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AC TIG welding with single-component oxide activating flux for AZ31B magnesium alloys

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Abstract Magnesium-based alloys are finding extensive applications foreground in aerospace and automotive applications. Weldability of magnesium alloys has recently been investigated with a variety of processes. In this article, the activating flux TIG (ATIG) welding of magnesium alloys with three single-component fluxes (TiO_2, Cr_2O_3 and SiO_2) under alternating current (AC) mode was studied. The effects of welding speed, weld current and electrode gap on the weld shape and the weld arc voltage in AC TIG welding with oxide fluxes were investigated on an AZ31B magnesium alloy substrate. The mechanisms of oxide fluxes on the arc shape and the arc voltage on the weld shape are discussed. The result showed that the TiO_2 and Cr_2O_3 increase the weld penetration of AC TIG welding of magnesium with good bead cosmetics. The SiO_2 increased the weld penetration with very poor formation of the weld surface. However, the arc voltage decreased with the used of TiO_2 flux, and increased with the used of Cr_2O_3 flux. The mechanism of TiO_2 and Cr_2O_3 fluxes increasing penetration should not accord with the "arc constriction". It would comply with some potential effects of the flux interacting with the liquid metal of fusion zone.

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Introduction

Considerable attention has been recently given to magnesium alloys because their combination of low density and high strength makes them particularly attractive for aerospace and automotive applications. However, industrial exploitation of magnesium alloys is still restricted, partly due to magnesium's low formability. In the absence of sheet products, welding has been confined to isolated applications [1]. However, realizing that welding, like forming, would open a whole new range of applications, weldability of magnesium alloys has recently been investigated with a variety of processes, particularly gas tungsten arc welding (TIG welding), laser beam welding, laser-TIG hybrid welding and friction stir welding [1–5]. Of all commercial magnesium alloys, those with aluminum as the primary alloying element are most weldable using any of these three processes [2–6]. With arc welding processes, lack of weld penetration is generally a limitation of the magnesium alloys. In arc welding with a nonconsumable tungsten electrode, the electric arc is struck by applying a direct current (DC), an alternating current (AC) or a current with other waveforms. For magnesium alloy, AC offers a major advantage over DC to initiate a weld pool, and this advantage is the cathodic cleaning of the magnesia covering the surfaces [6]. However, compared to DC where the electrode is negative and workpiece as a cathode, AC lowers the heat input to the base metal and produces shallower welds, especially when argon is selected over helium [6–8]. It must apply extra processes to welding magnesium alloys, like preheat process, welding cost increasing and welding efficiency decreasing. The plasma arc welding process can be used as an alternative to the TIG process, allowing a high welding penetration. However, plasma arc welding is much more complex and presents greater initial and operational costs than that for the TIG process.

Activating flux TIG (ATIG) welding is a variant of conventional TIG welding process, which was developed in the 1960s for the welding of titanium in the Paton Institute of Electric Welding [9–11]. This process is characterized by the application of a fine layer of a flux on the surface of the base metal. During welding process, part of the flux would be melted and vaporized by the heat of the arc. As a result, the penetration of the weld bead can be increased greatly and its sensibility to the chemical composition of the base metal reduced. Many researchers [9–16] have applied ATIG welding to titanium alloy, stainless steel, mild steel, aluminum alloy and so on, but little work has been devoted to this process for magnesium alloys.

Some authors [10–15] associate the great penetration of ATIG welding to a constriction of the electric arc caused by the presence of some components of the flux in the arc. This effect would increase the anode current density and the arc force acting on the welding pool and therefore increase the penetration of the welding bead, similar to what happens in plasma arc welding. Alternatively, it has been proposed that the increase in weld penetration results form a change in the liquid flow of the weld pool due to the flux interacting with the liquid metal. Otherwise, Marya [17] investigated the ATIG welding of magnesium alloys with a DC and a sing-component chloride flux. The ionization potential and electro negativity of metallic elements in the chlorides affected the weld penetration importantly in his work.

Many studies on the ATIG welding were under DC mode earlier. Sire and Marya [18] proposed a welding process called FBTIG (Flux Bounded TIG) with AC mode for aluminum alloys. Fan and Huang [16] studied the ATIG welding with AC mode for aluminum alloys. In this article, the ATIG welding of magnesium alloys with fluxes of simple composition under AC mode was studied, in order to evaluate the effect of single components on the process. The effects of welding speed, weld current and electrode gap on the weld shape and the weld arc voltage in AC TIG welding with oxide fluxes were investigated on an AZ31B magnesium alloy substrate. The mechanisms of oxide fluxes on the arc shape, the arc voltage on the weld shape are discussed.

