deformation stress and power and less energy storage in the material, as a result, producing less primary globular α phase. Moreover during slower cooling, β phase is prone to transform into coarse secondary α phase due to less nucleation sites. It is too difficult to obtain fine grains during deformation by breaking up these original large grains, so the superplasticity of this microstructure isn't ideal.

After hot-compressing at 940 °C, which is below the β transus, the weld microstructure appears a typical streaky α structure transformed from β phase, which is similar to the forged basketweave structure. The reason is maybe that a great quantity of deformation heat produced during hot-compression is used to raise the temperature of material above the β transus which leads to weld microstructure deformation with enough plastic strain, and the temperature becomes homogeneous distribution at 940 °C as the duration increases. Material finishes deformation in the range of $\alpha + \beta$ field, streaky α phase and lamellar α phase are precipitated during dynamic and static recrystallization. Thus, the streaky α phase precipitated along grain boundaries is distorted and penetrated by deformed lamellar α grains. At the same time the lamellar α phase in the grains is prolonged and distorted by deformation, resulting in the change of original irregular orientation and parallel alignment, whose pattern is similar to streaky structure in which a mixture of $\alpha + \beta$ is retained and formed basketweave-like microstructure.

From the similarity of microstructure between weld metal and base metal, it can be concluded that the effect of isothermal hot-compressing at 800 °C with only 40% reduction on the grain refinement of weld metal is obvious, but the superplasticity of weld metal can be improved further because its micrograph reveals the vestige that grains were stretched along metal flow direction during hot-compression. It can be deduced that more excellent superplasticity should have been obtained if weld metal deformed below 800 °C with more than 40% reduction.

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