Article ID: 1003 - 6326(1999)03 - 0535 - 06

Equalization of Ti-6Al-4V alloy welded joint by scanning electron beam welding①

Chen Xiaofeng(陈晓风)[1], Han Zhong(韩 忠)[2], Lou Xinfang(楼新芳)[1],
Hu Chuanshun(胡传顺)[2], Sun Changyi(孙长义)[1], Li Zhongku(李忠库)[1]

1. Institute of Metal Research, The Chinese Academy of Sciences, Shenyang 110015, P. R. China

2. State Key Lab for Corrosion and Protection, Institute of Corrosion and Protection of Metals, The Chinese Academy of Sciences, Shenyang 110015, P. R. China

Abstract: The equalization of Ti-6Al-4V alloy welded joint with base metal on corrosion resistance, strength and ductility was studied. The solidification microstructure is transformed from 650 μm columnar grains to 100 μm equiaxed grains by scanning electron beam welding. The anodic polarization curve of 150 μm equiaxed grains coincides with that of base metal. Equal corrosion resistance between weld metal and base metal was obtained. Uniform microstructure and solute distribution are the basis of equalization. Corrosion rate of weld with 150 μm equiaxed grains is the lowest, 2.45 times lower than that of 650 μm columnar grains. Weld strength is 98 % as much as that of base metal, yield-strength ratio is 99.5 %, which is 3.6 % higher than that of base metal.

Key words: scanning electron beam welding; titanium alloy; welding; equalization **Document code: A**

1 INTRODUCTION

Such as high strength Al alloy, Ti alloy and super high strength steel, their corrosion resistance was decreased due to welding[1,2], their strength and ductility were decreased to 60 % ~ 80 % as much as that of base metal[3]. To retrieve properties of large constructions is limited by the deformation caused by heat treatment. To increase strength by increasing thickness and alloying not only limits lighting of construction but also increases stress concentration coefficient, uneven corrosion and coarse solidification structure of weld metal. All above will result in fatigue cracks, leakage and happening of fracture accidents; and thus the safety, reliability and storage life of constructions are largely lowered.

Lighting welding constructions are often in service at such an environment as sea water, cave, low temperature, liquid fuel and solid coat etc, therefore equal corrosion resistance, strength and ductility between weld metal and base metal are demanded. We define the equality of corrosion resistance, strength and ductility of weld metal with base metal as equalization. Equalization is a foundation which makes welding constructions lighter and smaller.

With the increase of strength and elastic modulus of metals and metallic compounds, their property loss due to welding must be aggravated; the contradictions of strength, ductility and corrosion resistance between weld metal and base metal are even more protrusive. Although domestic and abroad welding workers have made a lots of researches to improve electrochemic corrosion resistance[4~6] and mechanical properties of weld metal, the contradiction has not been united because they all used equilibrium thermodynamics solidification theory to guide nonequilibrium welding solidification process.

In this paper, equalization of weld metal with Ti-6Al-4V base metal, including corrosion

① Project 58971017 supported by the National Natural Science Foundation of China and project 9521026 supported by the Natural Science Foundation of Liaoning Province. Received Oct.12, 1998; accepted Dec.30, 1998

resistance, strength and ductility, is studied by scanning electron beam welding (SEBW).

2 EXPERIMENTAL

2.1 Materials and equipment

Hot rolled Ti-6Al-4V alloy plate with 4 mm thickness was used in this experiment. The specimen size for tensile test was 115 mm × 12 mm × 3 mm. The specimen size for corrosion test was 35 mm × 6 mm × 3 mm[7].

A self-made 150 kV electron beam welder was used in this experiment, its maximum output is 22.5 kW, accelerating voltage is 0 ~ 150 kV, grid bias voltage is 0 ~ 2 000 V. There were two magnetic focusing systems, the minimum radius of the focus is 0.2 ~ 0.3 mm, the maximum deflection distance is 20 mm along *X*, *Y* axes. A microprocessor was used as electron beam scanning device.

2.2 Experimental methods

The electron beam scanning frequency was 0 ~ 1 000 Hz, accelerating voltage was 110 kV, beam current was 10 ~ 14 mA, welding speed was 1 000 ~ 1 200 mm/min, vacuum degree was 6.55×10^{-2} Pa.