Experimental

AZ31B magnesium alloy wrought plates with the average composition of 3.10% Al, 0.65% Zn, >0.20% Mn, <0.10% Si, <0.03% Fe, <0.10% Cu, <0.005 %Ni, <0.04% Ca and the rest of Mg were selected for the welding experiments and machined into 100 × 50 × 5 mm rectangular plates as test piece. AC-GTAW bead-on-plate welds were made with an automatic control system in which the test piece was moved at a constant speed. The standard welding conditions are listed in Table 1. The surfaces of the plates were chemically cleaned using acetone before welding to eliminate surface contamination. Three single fluxes, TiO_2, Cr_2O_3 and SiO_2, were used to examine the effect of the single flux on the welding process of the Magnesium alloy. The flux was supplied in powder form. Before welding, the flux powder was mixed with acetone to produce paint-like consistency. A brush was used to apply the mixture on half of the top surface of a test piece (see Fig. 1). During welding process the arc voltage was continuously monitored. The images of the electric arc for TIG welding both with and without activating flux were obtained with a high-speed camera and stored in a computer with a frame grabber. No technique to filter the light from the arc was used to enhance these images.

Table 1 Standard welding condition

Parameters	Value
Electrode type	AC, W–2% ThO_2
Diameter of electrode	2.4 mm
Vertex angle of electrode	60°
Shield gas and flow rate	Ar, 10 L min^{-1}
Arc length	1 mm
Welding current	100 A
Welding speed	300 mm/min

After welding, weld bead surface was first photographed. Weld cross-sections were prepared using standard procedures including grinding, polishing and etching. The cross-sectional macrographs were observed, and the penetration was measured.

Result and discussion

Weld bead morphology

Figure 2 shows the cross-sections of the weld beads under the standard welding conditions. The fluxes TiO_2, Cr_2O_3 and SiO_2 caused an increase in penetration when compared with TIG welding. This higher penetration occurred immediately after the transition from TIG to ATIG welding and was, therefore, associated directly with the presence of the flux. The penetration percentages (penetration with activating flux to penetration without activating flux) were about 114% (with TiO_2 flux), 150% (with Cr_2O_3) and 177% (with SiO_2 flux), respectively. It also can be seen that there are not any weld defects when the TiO_2 and Cr_2O_3 were used, while a big cavity was found in the weld bead

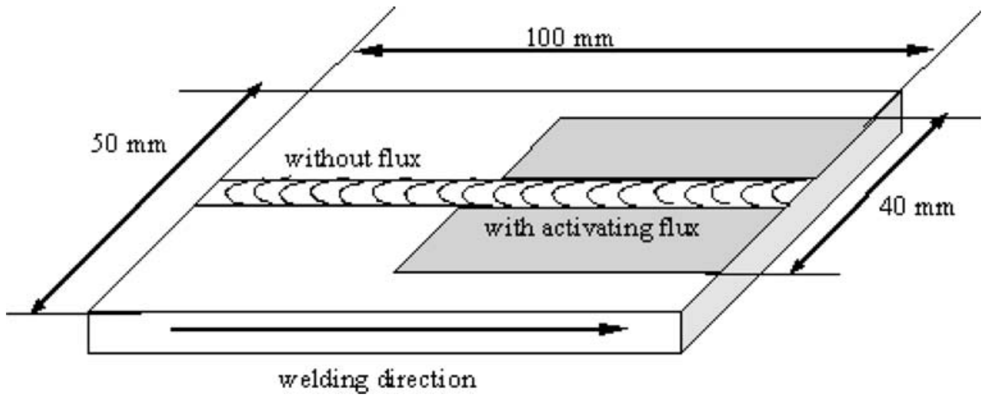

Fig. 1 Schematic representation of the specimen used in the ACTIG welding of Mg alloy

with SiO_2 flux. For the width of weld, it can be seen that the width of weld with oxide fluxes all increased than that of without flux.

