Effects of Welding Parameters on Mechanical Properties in Electron Beam Welded CuCrZr Alloy Plates

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Abstract: CuCrZr alloys are attractive structural materials for plasma-facing components (PFC) and heat sink element in the International Thermonuclear Experimental Reactor (ITER) fusion reactors. This material has gained so much attention because of its high thermal conductivity and fracture toughness, high resistance to radiation damage and stability at elevated temperatures. The objective of this work is to study the effects of electron beam welding parameters on the mechanical strength of the butt welded CuCrZr joint. Taguchi method is used as the design of experiments to optimize the input parameters, such as accelerating voltage, beam current, welding speed, oscillation amplitude and frequency. The joint strength and ductility are the desired responses, which are measured through ultimate tensile strength and percent elongation, respectively. Accelerating voltage and welding speed are found to have significant influence on the strength. A combination of low amplitude and high-frequency oscillation is suggested for the higher joint strength and ductility. There is a close agreement between Taguchi predicted results and experimental ones. Fractographic analysis of joint and weld zone analysis are carried out to study the failure behaviour and microstructural variation in the weld zone, respectively.

Keywords: CuCrZr alloy, Electron Beam Welding, Beam Parameters, Taguchi Method, Tensile Strength, Microstructure

1. Introduction

In most of the fusion reactors, such as an international thermonuclear experimental reactor (ITER), plasma facing components (PFCs) are the most crucial ones, which act as the barrier between various internal components and vacuum chamber from the direct heat of plasma irradiation. These PFCs contain one armor material with one heat sink component, which helps to transfer the heat from the armor to the water coolant. So, this heat sink material should have resistance to the high heat load, high flux energy ion and neutral particle irradiation [1]. ITER recommended Copper-Chromium-Zirconium (CuCrZr) alloy has the potential to be used as heat sink material due to the properties including high thermal conductivity, excellent welding properties, and relatively high strength. The relatively new fusion welding technology like electron beam welding (EBW) has the inherent advantage of high aspect ratio, minimal heat affected zone (HAZ) and high joint efficiency. The precipitation hardened CuCrZr alloy plates are welded using electron beam welding for industrial assembling within the ITER context [2].

Kanigalpula et al. [3] studied the effect of EBW input parameters on bead geometry, and a few mechanical properties of the bead-on-plate welded CuCrZr. Statistical regression was also carried out to find the input-output relationships and then, the same were used to construct the optimization problem in order to minimize weld-bead geometry. Gong et al. [4] conducted the laser-arc hybrid welding of pure copper and characterized the weld by microstructural variation, conductivity, and tensile strength. They found out the coarse and columnar grains in the fusion zone, which lead to lower conductivity of the weld. With the increase of heat input, the weld and HAZ area were increasing, but they found a little effect on the tensile behaviour. Durocher et al. [5] characterized the various copper alloys with electron beam welding and selected the optimized grade for electron beam welding. They found a repeated occurrence of hot cracks in the EB welded CuCrZr joint, which leads to a water leak in the heat sink element. It was also reported that EB welded CuCrZr joint has less ductility and strength than that of base metal. High zirconium (> 0.14 wt. %) content and low chromium (< 0.6 wt. %) content were recommended to increase the ductility and strength, respectively. Feng et al. [6] pointed out the problem faced with the traditional welding of CuCrZr and found a significant reduction in mechanical and electrical properties along with significant difference of microstructure in terms of grain size and precipitates between the weld and base metal. They had suggested continuous extrusion forming after flash butt welding, which leads to sub-micron scale grain through dynamic recrystallization. Siddaiah et al. [7] conducted bead-on-plate electron beam welding of AISI 304 stainless steel according to the full-factorial design of experiments with three inputs having three levels each and four weld responses. A multivariate regression analysis had been conducted to establish an input-output relationship.

From the literature review, it is found that although electron beam welding of CuCrZr is one of the preferred technologies for fabrication, it has some disadvantages like grain coarsening and strength reduction due to high power density. Thus, there is a need for the studies regarding the strength and ductility of EB welded CuCrZr joint. Apart from these, there is a need to study the effect of secondary welding input parameters like oscillation amplitude and frequency along with the primary parameters like voltage, current and welding speed. In the present study, Taguchi's experimental design based on L8 orthogonal array has been used in investigating the effects of electron beam welding input parameters on strength and dutility of the EB welded CuCrZr joint. The optimal parameters for maximization of strength and ductility have been evaluated along with a fractographic study to understand the failure behavior.