Under the guidance of theory of refining solidification structure by electron beam melting cutting[8,9], a mathematic model for simulating solidification front was established. The scanning electron beam welding was controlled by the program inputted into microprocessor.

The corrosion tests were carried out in $CuSO_4$ and saturated NaCl solution. Corrosion potentials and polarization curves were measured in $CuSO_4$ solution by M273-PAR342 system. A saturated calomel electrode and a platinum electrode were used as a reference and a counter electrode respectively.

TEM observation results were obtained by PHILIPS EM420.

3 EXPERIMENT RESULTS

3.1 Effect of scanning frequency on solidification structure of weld metal

The experimental results are shown in Fig.1. When scanning frequency is 0 ~ 200 Hz, the average maximum axis length of coarse columnar grains is about 400 ~ 650 μm. With the increase of frequency, the solidification structure becomes equiaxed grains. When frequency is 300 Hz, the equiaxed grain is 150 μm. When scanning frequency is 400 Hz, the minimum equiaxed grain is 100 μm. When scanning frequency is 500 Hz, the equiaxed grain grows to 150 μm. When scanning frequency is increased to 1 000 Hz, the grains size grows to 300 μm.

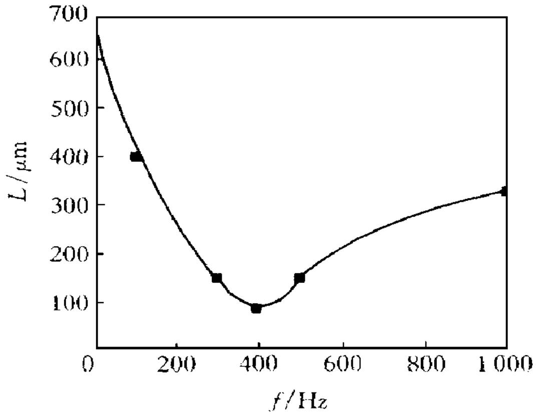

Fig. 1 Relation between frequency (*f*) and average maximum axis length of grains (*L*)

3.2 Relation between solidification structure and anodic polarization curve

The anodic polarization curve of metal is a criterion which indicates their electrochemic corrosion resistance. The first demand for equalization is the same compositions and equal corrosion resistance of weld metal with base metal. The regularity of change in solidification structure and anodic polarization curve of weld metal is measured. When the maximum axis length of columnar grains is 400 ~ 650 μm, there appear a corrosion current density peak value and an active-passive transition on each of their anodic polarization curves. Their active current density peak values reach 33.238 9 ~ 39.148 9 μA/cm^2. The passive current density is 1.8 ~ 2.4 times higher than that of base metal. The corrosion potential is decreased to 33 % ~ 38 % as much as that of base metal. As an example, Fig. 2 gives the anodic polarization curves of the weld metal with 650 μm columnar grains and base metal. From above results, these weld metals are easier to corrode prior to base metal. However, when the equiaxed grains in weld metal is 100 μm, there are no active-passive transition and corrosion current density peak value on its anodic polarization curves (see in Fig. 3). Its corrosion potentials are little higher than that of base metal, which indicates that base metal has a prior tendency to corrode.

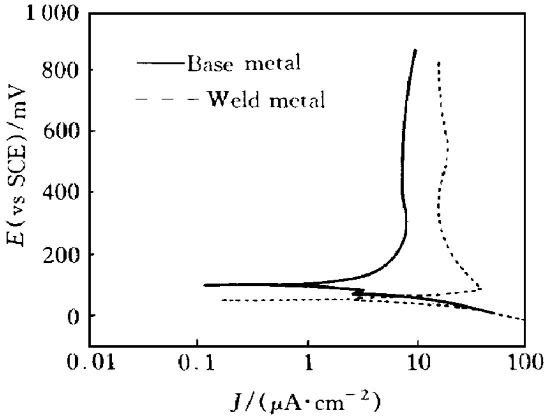

Fig.2 Polarization curves of weld metal with 650 μm columnar grains and base metal