Figure 3 shows the surface appearance of the weld beads under the standard welding conditions. It found that the top bead appearance with TiO_2 was better than that of without flux, with Cr_2O_3 have many ripples and some granular residue, and with SiO_2 created stiff black Si pieces at the both side of weld as well as white MgO, and at the same time a groove in the mid of weld also existed. This kind of flux also caused the strongest changes in arc voltage, presenting a maximum change in arc voltage of about 6 V: this was at least threefold as high as the values found with other fluxes. However, the arc voltage with the SiO_2 flux was so fluctuant that it cannot be recorded during the welding process. Hence the following discussion about the effect of welding parameter on the arc voltage with SiO_2 was not included. SiO_2 was chosen as the experimental activating flux by many researchers and has been proved to improve weld penetration obviously in A-TIG welding for steel and titanium alloy. For the magnesium alloy, SiO_2 can react with Mg ($2Mg + SiO_2 = 2MgO + Si$). It makes a mass of Mg element in the base metal lose and the white MgO and the Si slag remain beside the weld bead. The fluctuation of arc voltage should be induced by this reaction.

Effect of arc length on weld shape and arc voltage

Figures 4 and 5 show the weld penetration and arc voltage, respectively, under different electrode gap from 0.5 to

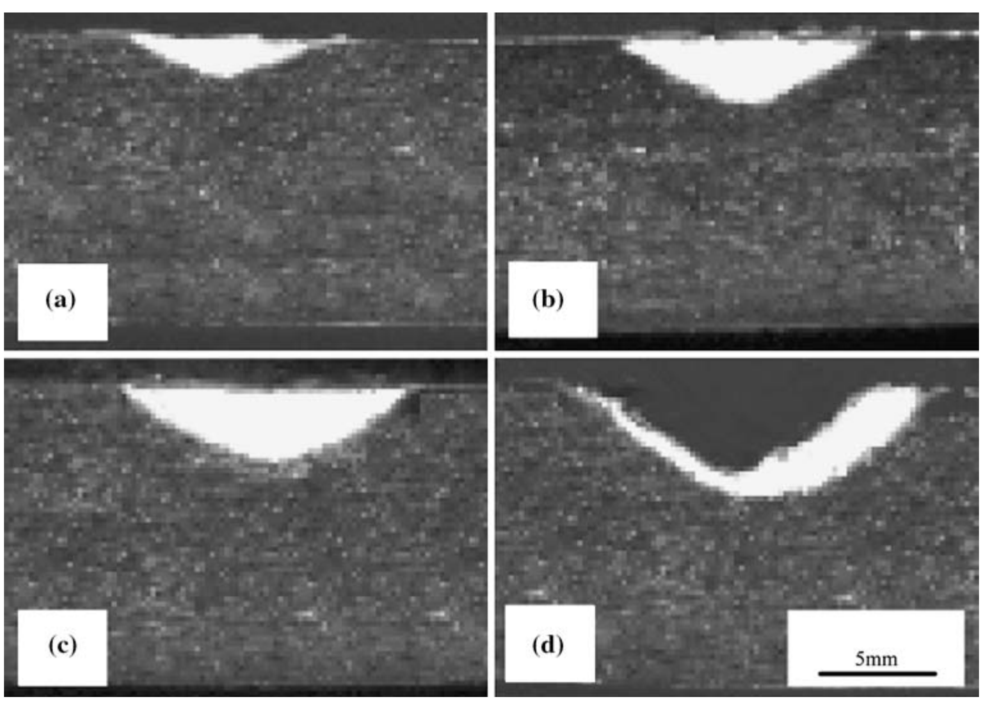

Fig. 2 Weld pool shapes without flux (**a**) and with fluxes of TiO_2 (**b**), Cr_2O_3 (**c**) and SiO_2 (**d**)

