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Research Article

Optimization of Multi-layer Welding of Titanium Alloy

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Abstract: Gas Tungsten Arc Welding GTAW process is a multi-input and output process in which the resultant joint strength is governed by both independent and combination of process parameters. The identification of suitable combination parameter is crucial to get desired quality of welded joint and hence, there is need for optimization of GTAW process to achieve a best result. The present work is based on the GTAW process parameters on multilayer welding of titanium alloy (Ti-6Al-4V). The design of experiment is done by response surface method to find the desired welding conditions for joining similar plates alloy material. Analysis of variance methods were applied to understand the GTAW process parameter. The considered parameters are filler diameter, welding current, welding speed and welding speed, while the desired output responses are heat input. From the results of the experiments, optimization is done to find optimum welding conditions of welded specimen to minimize the heat input by four welding pass is (5570 J/mm) and the total net heat input during welding for a GTAW procedure by four welding layers (3342 J/mm). In order to prevent structure changes especially for thick plates.

Keywords: GTAW, optimization, titanium alloy

INTRODUCTION

Titanium (Ti-6Al-4V) alloy is the most widely used material; it features good machinability and excellent mechanical properties. (Ti-6Al-4V) offers the best all-round performance for a variety of weight reduction applications in aerospace, automotive and marine equipment. This alloy is used at a minimum tensile strength of 1,193 MPa; it is used in the replacement of high-strength low alloy steel, 4340 M, at 1,930 MPa. This substitution resulted in a weight savings of over 580 kg (Boyer, 2003). The use of titanium in landing gear structure should also significantly reduce the landing gear maintenance costs due to its corrosion resistance. The low density and high strength make it very attractive for reciprocating parts, such as connecting rods for automotive applications. The structure in the engine and exhaust areas operates at elevated temperature, so the primary options are titanium-or nickel-base alloys however the latter would add significant weight. Titanium engine alloys are used up to about 600°C. Titanium alloys are considered one of the most difficult materials to machining. They possess very strong characteristics and cutting them involves a lot of problem. Followed by the problem reversible transformation of the crystal structure due to high temperatures during welding which were studied with Design of Experiments (DoE) of RSM. The heat input of welding process has a lot of problems which can occur. Heat affected zone, distortions, changes at the mechanical properties and microstructures which effect on the metals, leading to failure of the product and consequently loss of effort, cost, time and even sometimes live of people.

Heavy thickness uses: Given titanium's lightness, strength and resistance to corrosion and high temperatures, its most common use is in alloys with other metals for constructing aircraft, jet engines and missiles. Its alloys also make excellent armor plates for tanks and warships. It is the primary metal used for constructing stealth aircraft which are difficult to detect by radar (Krebs, 2006). The completed molds are then embedded on a casting table for centrifugal casting. Cast components of up to 2750 kg have already been successfully produced. Even larger structures are likely, but can also be manufactured by welding together two or more castings (Leyens and Peters, 2003). In addition, forging is one of process using to produce titanium productions for large ingots. Forging of large titanium ingots began/was undertaken in the early 1990s and the

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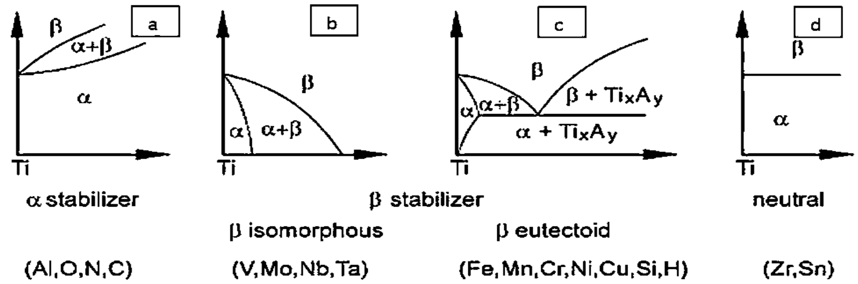

Fig. 1: Shows different types of phase diagrams of Ti; (a): is a schematic phase diagram for alpha stabilizing alloying additions; (b): is a schematic phase diagram for beta isomorphous alloying additions; (c): is a schematic phase diagram for eutectoid formers; (d): is a schematic phase diagram for neutral alloying element (Md Sajid, 2011)

forging process it can produces up to 600 mm or 4500 kg (Leyens and Peters, 2003).