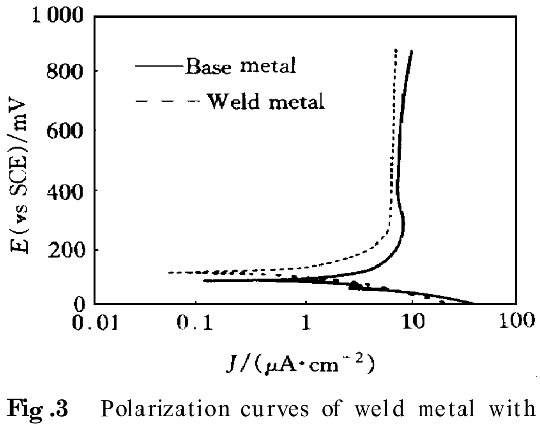

Fig.3 Polarization curves of weld metal with 100 μm equiaxed grains and base metal

Solidification structure is too fine to match base metal, therefore it does not suitable for the demand of equalization. When the equiaxed grains of the weld metal is 150 μm in size, its anodic polarization curve is similar to Fig.3. Through adjusting thermal cycle by scanning electron beam welding and controlling microstructure in 150 μm equiaxed grains, the anodic polarization curve is slightly regulated. The interface energy of crystal growth is increased properly, the crystal microstructure is changed. This interface energy is 1.3 times as much as that of the former by calculation. As shown in Fig.4, the anodic polarization curve of high interface energy welded joint with 150 μm equiaxed grains nearly overlaps that of base metal. The weld metal passive current density is 7.996 μA/cm^2 and approaches that of base metal. Their corrosion potential difference $\Delta E = 0$, indicating that there is no reaction between weld metal and base metal, and welding is in a stable passive stage. Weld metal and base metal have equal corrosion resistance.

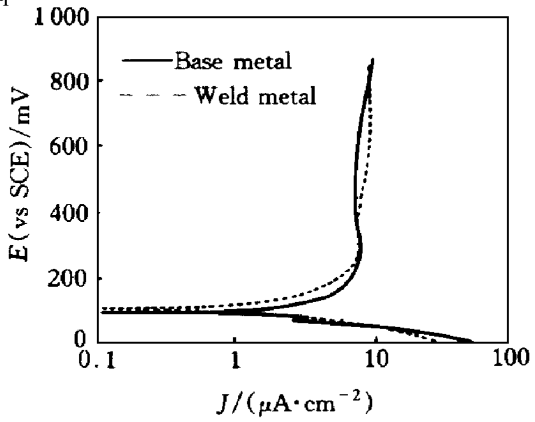

Fig.4 Polarization curves of high interface energy weld with 150 μm equiaxed grains and base metal

3.3 Effect of solidification structure on corrosion resistance

The relationships of solidification structure and corresponding passive current density, the corrosion potential and corrosion rate are shown in Fig.5. With the growth of grain size in weld metal, the passive current density is increased, the corrosion potential difference between weld metal and base metal is decreased, the corrosion rate is increased. When the equiaxed grain is 150 μm, the passive current density of weld metal is lower lightly than, or nearly equal to that of base metal, the corrosion potential difference is zero, the corrosion rate of weld metal is the lowest, being decreased to 2.45 times lower than that of

650 μm columnar grains. In saturated NaCl solution, the corrosion rate of 150 μm equiaxed grains is 1.5 times lower than that of 650 μm columnar grains, which shows stronger corrosion resistance to sea water.