2. Experiments and Methodology

2.1. *Materials and Design of Experiments*

Precipitation hardened CuCrZr alloy plates with the dimensions of 170 mm × 50 mm × 5 mm are used as the base material for this work. The chemical compositions of the material are as follows: 0.83% Cr, 0.06% Zr and remaining copper. At first, the as-received metal is cleaned and milled to get defect-free joint. In this study, beam oscillation parameters like oscillation amplitude and frequency are used as input parameters along with accelerating voltage, beam current and welding speed. The facility used in this study is an indigenously devolved EB welding setup (80kV-12kW) located at electron beam welding center of IIT Kharagpur. Taguchi L8 orthogonal array is used here for planning the experimental runs because of ease and minimum use of resources with the minimum numbers of experimental runs. In this study, five input parameters of electron beam welding with two levels each are used to establish the relationship between the response (mechanical strength and ductility) and input parameters. Table 1 represents the input parameters of EB welding and their levels. These experimental runs designed on the basis of Taguchi L8 OA along with responses are given in Table 2.

2.2. *Post Weld Characterization Techniques*

The EBW samples are cut, metallographically polished and then etched with the solution of $FeCl_3$ and HNO_3 to reveal the microstructure. Microstructures are captured using an optical microscope (Leica, Model: S8AP0) and scanning electron microscope (Zeiss, Model: Evo18 Research). The longitudinal tensile specimens are cut from the joint with CNC wire-EDM according to the ASTM E8-M standard [8]. The tensile tests are conducted with a strain rate of 1 mm/min in Instron universal testing machine to evaluate ultimate tensile strength (UTS), yield strength (YS), % elongation (%El) and failure location. The fractured surface of the tensile specimen is studied under scanning electron microscope to investigate the behaviour of failure.

Table 1. Experimental input parameters and their level

Parameters	Symbol	Unit	Level 1	Level 2
Accelerating Voltage	V	kV	50	70
Beam Current	I	μA	80	90
Welding Speed	S	mm/min	600	1000
Oscillation Amplitude	A	mm	0.1	0.5
Oscillation Frequency	F	Hz	400	900

Table 2. Experimental runs and responses

Run	V	I	S	A	F	YS	UTS	% El	Failure location	Remark on Penetration
1	50	80	600	0.1	400	107.7	146.3	9.308	Weld metal	Partial
2	50	80	600	0.5	900	95.31	114.7	8.36	Weld metal	Partial
3	50	90	1000	0.1	400	89.25	100.2	6.144	Weld metal	Partial
4	50	90	1000	0.5	900	87.58	99.8	6.236	Weld metal	Partial
5	70	80	1000	0.1	900	118.6	193.7	12.6	Weld metal	Almost Full
6	70	80	1000	0.5	400	107	186.3	11.71	Weld metal	Almost Full
7	70	90	600	0.1	900	137.9	260	19.43	Weld metal	Full
8	70	90	600	0.5	400	121.2	248.2	18.16	Weld metal	Full

3. Results and Discussion

Three response parameters (UTS, YS, % elongation) are considered for the experimentation. However, UTS and % elongation are only considered for further statistical analysis due to the very same nature of behavior observed by the yield stress and UTS. In this study, Taguchi method is used to determine the optimal input parameters of electron beam welding to maximize the ultimate tensile strength and ductility of the joint.

3.1. *Analysis of variance (ANOVA) for UTS and % Elongation*

Analysis of variance (ANOVA) is used to investigate which EBW parameters have significant effects on the response (UTS and % elongation) of the welded CuCrZr joint. Here, the variability of the S/N ratio is evaluted by the sum of squared deviation. The total sum of squred deviation is composed of sum of squared deviation contributed by each input parameter and the error in prediction [9]. An ANOVA result for UTS is shown in Table 3. It is seen from the UTS ANOVA table that welding speed and accelerating voltage are significant parameters for deciding the joint strength. Accelerating voltage and welding current have significant contribution of 82 % and 14%, respectively, in the calculation of UTS. Although the remaining three parameters have no significant effect, welder should give priority to the amplitude of beam oscillation, which directly influences the weld width and reinforcement height of the joint. Although the contributions of the input parameters are different, a similar trend is observed from the % elongation ANOVA table. It is also observed that accelerating voltage and speed have 76% and 23% contributions, respectively, towards the ductility of the joint.

