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Effect of weld microstructure on weld properties in A-TIG welding of titanium alloy①

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Abstract: Conventional TIG welding is known as its low productivity and limited weld depth in a single pass. Activating TIG welding (A-TIG) can greatly improve the penetration when compared with the conventional TIG welding. The effects of five kinds of activating fluxes with single component (NaF, CaF_2, AlF_3, $NaCl$ or $CaCl_2$) on penetration, microstructure and weld mechanical properties during the TIG welding of titanium alloy Ti-6Al-4V were studied. Compared with the conventional TIG welding, the experimental results show that the fluxes can greatly improve the penetration at the same welding specifications. This is because of the constriction of anode spots and the change of surface tension grads. Among them the effect of flux NaF is the best in the weld tensile strength, and the effect of flux CaF_2 on the weld bend intension is the best. The appearance of inferior crystal grains and the structure of trident crystal grains are the main reasons that the performance of weld with fluoride is improved. These experimental results can be used as an aid for selecting suitable activating flux for titanium alloy.

Key words: TIG welding; activating flux; penetration; microstructure; mechanical property
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1 INTRODUCTION

The activating TIG welding (A-TIG) was firstly developed by Paton Welding Institute, Ukraine, in the 1960s[1, 2]. It is not until the end of 1990s that A-TIG welding has been widely researched in Europe and US, for example, TWI and EWI[3]. The fluxes, which were developed by EWI, have been applied in the US Navy shipbuilding industry[4]. The principle of this technique is that a thin coating of activating flux is coated on the surface of the base metal before welding. Compared with the conventional TIG welding, the penetration can be greatly increased (up to 300%) under the same conditions. Furthermore, the plate with thickness up to 8 mm can be welded in a single pass without grooving. The heat input for the welding thin plate material can be reduced without changing welding speed[5, 6]. The A-TIG welding method has been successfully applied for welding materials such as stainless steel, carbon steel, nickel based alloy and titanium alloy. Therefore, compared with the conventional TIG welding, the A-TIG welding method can greatly increase the welding productivity, reduce the welding cost as well as the welding distortion, so it has a very significant prospect for industrial application[7].

The key factor of A-TIG welding is the selecting and proportioning of the activating flux compositions. The flux compositions include oxides and halides. Different material has its suitable flux composition. Titanium alloy can be oxidated easily in the welding, so the oxide must not be selected. The researches on A-TIG welding at present are mainly focused on the mechanism of the activating flux and the application of this technique for industrial use. In this paper, the effects of activating fluxes with single component on penetration and microstructure and weld mechanical properties have been investigated during the TIG welding of titanium alloy. The experimental results will provide a foundation for the selection of suitable activating flux composition in industrial welding production.

2 EXPERIMENTAL

The material to be welded in the experiments was titanium alloy TC4 and the activating fluxes with single component selected for trial were NaF, CaF_2, AlF_3, $NaCl$ or $CaCl_2$. The dimensional size of the specimens, which are used for measuring the penetration and the microstructure, is 150 mm × 30 mm × 3 mm. The welding specifications selected for trial are

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listed in Table 1. The dimensional size of the specimens, which are used for measuring the tensile strength and the bend intension, is 150 mm × 30 mm × 2 mm. The welding specifications selected for trial are listed in Table 2. The specimens were firstly ground using a piece of 80-grit sand paper and then cleaned with alcohol to remove the organism, such as oily soil. After that, the specimens were dried in order to avoid the potential effect of water on experimental results. Then the specimens were weighed to get the initial reading. The activating fluxes were mixed with acetone and coated manually with a brush to a layer thick enough to prevent visua observation of the base metal. After the acetone is completely volatilized, the coating quantity can be weighed with an electrical analytical balance (with accuracy of 0.1 mg). And then the coating quantity of the flux of a unit area can be calculated. Bead-on-plate welds were made in the experiments and the welding specifications and the arc length were kept constant during the welding process.