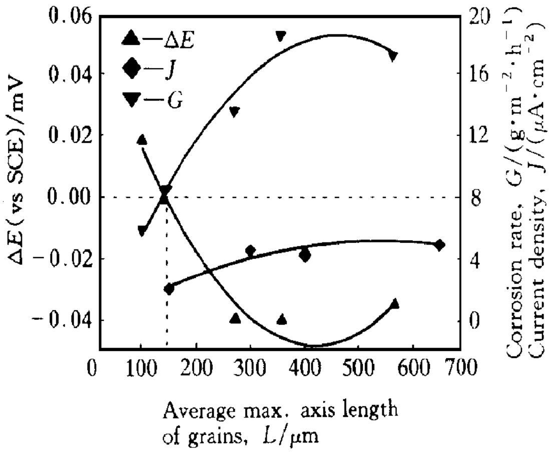

Fig.5 Relationship of solidification structure and corrosion resistance

3.4 Effect of solidification structure on weld strength and ductility

Equal strength and ductility of weld metal to that of base metal is demanded for equalization of welding constructions. Experimental results are shown in Fig.6. Fracture of each welded joint for tensile specimens is in weld metal. From Fig.6, the tensile strength and yield-strength ratio of weld metal are decreased slowly when columnar grains grows to 400 μm. With the columnar grains growing to 650 μm, the tensile strength of weld metal is decreased obviously, its strength coefficient is only 74.7 % as much as that of base metal. When the equiaxed grain is 150 μm in size, the tensile strength of weld metal gets to 98 % as much as that of base metal, 23 % higher than that of 650 μm coarse columnar grains. The yield-strength ratio reaches 99.5 %, 3.6 % higher than that of base metal. This indicates that the strength and ductility of weld metal with 150 μm equiaxed grains are nearly equal to that of base metal, which shows the equal mechanical property of weld metal with base metal. The optimum match of solidification structure of weld metal with that of base metal is achieved by equal corrosion resistance and equal

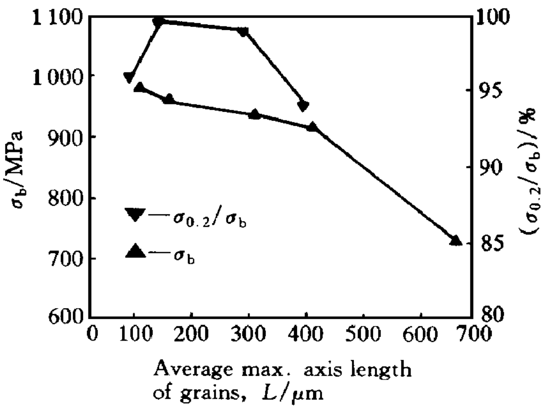

Fig.6 Relationship between solidification structure and mechanical property

mechanical property, that is to say, equalization of heterogenous welded joint with base metal is accomplished. A precedent for making high strength welding constructions smaller and lighter is set up.

4 ANALYSES AND DISCUSSION

4.1 Weld metal with 650 μm columnar grains

In order to know the microstructural effects on inferior corrosion resistance of weld metal with columnar grains, we observed the microstructure of weld metal with 650 μm columnar grains. Under optical microscope, there are a lot of coarse acicular ($\alpha+\beta$) phase and martensitic α phase. Under TEM, it can be observed that uneven quasistable β phase distributes between α plate (see in Fig.7). Dislocation groups distribute in α phase (see in Fig.8). Coarse solidification structure, coarse ($\alpha+\beta$) phase and β phase are the main cause of lower strength and corrosion property of weld metal. Grain boundary sliding is blocked by the dislocation groups, which is the main cause of lower ductility. Compositional nonuniformity resulted from coarse columnar grains can be seen in Fig.9. There is serious segregation of Fe and V in weld metal. Equalization is restricted by nonuniform distribution of chemical composition.

4.2 Weld metal with 100 μm equiaxed grains

Although the size of weld metal with 100 μm equiaxed grains approaches to that of base metal, its corrosion potential is higher than that of base metal. Potential difference $\Delta E > 0$, passive current density is 17 % lower than that of base metal. Therefore base metal has a preferred corrosion tendency. Under optical microscope, martensitic α' phase is increased. The increase of strength accompanies with the decrease of ductility. It isn't a best match between weld metal and base metal.