Table 3. Result of ANOVA for UTS

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Percentage of Contribution
Accelerating Voltage (V)	1	65.2621	65.2621	65.2621	120.61	0.008	82.54
Beam Current (I)	1	0.0371	0.0371	0.0371	0.07	0.818	0.05
Welding Speed (S)	1	11.4028	11.4028	11.4028	21.07	0.044	14.42
Oscillation amplitude (A)	1	1.0357	1.0357	1.0357	1.91	0.301	1.31
Oscillation Frequency (F)	1	0.2458	0.2458	0.2458	0.45	0.57	0.31
Residual Error	2	1.0822	1.0822	0.5411			
Total	7	79.0658					

3.2. *Main effect plot and parametric study*

The main effects plots show the influences of different input parameters on the responses, namely UTS and % elongation. Here, MINITAB 15 is used to draw the main effects plot. Main effects plots for UTS are given in Fig 1. Accelerating voltage is found to have the maximum significant effect on UTS. It is seen from the Fig 1 that a greater strength can be achieved with high accelerating voltage, high beam current, low welding speed and low beam amplitude and frequency. As the voltage is directly related to kinetic energy of electron beam, the latter increases with the increase of former, this helps the penetrating beam to go to the higher depth of weld profile. The remark on penetration status for each weld has been shown in Table 2. Samples-7 and 8 have high values of YS and UTS because of full penetration of the weld profile. A high beam current is suggested by the plot, as beam current assists to enhance the power density of beam for a constant beam radius. A low welding speed ensures high heat input per unit length for a constant power and high heat input ensures the better fusion of the joint. Beam oscillation amplitude and frequency decide the scan profile of the beam. It is seen from the main effect plot of UTS that a low oscillation amplitude and frequency ensure the better strength of the joint. However, the differences between high and low levels of amplitude and frequency are found to be low in Fig 1. It is difficult to conclude the optimum combination of beam oscillation parameters for a sound weld profile. It is noted that almost a similar trend has been observed in the main effect plot of % elongation. The optimal parametric conditions for maximizing % elongation are high accelerating voltage, high current, low welding speed, low amplitude and high frequencies.

3.3. *Regression analysis*

Minitab 15 [10] is used to conduct linear regression analysis in order to establish the input-output relationships of the electron beam welding process. The equations for UTS and % elongation are shown in equations (1) and (2), respectively.

$$\text{UTS} = 43.98 - 2.85\times V - 0.0681\times I + 1.1939\times S + 0.3598\times A + 0.1753\times F \quad (1)$$

$$\%\text{Elongation} = 20.48 - 3.1059\times V - 0.1768\times I + 1.7153\times S + 0.2539\times A - 0.0529\times F \quad (2)$$

3.4. *Confirmatory test result*

Based on the main effect plot and ANOVA, the optimum set of parameters for maximizing the strength and ductility of the joint is found to be V2I2S1A1F2. Table 4 displays the confirmatory test result. The experimental result has a good agreement with the predicted one, as the percent error in prediction is found to be equal to 0.0327%.

Table 4. Confirmatory test ı results

	Optimal Parameters	
	Prediction	Experimental
Factors level	V2I2S1A1F2	V2I2S1A1F2
S/N ratio	48.2825	48.2983
Error between S/N ratio	0.0327%	

3.5. *Metallurgical studies*

UTS and % elongation of base metal are found to be equal to 397.962 MPa and 16.486%, respectively. There are significant reductions in the UTS and YS of the welded sample, as compared to that of the base metal. This statement is supported by the fact that all the welded samples are broken in the weld zone of longitudinal sub-size tensile specimens. Due to the high thermal conductivity and soft nature of this copper alloy, it is difficult to achieve the parent material’s strength with any kind of fusion welding process. There is a significant amount of grain coarsening in the weld and heat affected zones of the joint, which is displayed in Fig 2. The fractured surface of the broken welding surface is studied under scanning electron microscope to understand the failure behaviour. The fractographic image of one of the samples is shown in Fig 3. The macrograph consists of fine and uniform dimples and micro-voids, which indicates that the specimen fails in a ductile mode under the action of tensile loading.