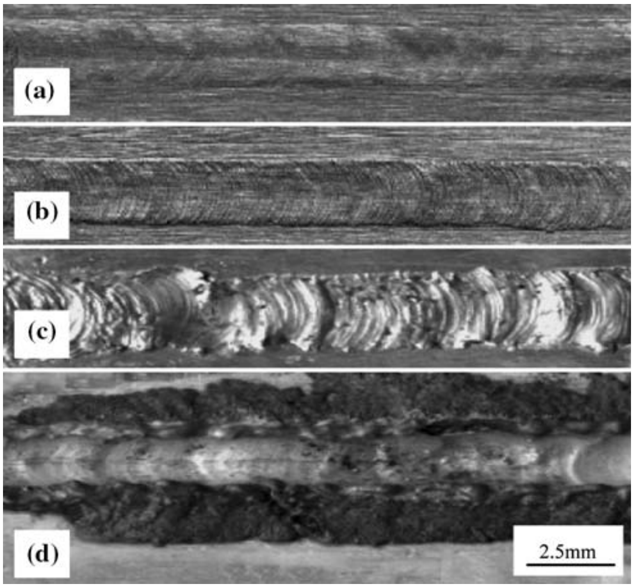

Fig. 3 Weld surface shapes without flux (**a**) and with fluxes of TiO_2 (**b**), Cr_2O_3 (**c**) and SiO_2 (**d**)

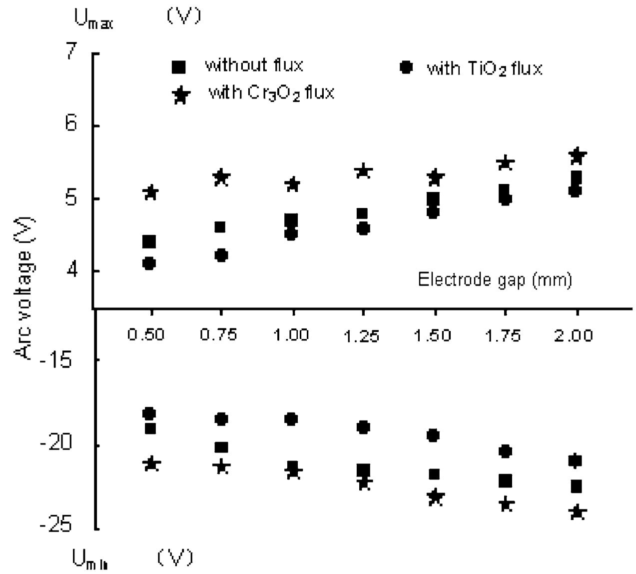

Fig. 5 Effect of electrode gap on arc voltage with and without flux (welding current: 100 A; welding speed: 300 mm/min)

2.0 mm. The weld penetration decreases obviously with the increasing electrode gap in the conventional TIG welding, while the weld penetration decreases slowly with TiO_2 and Cr_2O_3 fluxes. The effect of the electrode gap on the ability of oxide fluxes increasing penetration was lower. The arc voltage increases with the increasing of electrode gap. It showed that the arc voltage decreased with the use of TiO_2 flux than that of without flux, and increased with the use of Cr_2O_3 flux. The TiO_2 was metal oxide. It is a semiconductor, which has a lower electrical conductivity in high temperature. During the welding process, it makes the conduction of electricity easy and the arc stable. For Cr_2O_3, because of higher melting and boiling temperature and higher electrical resistively, the arc voltage increased. Hence the increasing of weld penetration did not bear on the change of arc voltage in TIG welding of magnesium alloys with oxide fluxes. It was found that the roles of the electrode gap in determining the weld penetration and the arc voltage are similar with and without flux.

Effect of welding speed on weld shape and arc voltage

Figures 6 and 7 show the role of the welding speed in determining the weld shape and arc voltage by varying the welding speed from 120 to 660 mm/min, with an interval of 60 mm/min. The penetration decreases with the

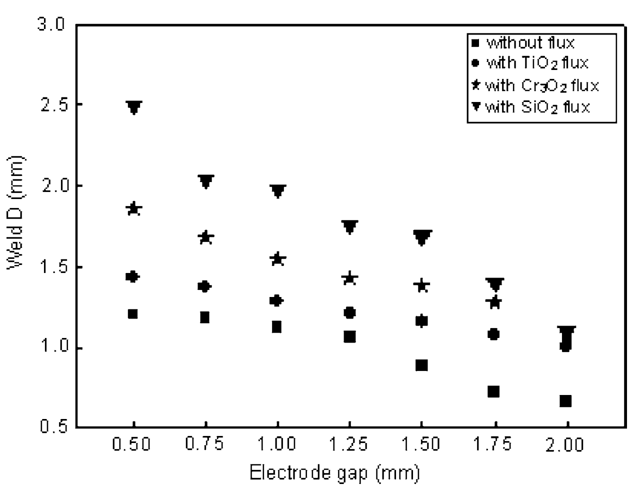

Fig. 4 Effect of electrode gap on weld penetration with and without flux (welding current: 100 A; welding speed: 300 mm/min)

