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WELDING OF Ti-6Al-4V IN AIR

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Abstract

It is demonstrated that titanium and its alloys can be laser welded in an air atmosphere when they are cathodically protected under a flux of a high-temperature molten salt. This enables the development of a new titanium welding process that does not require shielding the work piece with an inert gas.

Introduction

Welding of titanium and its alloys is difficult because there is frequently sufficient oxygen present during the welding process to alter the composition and thus the properties of the metal. Unlike the majority of metals, titanium and the other group IV metals have the unusual property that they can dissolve considerable quantities of oxygen in both the liquid and the solid state before forming a separate oxide phase. Any oxygen picked up during heating can then remain in solid solution upon cooling, which decreases the mechanical and fatigue properties of the weld metal. The heat affected zone on either side and at the back of the weld can also dissolve oxygen, which leads to a similar deterioration. Therefore, the volume of affected metal with inferior properties to the bulk can be substantial.

The problem of oxygen pick-up during welding has existed since titanium has become commercially available. Several methods of prevention have been proposed and these include [1]: welding the work piece under a shield of inert gas, welding in a cubicle flushed with inert gas, welding with a layer of flux around the weld. The disadvantage of these processes is that titanium will pick up oxygen from gases containing as little as a few ppm of oxygen and that it is virtually impossible to prevent gases of this composition reaching the weld. Larger sections of titanium are even more difficult to prevent from oxidation than thin sheets, especially when they are larger than the available cubicles. Various fluxes have been tried in the welding of titanium. However, many of these are based on oxides that can be reduced by the titanium to form titanium dioxide, which can then dissolve in the weld metal increasing the oxygen content. Fluoride-based fluxes are more suitable but these often contain calcium oxide which, again, can react with the titanium raising the oxygen content.

It is known that it is possible to remove dissolved oxygen from titanium and its alloys by making the metal cathodic in a bath of a halide of a very electropositive element, such as calcium chloride or calcium fluoride. In such an arrangement, the dissolved oxygen can ionise and dissolve in the salt at cathodic potentials more positive than those required for calcium to deposit [2,3]. As this method relies on the diffusion of oxygen in the solid metal, which is slow, it would not be applicable to thick sections of contaminated metal. However, a recent study has demonstrated that this concept can also be applied to preventing the oxygen reaching the titanium in the first place [4]. It has been shown that, when the metal was cathodically protected under a layer of a suitable molten salt flux, the pick-up of oxygen was insignificant and the extent of oxidation negligible. Those experiments were performed in air and, owing to practical constraints, at temperatures up to 1100°C only. This work now reports cathodic protection using a fluoride-based molten salt flux during the laser welding of a commercial titanium alloy, Ti-6Al-4V, at much higher temperatures.

Experimental

A beam from an Yb fiber laser was used as the heat source to generate spot welds in plates of commercial titanium alloy Ti-6Al-4V. Initially, a stationary laser beam and argon gas shielding were used in order to determine a suitable experimental set-up and identify typical power inputs required to create spot welds of sufficient size for analysis. Then, a moving laser beam was used to identify the conditions needed to melt powder layers of CaF_2/NaF mixtures with various compositions and approximate volumes of 30 x 50 x 10 mm^3, placed on top of the Ti-6Al-4V plate. Finally, a static beam was used again to make spot welds in the metal underneath the molten flux layer. For each of these three steps, appropriate experimental parameters had to be established empirically.

The effect of cathodically protecting the spot weld was investigated by making the Ti-6Al-4V plate the cathode against an iridium foil anode in the molten CaF_2/NaF flux, while creating spot welds in the metal using the previously optimized parameters. Earlier work had shown that iridium, which does not oxidize at elevated temperatures, is ideal as an inert anode in high-temperature molten salts [4,5]. During the welding experiments the potential was kept at values between 2 and 4 V. In addition, control experiments were carried out with no protective potential applied. Both inert argon and reactive air atmospheres were used. A schematic of the experimental arrangement is shown in Figure 1, and photographs of the actual equipment before and after the welding experiments are shown in Figures 2 and 3.

Metallographic samples were prepared from the cooled and solidified spot welds to assess their volumes and shapes. Bulk oxygen and nitrogen measurements of the spot welds were undertaken to discover the overall extent of gas dissolution. The results obtained from the experiments done with inert gas shielding and in air were referenced to the composition of the initial parent metal.

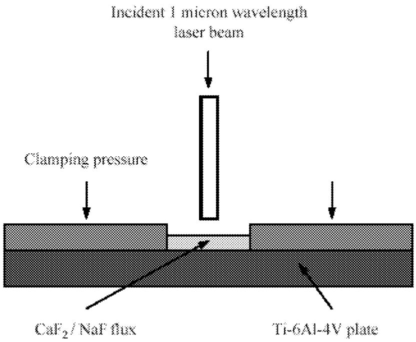

Figure 1. Schematic diagram of experimental arrangement.

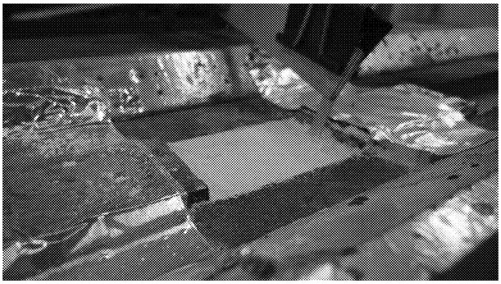

Figure 2. Photograph of experimental arrangement before laser welding experiment.

