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Effect of microstructure on impact toughness of pulsed current GTA welded α–β titanium alloy

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Abstract

The preferred welding process for titanium alloys is frequently gas tungsten arc (GTA) welding due to its comparatively easier applicability and better economy. In the case of gas tungsten arc welding, the pulsed current has been found to be beneficial primarily due to its advantages over the conventional continuous current process. Design of Experiments concept has been used to optimize the experimental conditions. Grain size has profound influence on impact toughness. However, impact toughness is inversely related to grain size. Boundaries of primary α grains were observed to be preferential sites for crack nucleation and provide easy path for fracture propagation.

Keywords: Pulsed current; Gas tungsten arc welding; Impact toughness; Titanium alloy; Ti-64; Design of experiments

1. Introduction

In the present study, a Ti-6Al-4V (Ti-64) titanium alloy was welded by pulsed current gas tungsten arc welding. It is widely understood that the mechanical properties of titanium alloys are very sensitive to the characteristics of the microstructure. Malinov and Sha; Yunlian et al. [1,2] described, that the type of phases, grain size, grain shape and distribution of fine microstructure determine the properties and therefore the application of the titanium alloy. Wang and Wei [3] described that the microstructure of Ti-64 alloy consists of a mixture of α and β phase and measured volume fraction of α and β phase is about 65 and 35% respectively. They reported that the mixed fine elongated α and β phases have a grain size of about 5–20 μm.

Current pulsing has been used in the past for obtaining grain refinement in weld fusion zone. Significant refinement of the solidification structure and a transition from columnar to equiaxed growth were reported in aluminium alloys by Madhusudhan Reddy et al. [4,5], austentitic stainless steels by Ravivishnu [6] and tantalum by Grill [7]. Several investigators namely Sundaresan et al.; Prasad Rao [8–10] used current pulsing to obtain grain refinement in weld fusion zones and improvement in weld mechanical properties. However, published work on relating the pulsed current parameters, microstructure and impact toughness is minimal. Systematic studies have not been hitherto reported to correlate the pulsed current parameters, grain size and impact toughness.

In continuous current welding, microhardness study of the welded joints revealed largest grains with highest hardness and had columnar grain morphology. Zhou Wei and Chew [11] found that significant improvement in impact toughness was shown to be due to the much reduced amount of primary α grain in the weld metal. Senthil Kumar et al.; Balasubramanian et al. [12–14] have recently demonstrated the effectiveness of the pulsed current in refining the grain size by modeling and optimization. The investigation was conducted to gain a better understanding of the welding behaviour of α–β Ti-64 alloy especially in pulsing current. In this investigation the microstructure and impact toughness of the welds were examined in the as-welded condition.

2. Experimental work

The feasible limits of the parameters were chosen such that the Ti-6Al-4V alloy could be welded without any weld defects.

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Table 1
Design matrix and experimental results

Experimental number	I_p 60–100A	I_b 20–60A	F 0–12 Hz	t_p 35–55%	Impact toughness[a] (J)	Fusion zone grain size (μm)
1	70	30	3	40	7	240
2	90	30	3	40	10	180
3	70	50	3	40	6	260
4	90	50	3	40	9	210
5	70	30	9	40	8	220
6	90	30	9	40	10	160
7	70	50	9	40	7	250
8	90	50	9	40	10	190
9	70	30	3	50	7	270
10	90	30	3	50	9	200
11	70	50	3	50	6	280
12	90	50	3	50	8	230
13	70	30	9	50	7	250
14	90	30	9	50	9	180
15	70	50	9	50	6	300
16	90	50	9	50	9	220
17	60	40	6	45	10	140
18	100	40	6	45	8	170
19	80	20	6	45	11	100
20	80	60	6	45	10	150
21	80	40	0	45	7	340
22	80	40	12	45	9	260
23	80	40	6	35	10	120
24	80	40	6	55	9	190
25	80	40	6	45	12	70
26	80	40	6	45	11	60
27	80	40	6	45	11	110
28	80	40	6	45	12	60
29	80	40	6	45	11	90
30	80	40	6	45	12	100
31	80	40	6	45	13	80

[a] Average value of three test results.