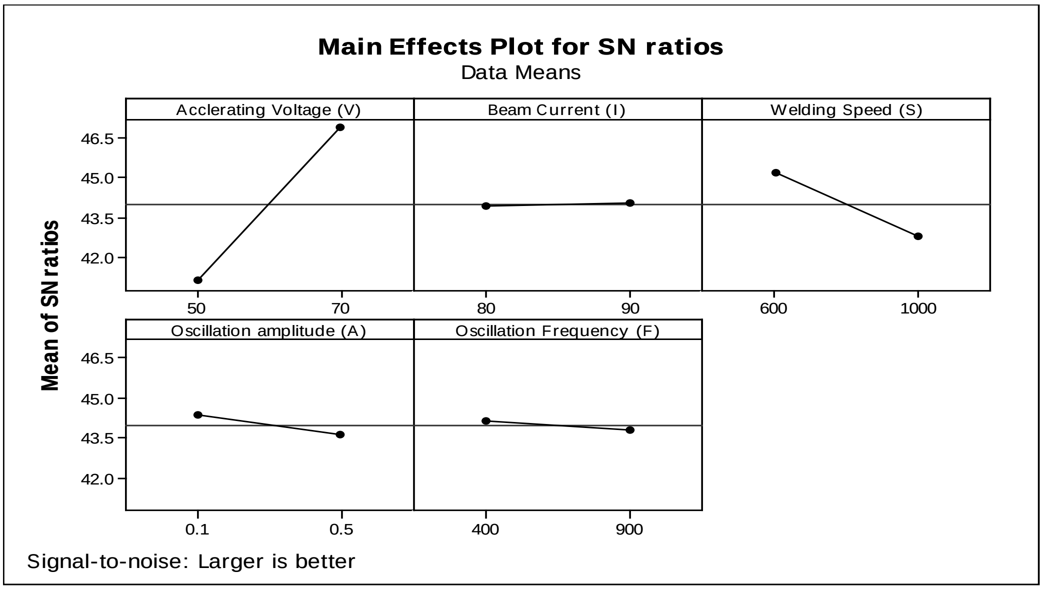
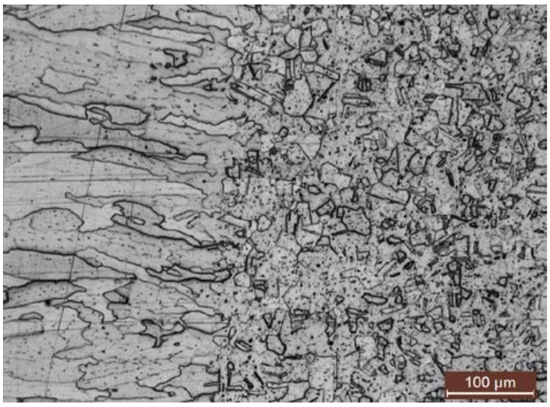


Figure 1. Main effects plot for ultimate tensile strength (UTS)



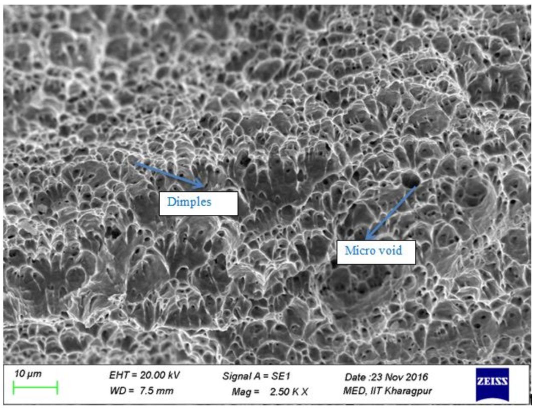


Figure 2. Microstructure of weld interface

Figure 3. Fractography of tensile specimen

4. Conclusion

The aim of this work is to study the effects of EBW process parameters on the mechanical strength of butt welded CuCrZr and to optimize these parameters for achieving the maximum strength and ductility. Both accelerating voltage and welding speed have the significant contributions for achieving the maximum strength and ductility. It is concluded from the main effects plot that high levels of voltage and current, low level of welding speed, and low and high levels of oscillation amplitude and frequency, respectively, are required for the maximization of strength and ductility, for a fixed thickness of CuCrZr plate in EBW. All welded tensile samples undergo ductile failure under tensile

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loading, which is indicated by the presence of dimples. The strength of welded CuCrZr reduces significantly, as compared to that of base metal due to grain coarsening and generation of intense heat during EBW. There is a good agreement between the predicted and experimental results.

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