Figure 3. Photograph of experimental arrangement after laser welding experiment.

Results and Discussion

The initial set of experiments aimed at the identification of conditions required for creating appropriate spot welds in an inert gas shielded plate of Ti-6Al-4V alloy. It was found that using a stationary 5 kW laser beam focused 170-200 mm above the plate surface for up to 16 s produced spot welds of several millimeters in diameter and in depth. These were considered suitable for subsequent analysis.

Further experiments identified conditions needed to melt the salt powder placed on top of the Ti-6Al-4V plate. Here it was found that fluxes consisting of CaF_2 and NaF can be fused by using a moving low power laser beam of 2.75 kW for 60 s. Melting was facilitated strongly by the addition of Fe powder of approximately 1.25 g for every 20 g of flux to assist the coupling of the beam into the otherwise low-absorption flux powder. The pre-melting treatment resulted in the formation of a glassy and compact salt body on cooling. This solidified flux could then be re-melted using an even lower power static beam of 1 kW for 120 s.

With the re-melted flux in place, parameters were identified to create appropriate spot welds in the flux-covered Ti-6Al-4V alloy plate. It was found that now it was necessary to use a more concentrated 5 kW stationary beam, which was focused only 20 mm above the top surface of the metal plate and applied for 12-16 s. Without the more concentrated beam, the molten flux presented an effective thermal barrier between the laser beam and the metal.

At the end of each flux welding experiment, the solidified flux was well adhered to the surface of the Ti-6Al-4V plate. The flux left a black deposit on the metal surface after being removed, which made it difficult to determine the amount of oxidation by visual examination. Electron microprobe analysis showed that the black deposit consisted of very fine titanium alloy particles. The iridium anode, pre-positioned off to one side of the laser beam, survived all steps of the experimental procedure. It remained mechanically intact and only underwent some surface discoloration. The typical appearance of flux and anode after a welding experiment is shown in Figure 3.

Metallographic sections of the solidified spot welds revealed that weld pools of similar dimensions had been formed when using the parameters optimized for welding either with inert gas shielding or in the presence of a molten salt flux. This is in stark contrast to welding in air without any protective measures, which was catastrophic as a significant amount of the metal oxidized. Two representative sectioned spot welds are shown in Figure 4.

Bulk analysis of the oxygen and nitrogen contents of the solidified weld pool materials showed that the flux offered significant protection during welding in air provided cathodic protection was applied. The result was close to that observed for welding with inert gas shielding. When the flux was used as a plain mechanical barrier without cathodic protection, the results were significantly worse. The averaged results of the various analyses are compiled in Figure 5.

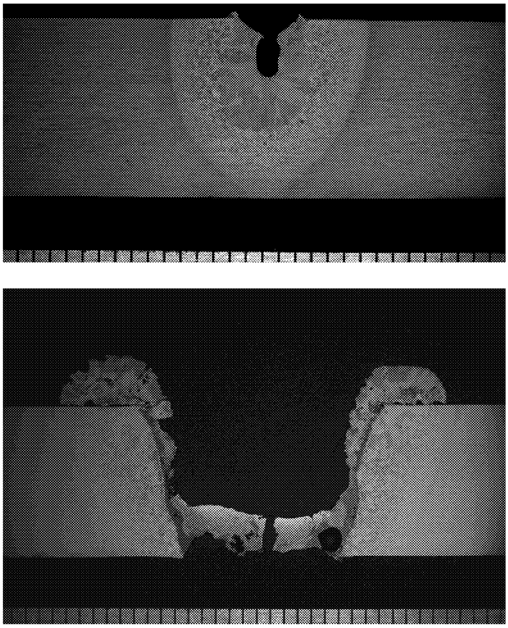

Figure 4. Cross sections of selected solidified spot welds, upper image: flux protected with an applied voltage of 3.5 V in air, lower image: not flux protected in air.
(The bars at the bottom of the images denote millimeters.)

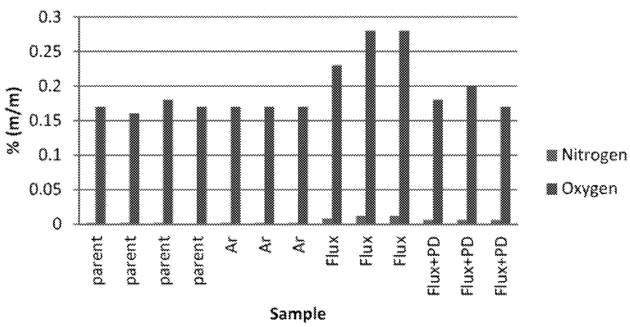

Figure 5. Oxygen and nitrogen contents for spot weld materials and parent metal.
('PD' denotes potential difference.)

Conclusions

The results of this study indicate that the use of a fluoride-based molten salt flux, when coupled with cathodic protection, can provide a route which allows welding of titanium and its alloys in air without the need of inert gas shielding. This may offer considerable advantages in cases where it is difficult to get access to a supply of inert gas.

Thus far, only a limited number of CaF_2/NaF fluxes were tested and the applied potential was only varied between 2.0 and 4.0 V. It is therefore possible that additional improvements may be achieved by further optimizing flux composition and cathode potential.

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