Due to a number of factors, it was decided to use four factors, five levels, rotatable central composite design matrix to optimize the experimental conditions. Table 1 presents the ranges of factors and 31 set of conditions used to form the design matrix. GEP Box [15] has given the method of designing such matrices.

From prior literature of Madhusudhan Reddy et al.; Sundaresan et al.; Prasad Rao [5,8–10], the predominant factors, which have a significant influence on the fusion zone grain refinement and hence the toughness of pulsed current GTA welding process have been identified and welding was performed with utmost care. Specimens used in the investigation were detached from butt-welded joints of a Ti-6Al-4V titanium alloy.

At room temperature, the parent metal was found to have a yield strength (at 0.2% offset) of 910 MPa, ultimate tensile strength of 998 MPa, and elongation of 10%. Autogenous welds were deposited on the as-received titanium alloy sheet of 1.6 mm thick, as shown in Fig. 1a. High purity argon was used as the shielding gas during welding and as the trailing gas after welding to prevent absorption of oxygen and nitrogen from the atmosphere. The major welding parameters are summarized in Table 1. Standard Charpy V notch impact specimens were machined in accordance with ASTM E23-96 specification. The Charpy specimen has a cross-section of 10×1.6 mm^2 and contains a 45^0 V notch, 2 mm deep with a 0.25 mm root radius. The photograph of the Charpy impact specimen is shown in Fig. 1b. The samples for optical microscopy were cutoff from the joint, mounted, polished and etched with kroll solution (H_2O 100 ml, HF 3 ml and HNO_3 5 ml). Quantitative grain size measurements were made by intercept method.

3. Results and discussion

The microstructures of the fusion zone at high magnification for the Ti-64 welds are exhibited in Fig. 2. The microstructure at the fusion zone of the pulse TIG welded α–β Ti-64 alloy consist of acicular α and needle like martensite α′. This has lead to highest hardness (490HV). The microstructure of acicular α and α′ is exhibited in Fig. 3. The fusion zone exhibits prior beta grains as evidenced from Fig. 2. The welds exhibit equiaxed grain morphology due to the pulsing nature of the current in contrast to the columnar grain morphology in continuous current welding.

(a) (b)

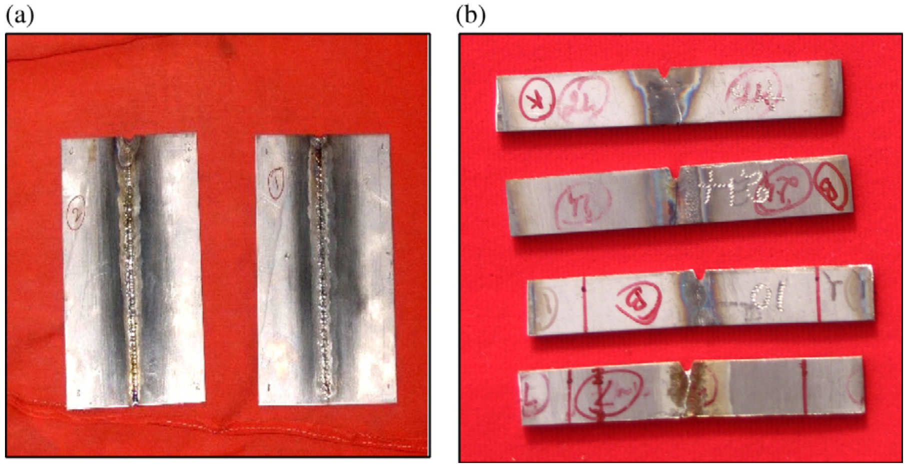

Fig. 1. (a) Joint preparation (b) Impact specimen.