Table 1 Welding specifications used in experiments for penetration and microstructure measurements

Current, I/A	Welding speed, v_w/(mm•min^{-1})	Flow rate of argon, q_v/(L•min^{-1})
60	250	15
Arc length, L/mm	**Electrode diameter, D/mm**	**Electrode tip angle, θ/(°)**
2.5	3.2	60

Table 2 Welding specifications used in experiments for tensile strength and bend intension measurements

Current, I/A	Welding speed, v_w/(mm•min^{-1})	Flow rate of argon, q_v/(L•min^{-1})
130	200	15
Arc length, L/mm	**Electrode diameter, D/mm**	**Electrode tip angle, θ/(°)**
2	3.2	60

3 RESULTS AND ANALYSIS

3.1 Effect of flux on penetration

The welds were cut vertically to the welding from the mid position. The cross section was ground with a piece of sand paper, polished, corroded and taken pictures. Fig. 1 shows the cross sections in the most penetration of the weld of the specimen without flux coat and of $CaCl_2$-coated welds, respectively. It can be seen that the penetration is dramatically improved after coating with activating flux[8-13].

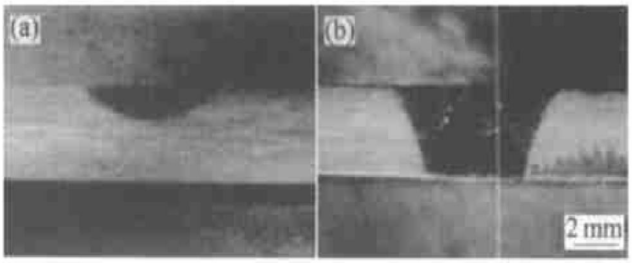

Fig. 1 Photos of weld cross sections in most penetration of specimens with or without flux coat
(a) —Without flux; (b) —With $CaCl_2$ flux coat

1) At a high temperature, activating flux is vaporized as a form of atoms, which surround the circuit of the arc area. For the temperature is rather low at the circuit of the arc area, vaporizing atom of activating flux catches electron in this area and forms negative ions which dissipate to outward area. It makes electrode number take on reducing tendency, the tracheal capacity weaken. The ultimate result is that the arc produces auto-constriction.

2) In conventional TIG welding, the surface tension coefficient of the liquid metal decreases with temperature increasing (namely $d\sigma/dT < 0$). The molten metal in the center of the molten pool tends to flow toward the fusion line. So the weld is wide and shallow. When the molten metal contains activating elements, the surface tension coefficient increases with temperature increasing (namely $d\sigma/dT > 0$). The molten metal near the fusion line tends to flow toward the center of the molten pool. Increasing the heating efficiency at the pool bottom can form deeper penetration.

Different fluxes take on different ionization temperatures and resistance rates and have different influences on the arc constriction and the anode spot constriction, which also raises arc voltage to different degrees, therefore they result in different arc temperatures and electromagnetism powers. In addition, different fluxes lead to different changes of surface tension grads, thus resulting in different degrees of the increasing penetration. The result that flux $CaCl_2$ possesses higher ionization temperature and resistance rate and bigger electromagnetism power, which can effectively transfer the quantity of heat to the bottom of the pool, makes for the formation of bigger penetration.

3.2 Effect of flux' on weld microstructure

Fig. 2 shows the microstructures of the specimen with no flux coat and of flux-coated sections of the welds, respectively. As shown in the figure, the size of the crystal grain of the weld without coat is smaller, the shape of the crystal grain is hexagon; the size of weld crystal grain coated fluoride is bigger, and the