Structure of titanium alloys: The classifications of titanium and its alloys follow the amount of alpha and beta kept in their structures at room temperature and they include commercially pure, alpha and near alpha, alpha-beta and metastable beta. In essence, the commercially pure and alpha alloys have all-alpha microstructures. Beta alloys primarily have all-beta microstructures after air-cooling process from the solution treating temperature above the beta transus. Alpha-beta alloys carrya mixture of alpha and beta phases at room temperature (Rti and Metals, 2000; ASM.org., 2013).

α-stabilizers: Pure titanium at room temperature has an alpha (α) hexagonal close-packed crystal structure. The α-stabilizers have both substitutional and interstitial alloying elements. The substitutional α stabilizers are Al, Ga, Ge and interstitial α stabilizers are O, N and C. Among the substitutional alloying elements, Al is the most extensively used since it has large solubility in both α and β phase and it lessens the alloy's density. In Ti-alloys, Al addition is limited up to 5-6 wt % since the Ti-3Al (α2) phase will be formed with the increasing Al content. The two phase region α + Ti-3Al starts about 5 wt % Al. The formation of Ti-3Al (α2) coherent phase makes the Ti alloys brittle. The equivalent Al content in multi-component Ti-alloys is shown in Fig. 1a. A schematic of a phase diagram with α stabilizing element is shown in Fig. 1. Other substitutional alloying elements are Ga, Ge and rare earth elements despite the fact that their solubilities are much lower than Al and O. O, N and C all are strong α-stabilizer. These alloying elements tend to be stronger but it also lowers the ductility of Ti alloys. At room temperature, commercially pure titanium is composed primarily of the alpha phase. As alloying elements are added to titanium, they tend to alter the amount of each phase that is present and the beta transition temperature (Rti and Metals, 2000; Md Sajid, 2011; ASM.org., 2013).

B-stabilizers: The alpha (α) transforms to a beta (β) body-centered cubic structure at a temperature of approximately 885°C (1625°F) (Fig. 1). This transformation temperature, alternatively known as the beta transition temperature, can be raised or lowered governed by the type and amount of impurities or alloying additions. Broadly speaking, β-stabilizers are transition metals and they are divided into two categories, namely β-isomorphous and β-eutectoid. β-isomorphous stabilizers have thorough solid solubility with β Ti. β isomorphous elements adopted in titanium alloys are V, Mo and Nb. It is possible for sufficient concentrations of these elements to stabilize the β phase to room temperature as shown in (Fig. 1b) Ta and W are seldom used due to their density considerations. The β-eutectoid stabilizers commonly used for alloying with Ti are Cr, Fe and Si while W, Cu, Ni, Mn are Bi are known to have highly restricted usage. A schematic phase diagram is shown in (Fig. 1c). Hydrogen is also a β eutectoid forming element and has a low eutectoid temperature of 300°C. The high diffusivity of hydrogen causes it to adopt a special process of microstructure refinement, which uses hydrogen as a impermanent alloying element. Cr is restricted up to 5 wt % because otherwise, it will form the intermetallic compound $Ti\text{-}Cr_2$ which is undesirable. Similarly, Fe is limited to 5.5 wt %. Si is a common addition to titanium alloys for high temperature applications and it can improve creep resistance (Rti and Metals, 2000; Md Sajid, 2011; ASM.org., 2013).

α+β alloys: α+β alloys contain more β phase than the near-α alloys. These alloys can be fortified by heat treatment or thermo-mechanical processing (Fig. 2). They have better combinations of strength and ductility than the near alpha alloys. Application of α+β alloys include structural components of military and commercial aircraft, fan and compressor blades in gas turbine engines and risers on offshore oil and gas rigs (Rti and Metals, 2000; Md Sajid, 2011; ASM.org., 2013).

Response Surface Methodology (RSM): Response Surface Methodology is one of the optimization techniques in describing the performance of the

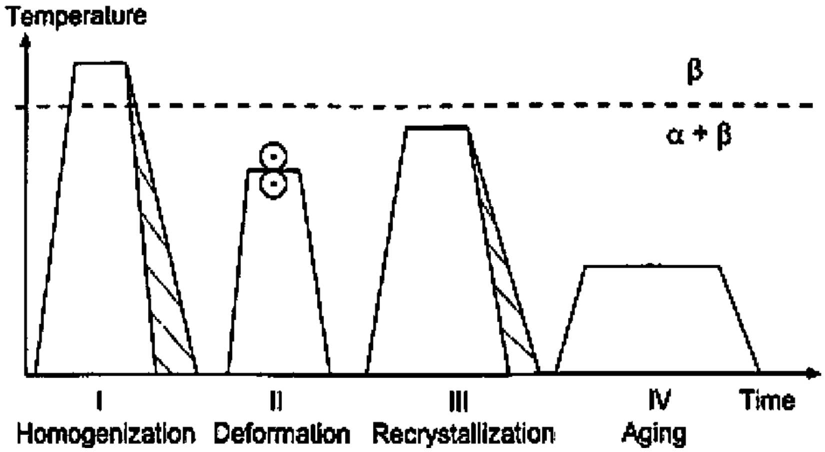

Fig. 2: The effect of heat treatment process on the amount of α and β (Md Sajid, 2011)