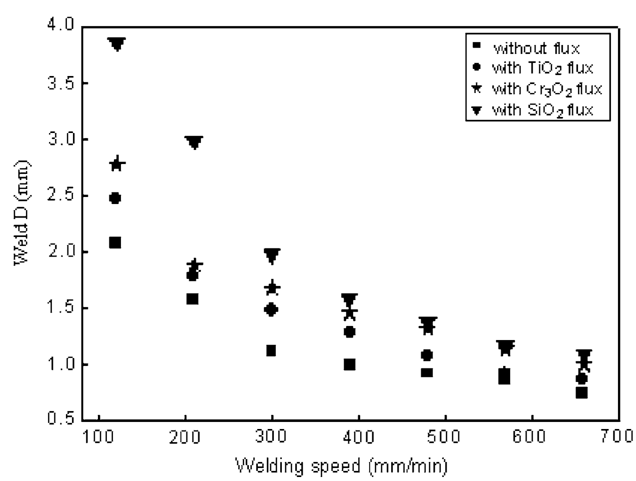

Fig. 6 Effect of welding speed on weld penetration with and without flux (welding current: 100 A; electrode gap: 1 mm)

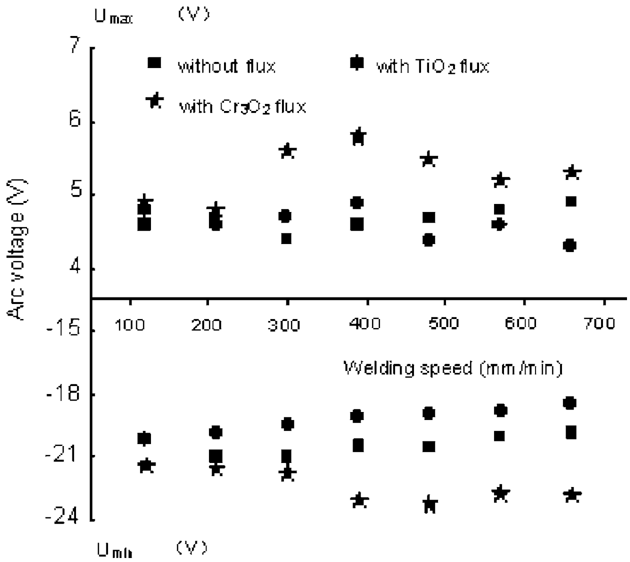

Fig. 7 Effect of welding speed on arc voltage with and without flux (welding current: 100 A; electrode gap: 1 mm)

increasing of welding speed for with and without oxide fluxes. The abilities of oxide fluxes increasing the weld penetration decrease with the increasing of welding speed. In the conventional TIG welding, the arc voltage increase a little with the increasing of welding speed. However, the arc voltage changes indistinctively with increasing travel speed when the oxide fluxes are used. The TiO_2 flux decreases the arc voltage and the Cr_2O_3 increase the arc voltage. In numerical value, the arc voltage changed by <1%, much smaller differences of arc voltage (<2.5 V) when comparing TIG to ATIG welding. Because the change of arc voltage may be associated with the changes of electric arc, this result suggests that the variations in bead penetration should not be linked directly to an effect of the flux on the arc. Therefore, this result does not support the model that associate the increase of penetration in ATIG welding to a constriction of the arc by flux elements vaporized to the arc. When the welding speed is slow, the weld penetration increased more efficiency with fluxes, and at the same time, the holding time of molten pool will prolong. This is beneficial for the flowing of molten pool metal and the interaction of flux with weld metal. It maybe includes the different mechanism in activating flux increasing penetration.