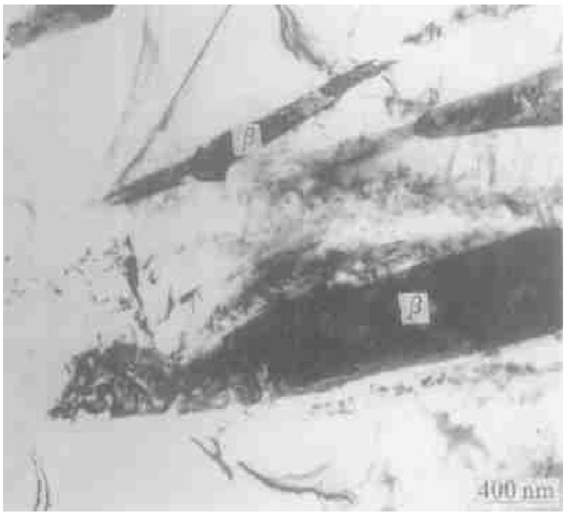

Fig.7 TEM bright field image of quasistable β phase

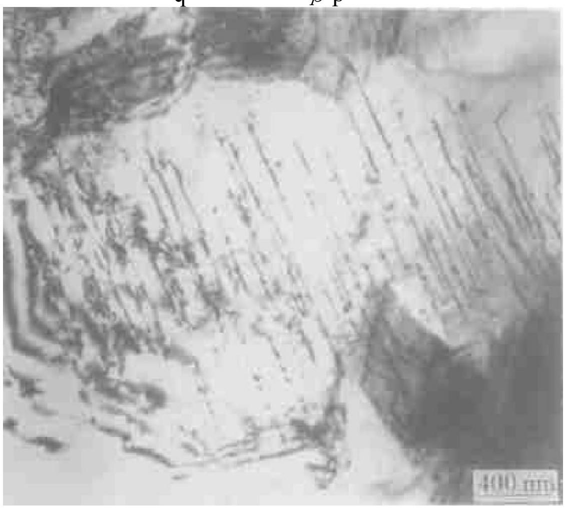

Fig. 8 Dislocations in α phase

4.3 Weld metal with 150 μm equiaxed grains

The anodic polarization curve of weld metal with 150 μm equiaxed grains is similar to that of 100 μm equiaxed grains. Although it shows that the base metal has a preferred corrosion tendency, the corrosion potential is nearly equal to that of base metal, which indicates that the preferred corrosion tendency of base metal is weakened. When the interface energy of solidification front is increased to 1.3 times, its anodic polarization curve nearly overlaps that of base metal. The passive current density difference between weld metal and base metal is very little, $\Delta I = 0.068$ μA/cm^2, the corrosion potential difference tends to be zero. Electrochemic reaction does not happen between weld metal and base metal, so the corrosion rate is the lowest. The assumption of equal potential and equal corrosion resistance is achieved. In comparison with metallographic structure, it can be seen that acicular ($\alpha + \beta$) phase and martensitic α' phase in higher interface energy is transformed from unidirectional long acicular to multidirectional short acicular. Under TEM, it can be observed that the fine quasistable β phase distributes uniformly between α phase (see Fig.10). There are only a little dislocations in α phase. Al, V, Fe distribution is more uniform than that of weld metal with columnar grains (see in Fig.11), which indicates that the strengthening of solidification structure also accompanies with the enhancement of ductility and the corrosion resistance. This results in the strength being 98 % as much as thatof base metal, yield-strength ratio being 99.5 %, 3.6 % higher than that of base metal,