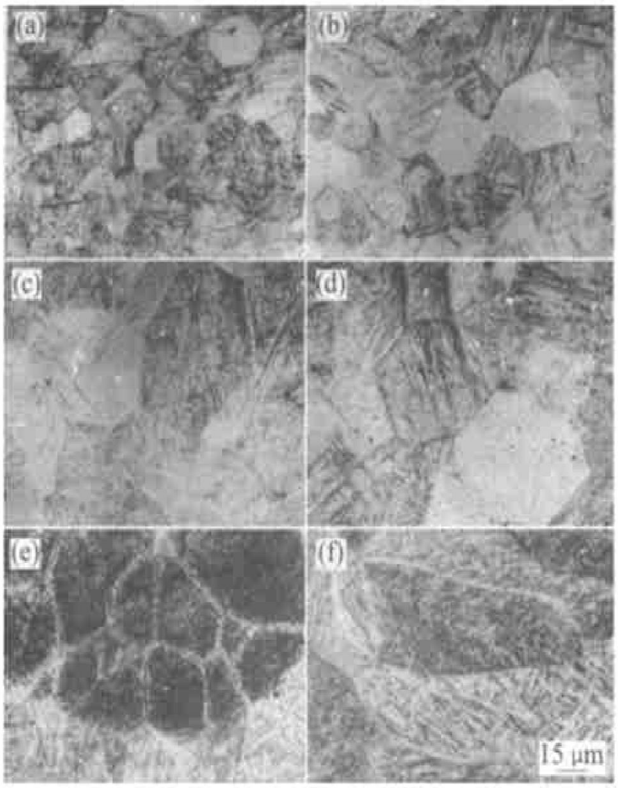

Fig. 2 Microstructure of weld section of specimens without and with different flux coat
(a) —Without flux; (b) —With CaF_2 coat; (c) —With NaF coat; (d) —With AlF_3 Coat; (e) —With NaCl coat; (f) —With $CaCl_2$ coat

shape of the crystal grain does not change; the size of the crystal grain of weld coated chloride is also bigger, and the shape of the crystal grain is pentagon. In addition, Fig. 2 (d) shows the appearance of inferior crystal grain inside of the crystal grain, which is to say the crystal grain is fined.

The main reason of the appearance of inferior crystal grain is the presence of the high melting point matter, which comes from the reaction between fluxes and titanium alloy. As the agent of forming nucleus the matter promotes to form a lot of unsymmetrical crystal cores to refine the crystal.

3.3 Effect of flux on weld properties

3.3.1 Effect of flux on maximum tensile strength

The vertical welding was used in studying the effects of five kinds of fluxes (CaF_2, NaF, AlF_3, NaCl and $CaCl_2$) on the maximum tensile strength for the welds. Three specimens of every flux were made, then tensile experiments were carried out in the base metals and the welds of the specimens without and with flux-coated. Fig. 3 and Table 3 show the comparison of the maximum tensile strength of the base metal and of the welds of the flux-coated specimens, respectively.

From Fig. 3, it can be seen that when the coating quantity is nearly the same, all of these five types of activating fluxes have obvious effects on the weld tensile properties of titanium alloy TC4. Compared with conventional weld of the specimen without flux, the tensile strength of welds coated with flux increases to a large extent. Among them, the maximum tensile strength of welds coated with flux NaF is the best, which increases by about 20% compared with the weld without flux, while the increase of that of flux NaCl is the smallest.

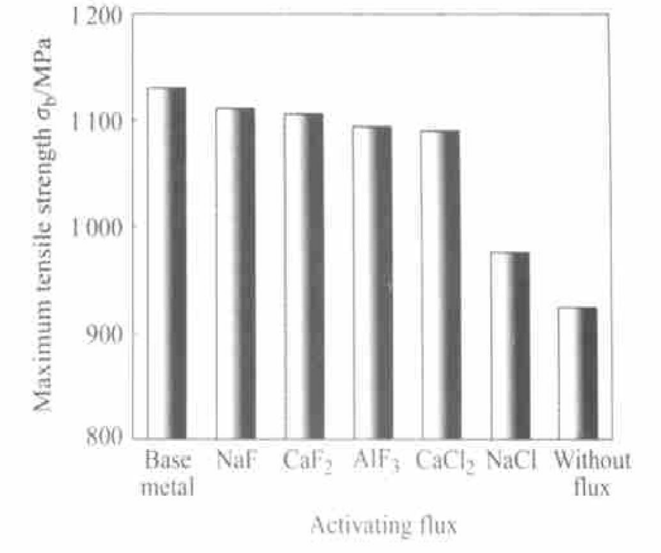

Fig. 3 Comparison of maximum tensile strength of base metal and welds of specimens with and without fluxes