Table 1: GTAW input variable and experimental levels

Filler diameter (mm)		Welding current (A)		Welding voltage (V)		Welding speed (mm/sec)	
Min. (-1)	Max. (1)	Min. (-1)	Max. (1)	Min. (-1)	Max. (1)	Min. (-1)	Max. (1)
1	2	70	120	11	13	50	70

Table 2: Design of the welding sequence according to design of experiments

Sq.	Filler diameter	Welding current	Welding voltage	Welding speed
1	1	0	1	0
2	0	0	1	1
3	-1	0	-1	0
4	-1	0	1	0
5	-1	0	0	-1
6	0	0	0	0
7	0	1	1	0
8	0	-1	1	0
9	0	0	1	-1
10	0	1	0	-1
11	1	-1	0	0
12	1	0	0	-1
13	0	1	-1	0
14	0	1	0	1
15	1	0	-1	0
16	0	0	0	0
17	0	-1	-1	0
18	-1	0	0	1
19	0	0	-1	1
20	0	-1	0	-1
21	-1	-1	0	0
22	0	-1	0	1
23	0	0	-1	-1
24	0	0	0	0
25	1	0	0	1
26	-1	1	0	0
27	1	1	0	0

welding process and finding the optimum setting of parameters.

RSM also specifies the relationships among one or more measured responses and the essential controllable input factors. When all independent variables are measurable, controllable and continuous in the process, with negligible error (Huamin, 2013; Khorram *et al*., 2011).

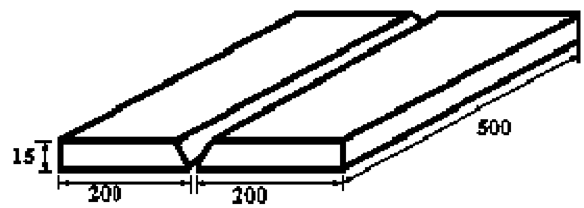

Fig. 3: Dimensions of joint configuration (unit: mm)

Experimental design: A welding design including four levels of factors is employed. Linear and second order polynomials were fitted to the experimental data to obtain the regression equations. The lack of fit test, variance test and other adequacy measures were used in selecting optimum models. Diameter of filler metal, welding current, welding voltage and the welding speed considered as independent input variables. Table 1 and 2 shows GTAW input variables and experiment levels.

Experimental work: Titanium alloy (Ti-6Al 4V) plate (Grade 5) with chemical composition presented in Table 3 was used as work piece material as shown in Fig. 3. The dimension of each sample was 500 mm long×200 mm width with thickness of 15 mm, weld by Gas Tungsten Arc Welding (GTAW) with filler metal which are given in ASME (2010) specification. To avoid any systematic error, experiments were conducted in random order using design of experiments and ANOVA provided by MINITAB software. Table 4 shows the details for a welding process.

Welding process has been completed successfully and certified according to Procedure shown in Table 4, in absence of visible welding defects. To determine the working levels of each variable, several experiments were conducted.

Table 3: Chemical composition of base metal

	Elements							
Material	%N Max	%C Max	%H Max	%Fe Max	%O Max	%Al	%V	%Ti
Ti-6Al-4V	0.00	0.04	0.012	0.2	0.10	5.8	4.1	Balance

Table 4: Procedure of welding process

Process or item		Characteristics	Process or item		Characteristics
Welding type		GTAW	Classifications of tungsten electrode	Classifications	EWCe-2
Joint type		Butt		Color	Orange
Electrical characteristic	Type of welding current	DCEN			
	Welding Voltage (V)	12-16		Alloying element	Cerium
	Welding current (A)	70-120		Alloying oxide	CeO_2
Travel speed (mm/min)		180-200		Nominal weight of alloying oxide percent's	2
				Tungsten diameter in inch. (mm)	3/32 (2.4)
Shield gas specifications	Type of shield gas	Argon		Cup size	5,6
	Shield gas flows (L/min)	8-12	Filler metal	Filler metal type	ER Ti-5
				Classification	AWS A5.16