Effect of welding current on weld shape and arc voltage

Figures 8 and 9 show the influence of the welding current on the weld penetration and the arc voltage with oxide fluxes; a series of experiments were carried out varying welding currents from 60 to 120 A, while the other parameters were

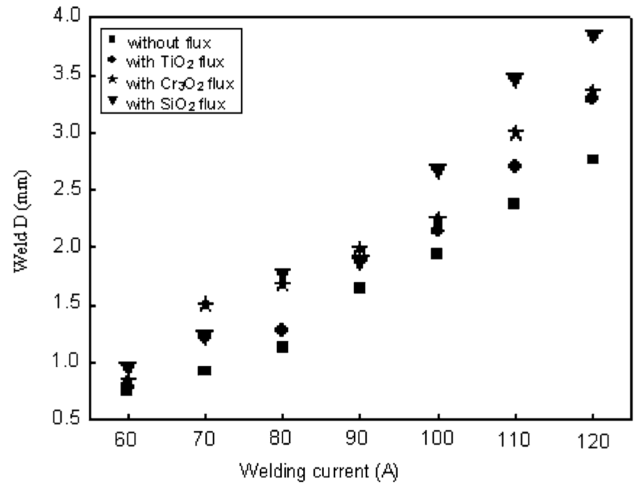

Fig. 8 Effect of welding current on weld D with and without flux (welding speed: 300 mm/min; electrode gap: 1 mm)

kept at their standard values (Table 1). The results clearly demonstrate that, with increasing of welding current, the weld penetration increases, but the role of the arc voltage was confusion. As expected from Ohm's law, that increase of current should correspond to the increase of voltage. Changing the welding current will directly alter the heat input and weld area. Considering the ruleless arc voltage changed, weld penetration in TIG would be determined by the fluid flow mode in the weld pool, which is driven by the electromagnetic force, surface tension gradient, buoyancy force and impinging force. Among them, the surface tension gradient on the welding pool surface is the primary variable that changes the convection mode. When the welding conditions were not changed during a trial, electromagnetic, gravitational and drag forces should not be altered. Thus, the

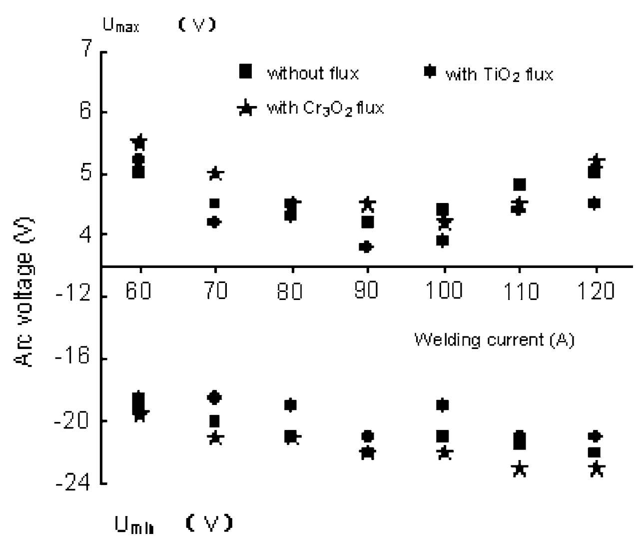

Fig. 9 Effect of welding current on arc voltage with and without flux (welding speed: 300 mm/min; electrode gap: 1 mm)

changes in bead shape should be probably linked to the Marangoni effect, which is determined by the surface tension gradient. This effect is used extensively to explain changes in the bead shape in austenitic stainless steels and other alloys associated with variations in the content of residual elements, particularly sulfur and oxygen. For magnesium alloy, the element that could change the Marangoni flow in the melted pool has not been reported. The effect of oxide flux on the melted pool in TIG welding should be investigated in further studies.

Arc observation measurement

Figure 10 shows the arc images of front view and side view of magnesium alloy TIG welding process with and without oxide fluxes under standard welding conditions (listed in Table 1).

A high-speed camera (CPL 250K CMOS) with the sampling frequency of 1,072 frames/s was used to monitor the weld arc. For the AC mode TIG welding, it includes EN (negative electrode period) cycle and EP (positive electrode period) cycle. The views of Fig. 10 for EN period suggest that the arc was dispersed on each side when oxide fluxes were present, while the views for EP period suggest that the arc was expanded. It is clear that the brightest region was at least 100% broader when oxide flux was present. The enlargement of the brightest region relates to the radiated intensity of vision emission. In terms of the mechanisms of the activating flux on the TIG welding, Simonik [19] proposed a theory for the effectiveness of the fluxes based on an arc constriction mechanism. In this article, Simonik's theory appears plausible and does not occur with the experimental observation in this article. Therefore, it must correlate to the arc temperatures and the electrical energy dissipated into the arc. It is can be seen that the arc images of ACTIG welding of Mg alloy with Cr_2O_3 are similar to the arc images with TiO_2 flux, while only the enlargement of the brightest region is bigger. However, the side view of plating SiO_2 was different from other fluxes. It became brightest and biggest. This would correlate to the reaction of SiO_2 and Mg, and the products of the reaction engender the gaseous vapor around the tungsten electrode. In a word, the arc images with the oxide fluxes were only the enlarged form of the arc images without flux. This can explain that the arc voltage with the oxide fluxes has a little change than without flux. Therefore, the increasing of weld penetration will attribute to the interaction of flux and weld metal. Based on the chemistry mechanism, the TiO_2 and Cr_2O_3 also can react with Mg. It is also suggested that a different mechanism in activating flux increasing penetration includes. Through the chemistry reaction, the elements Ti, Cr and O can diffuse into weld pool.