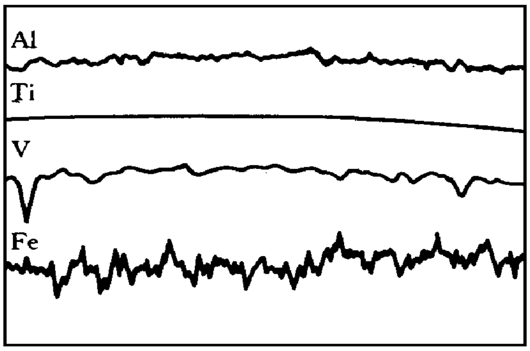

Fig.9 Al, V, Fe distribution in weld metal with 650 μm columnar grains

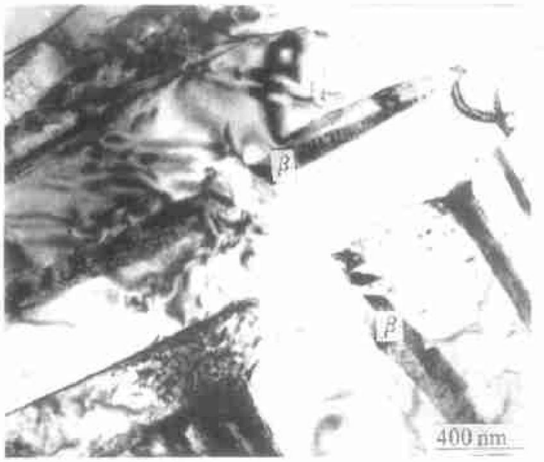

Fig.10 TEM bright field image of fine quasistable β phase

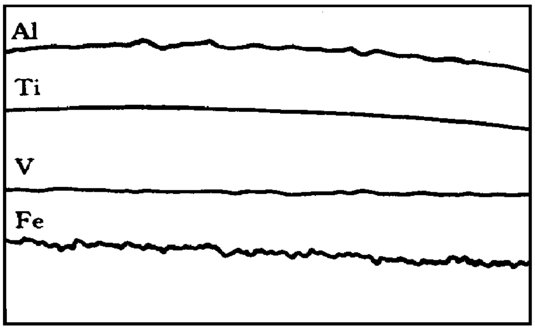

Fig.11 Al, V, Fe distribution in weld metal with 150 μm columnar grains

and the corrosion rate of weld metal being the lowest, which is 2.45 times lower than that of 650 μm columnar grains.

5 CONCLUSIONS

(1) The unidirectional acicular ($\alpha+\beta$) phase, acicular martensitic α' phase and V, Fe element segregation in weld metal with 400 ~ 650 μm columnar grains, make weld metals have a preferred tendency to corrode and their strength be only 74.7% as much as that of base metal.

(2) The multidirectional acicular ($\alpha+\beta$) phase and more acicular martensitic α' phase in weld metal with 100 μm equiaxed grains make it have a higher strength. Uniformity of Al, V, Fe element makes the corrosion resistance of weld metal get better than that of base metal. Preferred corrosion may be occurred in base metal.

(3) The unidirectional acicular ($\alpha+\beta$) phase and a little acicular martensitic α' phase in weld metal with 150 μm equiaxed grains make weld have lower strength. Weld metal with homogeneity of Al, V, Fe element has the same corrosion resistance as weld metal with 100 μm equiaxed grains.

(4) For weld metal with 150 μm equiaxed grains, when the interface energy of the front is increased by SEBW, the multidirectional acicular ($\alpha+\beta$) phase, a proper amount of acicular martensitic α' phase, fine quasistable β' phase between α phase, and uniformity of Al, V, Fe elements, are all the reasons that its tensile strength reaches 98% as much as that of base metal, yield-strength is 99.5%, and anodic polarization curve nearly overlaps that of base metal. This is an equal corrosion resistance between weld and base metals.

(5) Controlling solidification microstructure, solute distribution, and changing phase structure is an effective method for equalization between weld and base metals.

REFERENCES

1 Rothwell N *et al*. Mater Perform, 1990, 29(2): 55.
2 Cui W F, Sun Q X and Wei H R. Rare Met Mater Eng, (in Chinese), 1993, 22(5): 52.
3 Seio M. Welding of Aluminum and Aluminum Alloy. Beijing: Metallurgical Industry Press, 1985: 1.
4 Satch H *et al*. In: Lacombe P *et al* ed. Proc of 6th World Conf on Titanium. Les Ulis Cedex: Les Edition de Physique, 1988: 489 ~ 494.
5 Boldyrev A M, Petrov A S and Dorofeev E B. Automatic Welding, 1983, 36(5): 69.
6 Zamkov V N *et al*. Weld Int, 1990, 4(1): 5.
7 Henthorne M. Corrosion, 1974, 30(2): 39.
8 Chen X F, Shi C Y, Li Z K *et al*. Weld J, (in Chinese), 1987, 8(1): 45.
9 Wang S Q, Liu F J and Chen X F. J of Mater Res, (in Chinese), 1996, 10(2): 161.

(Edited by Yuan Saiqian)