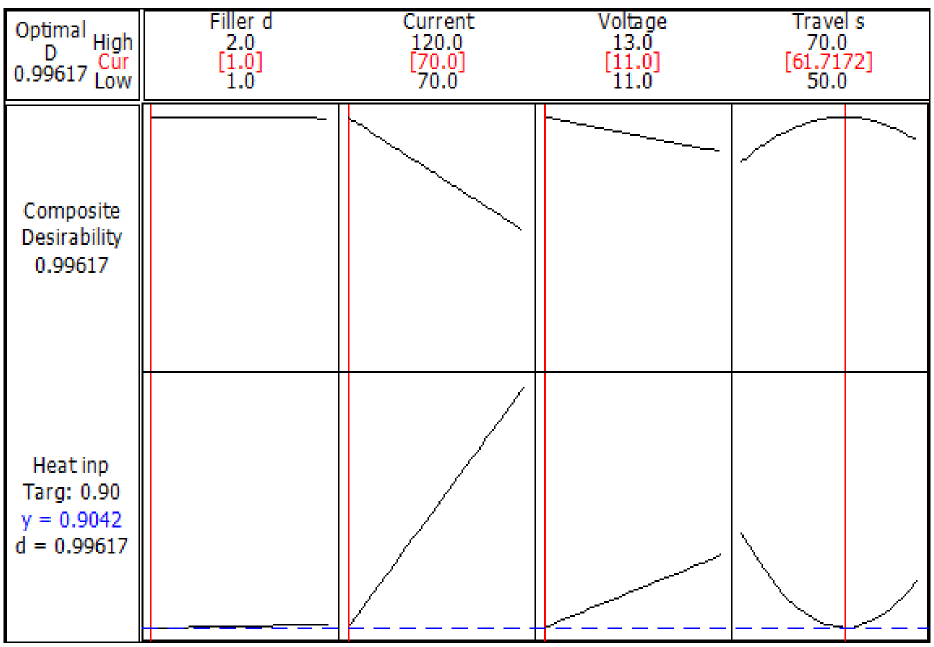

Fig. 4: Optimization plot for welding parameters

RESULTS AND DISCUSSION

An optimization plot shows how different experimental settings affect the predicted response for factorial, response surface and mixture designs. The optimal solution serves as the initial point for the plot. For mixture designs, it can adjust component, process variable and amount variable settings as shown in Fig. 4. The optimization plot shows the effect of each factor as Filler diameter, welding current, welding voltage and welding speed on the heat input as a response. The vertical red lines on the graph represent the current factor settings. The numbers displayed at the top of a column show the current factor level settings (in red). The horizontal blue lines and numbers represent the responses for the current factor level. Optimization result shows in order to attain the heat input the first three factors must be at their minimum value and the last one must be at its intermediate value. So the minimum of heat input will be attained when the following values are chosen for the five factors as shown in Table 5.

MATLAB Optimization toolbox was used for this optimization problem. The objective of Analysis of Variance (ANOVA) is investigating whether the process parameters have significant effects on the output signatures and conducting quantitative analysis of the impact of various factors on experimental results, so as to indicate whether the model developed is meaningful.

Table 5: Optimize values of independent variables

Independent variables	Filler diameter (mm)	Welding current (A)	Welding voltage (V)	Welding speed (mm/sec)
Optimize values	1	70	11	61.7172
Target heat input	0.904 KJ/mm			