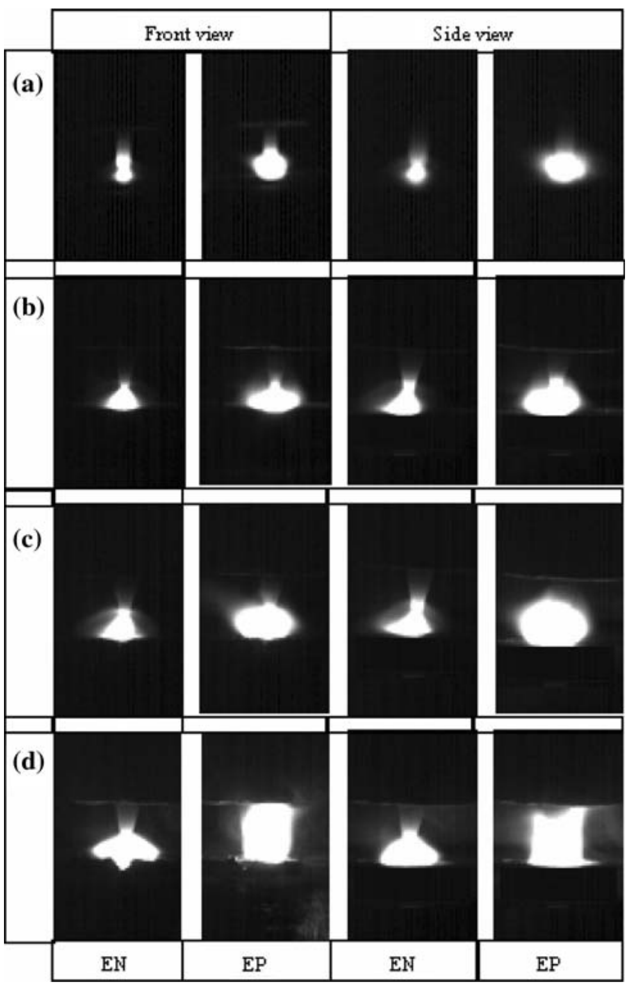

Fig. 10 Arc image of ACTIG welding of Mg alloy without flux (**a**) and with TiO_2 (**b**), Cr_2O_3 (**c**) and SiO_2 (**d**)

Summary and conclusions

This article depicts the influence of welding parameters on arc voltage and weld penetration during AC mode TIG welding magnesium alloy with three different oxide fluxes (TiO_2, Cr_2O_3 and SiO_2). Compared to the conventional AC mode TIG, welding penetration with oxide fluxes is about two times greater than that of without flux under optimal parameters. The results of experiments also demonstrate that the voltage changed inconspicuous when oxide fluxes were used. Besides, the phenomenon of arc spread was observed in AC mode TIG welding of magnesium alloy with oxide fluxes. The SiO_2 flux induced a quantity of losing of Mg element, and a cavity existing in the surface of weld bead. It also made the arc voltage fluctuant during the welding process with SiO_2 flux. Hence SiO_2 cannot be the flux used for magnesium alloys as a single-component, though it was chosen as the experimental activating flux by many researchers and has been proved to improve weld penetration obviously in A-TIG welding for stainless steel, mild steel, aluminum alloy and so on. The TiO_2 and Cr_2O_3 increase the weld penetration of AC mode TIG welding of magnesium with good bead cosmetics. The mechanism of TiO_2 and Cr_2O_3 fluxes increasing penetration should not accord with the "arc constriction". It would comply with some potential effects of the flux interacting with the liquid metal of fusion zone.

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