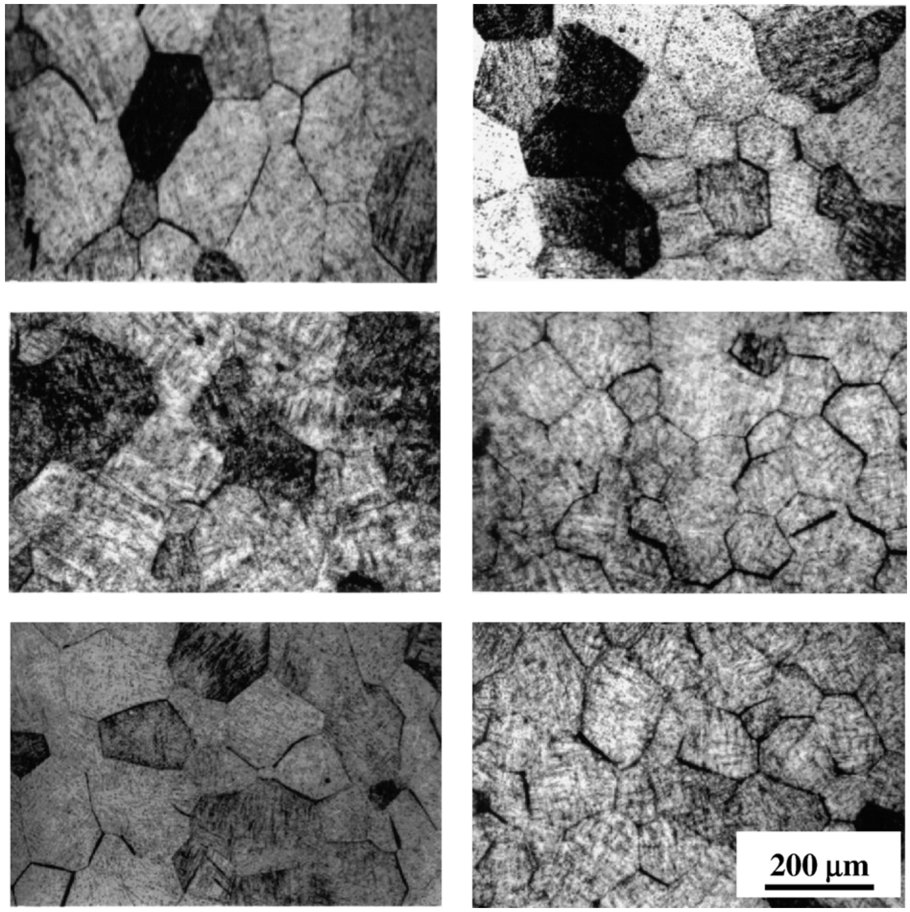

Fig. 2. Few optical micrographs of fusion zone.

Graphs were plotted between grain size and impact toughness at various peak current and pulse frequencies holding the base current and pulse-on-time constant. It is evident from the graphs that the impact toughness of the joints was having inversely proportional relationship to grain size (Fig. 4a–d). However, while varying the peak current at any pulse frequency, the effect of grain size on impact toughness is almost strictly a straight line (Fig. 4b, d).

It is also evident from the graph that up to a particular value of pulse frequency (6 Hz), grain size decreases causing a rise in impact toughness and then grain size increases resulting in the fall of impact toughness (Fig. 4e-h). It can very well be noticed from the Fig. 4f and h that when varying the peak current at a particular frequency, the plot indicating the effect of grain size on impact toughness increased and progressed in the upward direction and then almost followed the same path downstream after a particular point (80A). However, when pulse frequency is varied for a fixed peak current, the curve after progressing upward up to a pulse frequency of 6 Hz took a different path in the downward direction (Fig. 4e and g).

Fig. 3. Microstructure of the fusion zone, martensite α' (dark) needle like precipitate in β grains (light).

To summarize, irrespective of changes in peak current and pulse frequency, the grain size is observed to have an inversely proportional relationship to impact toughness of pulse TIG welded $\alpha-\beta$ titanium alloy. The effect of grain size on impact toughness increases up to a pulse frequency and then decreases. The effect of grain size on impact toughness is attributed to the pulsing nature of the current. At low frequencies, minimum is the effect of succeeding pulses on the weld bead. However at very high frequencies the amplitude of the vibrations induced in the weld pool and of the temperature oscillations are considerably reduced. Thus there exists an optimum frequency at which the greatest effect is produced.

4. Conclusions

Impact toughness of the joints is having inversely proportional relationship to grain size.

Peak current and pulse frequency are having profound influence on the effect of grain size on impact toughness.