Table 3 Maximum tensile strength of base metal and flux-coated specimens welds

Flux	Coating quantity of fluxes/ $(mg \cdot cm^{-2})$	σ_b/ MPa	$\sigma_{0.2}$/ MPa	δ/ %	ϕ/ %
Base metal		1 130	1 110	11.88	10.50
Weld with no flux coat		924	918	2.97	2.88
NaF	2.32	1 111	1 085	7.84	7.27
CaF_2	2.13	1 106	1 090	3.82	3.68
AlF_3	2.03	1 094	1 080	4.53	4.33
NaCl	2.04	976	970	4.65	4.44
$CaCl_2$	2.08	1 090	1 070	4.51	4.32

3.3.2 Effect of flux on maximum bend intension

The effects of five kinds of flux (CaF_2, NaF, AlF_3, NaCl and $CaCl_2$) on the maximum bend intension were studied, respectively. Three flux coated specimens for every flux were made, then the maximum bend intension was measured. The results gained are shown in Table 4 and Fig. 4.

From Fig. 4, it can be seen that when the coating quantity is nearly the same, all of these five types of activating fluxes have obvious effects on the weld bend properties of titanium alloy TC4.

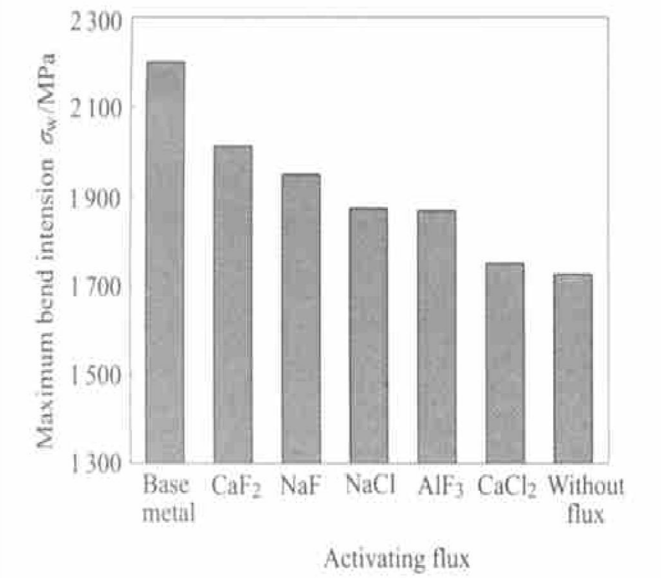

Fig. 4 Comparison of maximum bend intension of base metal and welds of specimens with and without flux coat

Table 4 Maximum bend intension of base metal and of specimens with/without flux-coat

Flux	Coating quantity /(mg•cm^{-2})	Maximum bend intension σ_w/MPa
Base metal		2 206
Without coat		1 727
NaF coated	1.26	1 953
CaF_2 coated	1.25	2 016
AlF_3 coated	1.20	1 871
NaCl coated	1.29	1 876
$CaCl_2$ coated	1.30	1 752

Compared with conventional weld of the specimen without flux coat, the bend intension of welds made with flux increases to a large extent. Among them, the maximum bend intension of welds made with flux CaF_2 is the best, which increases by about 17% compared with the weld of the specimen without flux coat. While the increase of the quantity of flux $CaCl_2$ is the smallest. This may be attributed to the better desulphating and deoxidizing ability of element calcium. Due to this advantage of Ca, the shape and distribution of the inclusion existing in the welding can be improved, thus it can improve the performance of welded structure. Therefore, when the activating flux is applied in the weld metal, the sulfur content is reduced and the tensile performance of the material is increased.

3.3.3 Reason of increasing intensity and tenacity of weld of coated flux

Coated with an activating flux, the intensity and the tenacity of the weld have different increasing extent. The reason as follows.

The microstructure shows the size of the crystal grain of the coated-flux weld increases. But as shown in Fig. 5, the little black grain in the big grain is inferior grain, which is to say there are smaller grains in the alloy. The appearance of inferior grains makes the intensity and the tenacity of the alloy get the greatest matching. Stretch distortion begins at the specific inferior grain as the form of slippage at first. The slippage from an inferior grain to the adjacent inferior grain is easier than from a grain to an adjacent grain, because the distance between an inferior grain and the adjacent inferior grain is small in grains. With distortion increasing, slippages occur in more and more inferior grains, and extend to a big grain step by step. So the formation and development of the cavitation are slower and it produces much distortion before cracking. Thereby, it can obtain higher tenacity and increase the intensity and the tenacity.