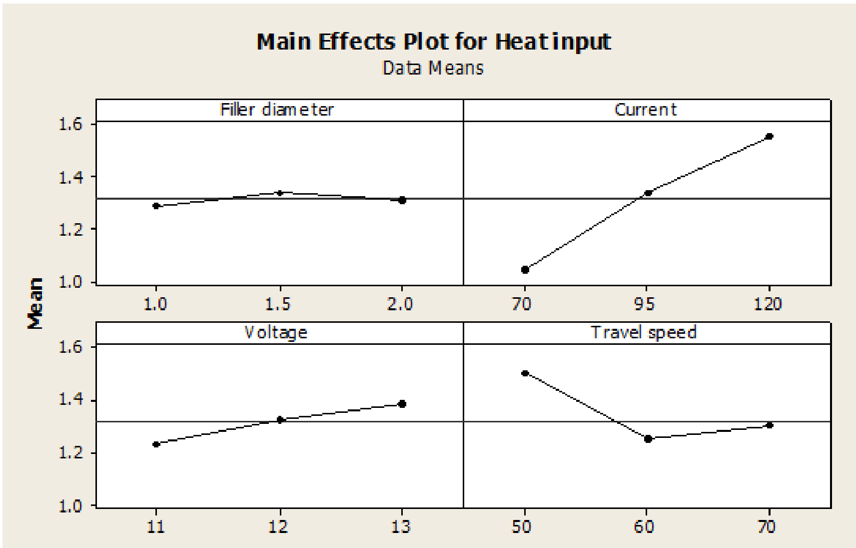

Fig. 5: Main effects of each welding parameters for heat input

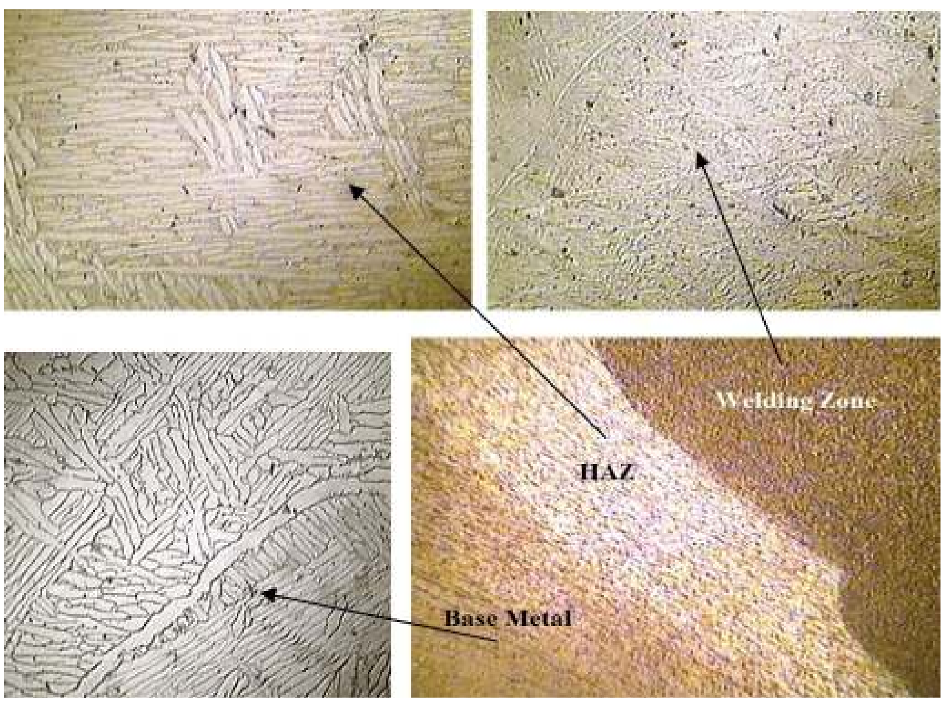

Fig. 6: Microstructure of an alpha-beta titanium alloy (Ti-6Al-4V) after welding process showing three zones

It is observed that the heat input is higher at the welding current and welding voltage is high. The heat input is lower as the welding speed decreased to its intermediate level. Generally, the increase of welding till certain speed will decrease the surface On the other hand; the changing in filler diameter will take no effect on heat input as shown in Fig. 5.

The effect of heat on the microstructure of titanium alloy (Ti-6Al-4V): In the weld metal of a multi pass weld, reheating effects will lead to a gradient in microstructure similar to the case of the HAZ. The properties of the weld metal depend on the relative area or volume fractions of the two regions, which in turn depend on the welding procedure.

Figure 6 shows the microstructure of an alpha-beta titanium alloy (Ti-6Al-4V) after slow cooling. The white plates are α and the dark regions between them are β for the regions as base metal, HAZ and weld zone.

CONCLUSION

From the study, the following points can be concluded:

- GTAW is a suitable technique to weld titanium Ti-6Al-4V with a heavy thickness, in order to obtain the best welding joints.
- Direct Current Electrode Negative (DCEN) polarity or (DCSP) is suitable for thick titanium plate. DCEN polarity obtains a full penetration with strong joints compound with closed system welding by injecting of Argon gas during the process to avoid pollution of welding pool.
- A multipass GTAW weld joint is possible for 15 mm thick plate, butt joint with a single V design and full penetration joint.
- The optimum values of welding parameters as filler diameter 1mm, current 70 (A), welding voltage 11 (V) and travel speed 61.717 (mm/sec). The total amount of heat input under optimum condition is (5570 J/mm) and the total net of heat input during welding for a GTAW procedure by four welding layers (3342 J/mm).
- Due to the heat input in the welded joint during welding processes, microstructure of the HAZ and weld zones formed different microstructures. The microstructure of the weld zone in all the samples contained small quantities of primary alpha, acicular alpha and massive beta. This change had a small effect on the microstructure.

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