The effect of pulsing current increases the impact toughness up to a particular frequency (6 Hz) and then drops down.

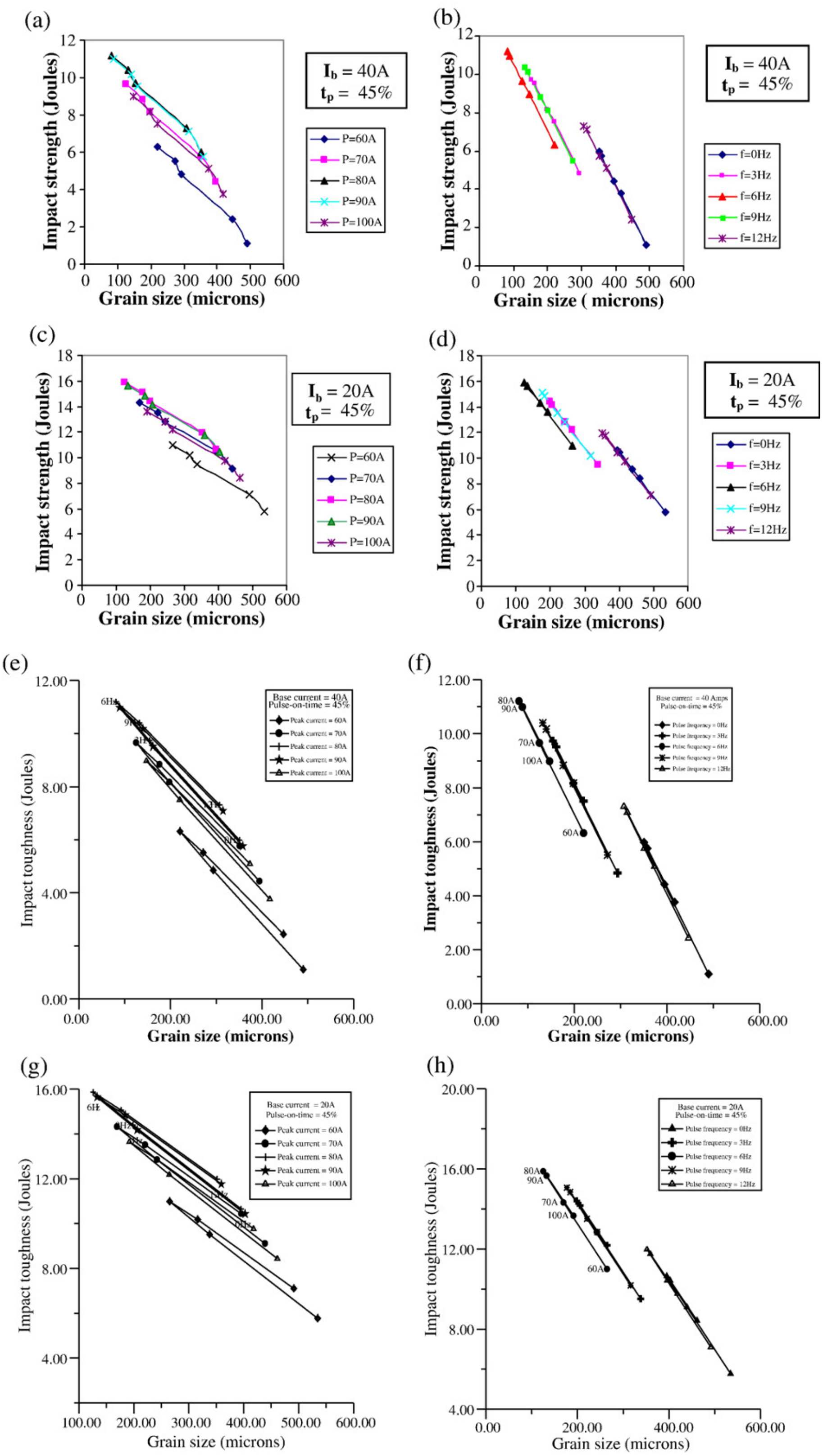

Fig. 4. (a, b, c, d) Effect of grain size on impact toughness. (e, f, g, h) Effect of peak current and pulse frequency on grain size and impact toughness.

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