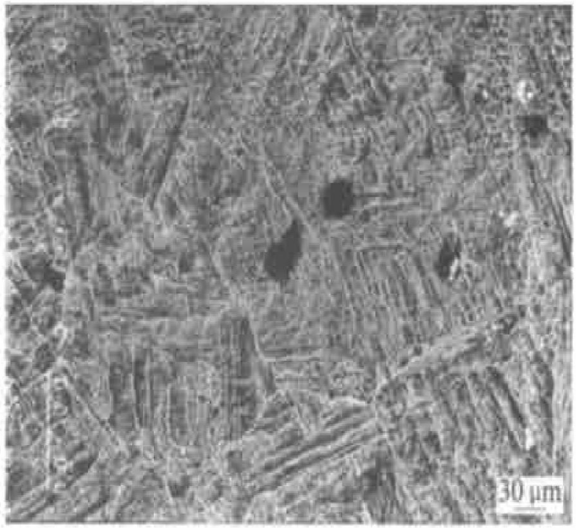

Fig. 5 Inferior grain in grain of coated-flux weld

The grains of the coated-fluoride weld are trident crystal, but there is four-fork brilliant crystalline in the coated-NaCl weld, as shown in Fig. 6. Stress concentrating is easier to produce at the intercrossing during the alloy distortion and cracks propagate along with the interface of grains. So the intensity of the coated-NaCl weld is decreased little.

4 CONCLUSIONS

1) Compared with conventional TIG welding, the above mentioned fluxes can greatly improve the penetration at the same welding specifications. This is because of the constriction of anode spots and the change of surface tension grads.

2) Though the size of grains in the coated-fluoride weld is bigger than that of with no flux-coated, the appearance of inferior grains equals fine crystalline grain.

3) The intensity of the coated-NaF flux weld is

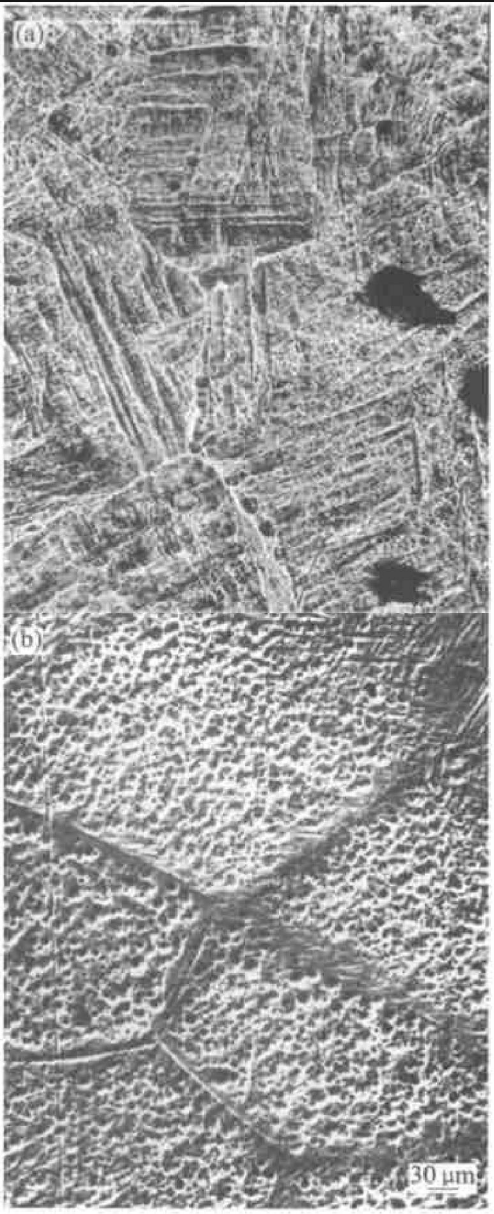

Fig. 6 Interface structure of grains in weld of specimen coated-fluoride(a) and coated-NaCl(b)

the best. The tenacity of coated-CaF_2 flux weld is the best.

4) The appearance of inferior crystal grains and the structure of trident crystal grains are the main reasons that the performance of weld with fluoride is improved.

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