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Electron beam butt welding of Cu-Cr-Zr alloy plates: Experimental investigations, studies on metallurgical and mechanical properties

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ABSTRACT

Studies related to butt welding of precipitation hardened (PH) Cu-Cr-Zr alloy plates using electron beam were carried out. Significant reductions in strength and microhardness were observed for all no-aged electron beam welded joints. The microstructural studies of fusion zone of the welded samples were analyzed in order to understand the reasons behind their loss of micro-hardness and tensile strength. Precipitation behaviors of different zones were also studied using X-ray Diffraction (XRD), Energy Dispersive X-ray Spectrometry (EDS) and transmission electron microscopy (TEM). All the metallurgical studies indicated reduction of precipitate and intermetallic density in the fusion zone of the weld. In addition to that, the effects of process parameters, namely accelerating voltage, beam current and welding speed, were studied on the responses, such as micro-hardness and tensile strength of the welded sample. A set of optimal input parameters was also determined in order to obtain the maximum microhardness and tensile strength. Fractographic analyses of the joints were carried out to study the failure behavior of the butt-welded specimens.

1. Introduction

Copper-Chromium-Zirconium (Cu-Cr-Zr) alloy has various industrial applications, in nuclear, aerospace, automobile industries, and so on. This precipitation hardened (PH), Cu-Cr-Zr has mostly attracted nuclear industries, as it can be used as a heat-sink material in a fusion machine for heat extraction from plasma facing components [1,2]. The attributes that make it suitable are the good thermo-mechanical properties at elevated temperatures [3]. For various applications, it might be required to join two plates of Cu-Cr-Zr alloy through butt welding. To perform this task, electron beam welding (EBW) is preferred to other welding processes in industries, due to the reasons that it can produce clean, distortion-free, narrow and deep welding with a reasonably high speed [4]. Precipitation hardened CuCrZr alloy plates are welded with electron beam welding for industrial assembly within the ITER (International thermo-nuclear experimental reactor) context [5].

Experiments had been conducted in the past to study the microstructure and precipitation behavior of PH, Cu-Cr-Zr plates and electron beam welding of the alloy. Fuxiang et al. [6] carried out phase analysis of Cu–0.31%Cr–0.21%Zr alloy and concluded that mechanical behavior of the alloy could be improved by either avoiding coarse precipitation during solidification or fragmenting the coarse precipitates and redistributing the alloying content. Kanigalpula et al. [7] studied the effects of input parameters during bead-on-plate welding of CuCrZr using electron beam on the bead geometry and some mechanical properties of the weld. Statistical regression was also carried out to find the input-output relationships, and then, the same was used to formulate the optimization problem in order to optimize the weld-bead geometry. They suggested different welding conditions also to minimize the weld width and maximize penetration depth and microhardness. Bi et al. [8] studied the phases in Cu-15%Cr-0.24%Zr alloy. A large number of Cr-precipitated phases were observed in the Cu matrix, and Cu_5Zr particles were seen in its grain boundary. The high-resolution transmission electron microscopy (HRTEM) images proved that there was a semi-coherent relationship between Cu_5Zr and Cu matrix. Edwards et al. [9] investigated the effects of heat treatment on precipitate microstructure and mechanical properties of Cu–0.73%Cr–0.14%Zr alloy. They found that coarsening of the precipitates due to over-aging could produce a significant decrease in the tensile strength and some improvement in fracture toughness properties of the alloy. Ivanov et al. [10] studied the effects of heat treatment on the properties of Cu-Cr-Zr alloys and found that the most reasonable range of the aging temperature for providing a high strength of the material was 480–5500 C for 2 h.

Durocher et al. [11] investigated the effect of chromium content in the butt welded joint of CuCrZr-CuCrZr. They carried out tensile tests on the welded joints of age-hardened Cu-Cr-Zr at room temperature and

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4000°C, and found that with the increase in chromium content, there was a significant decrease in ductility of the copper alloy. For enhanced weldability, the specified Cr content was below 0.6 wt%, and there was a high Zr content above 0.14 wt%. From micrographic examination, they also found that the grain size was not directly correlated to the percent of cracks obtained after electron beam welding. Feng et al. [12] found a significant reduction in mechanical and electrical properties along with a significant difference in microstructure in terms of grain size and precipitations between the fusion zone and the base metal during a traditional fusion welding of CuCrZr alloy plate. They had suggested continuous extrusion formation after flash butt welding, leading to granularity at a sub-micron scale through dynamic recrystallization. These grains and sub-micrometer precipitates helped to improve the properties of the CuCrZr alloy joint. Lipa et al. [13] discussed the use of Cu-Cr-Zr in the fabrication of actively cooled plasma facing components for Tora Supra (TS) and JET high heat flux elements for the beam lines. The mechanical characterization for joining of different material components was done by focusing especially on fusion welding of CuCrZr-CuCrZr. They observed that the higher Zr content influences the mechanical properties of the alloy at elevated temperature positively. He et al. [14] had investigated the effects of friction stir welding (FSW) on the microstructure and mechanical properties of Cu-Cr-Zr alloy joints. They compared the microstructures of the base metal with those of the welded zones using optical metallography (OM) and transmission electron microscope (TEM). Micro-hardness profiles and the corresponding tensile strength values were correlated with the microstructures. The micro-hardness and tensile strength of the welded joints were found to be lower than that of the base metal.

From the literature review, it is found that EB welding is one of the preferred methods for the fabrication of ITER recommended CuCrZr-CuCrZr joint. A few articles are available on the EB welding of CuCrZr, which mostly focused on the cracking behavior and bead-on-plate characterization. So, it is necessary to evaluate metallurgical, mechanical characteristics and their correlation in EB butt-welded CuCrZr plates. This study also explores the application possibility of EB welded CuCrZr in ITER components, as the requirements of CuCrZr are as follows: Grain size < 200 μm and YS ≥ 175 MPa. It gives an overview about the possibility of a few combinations, which satisfy the requirement. In addition to this, this study helps to design the process parameters' window to obtain the suitable parameters' ranges in order to get the desired mechanical properties of the fabricated plates. It is also seen from the literature survey that available literatures only investigated the precipitate behavior for the base material and heat-treated CuCrZr alloy. Therefore, this study tries to establish the relationships of precipitation behavior and microstructural variation on EB welded joint with respect to the mechanical properties.

The remaining part of the text is organized as follows: Section 2 explains the method adopted for conducting the experiments and the tools and techniques used in the analysis. Results are stated and discussed in Section 3. Some concluding remarks are made in Section 4.

2. Experimentation and methodology

Precipitation hardened CuCrZr alloy plates with the dimensions of 100 mm × 55 mm × 5 mm were utilized as the base material for this work. The chemical composition of the base material was analyzed with XRF and found to be, as shown in Table 1. There were no traces of O, H, Cd in the XRF results. In addition to this, the main impurities like Co, Nb and Ta were also within the permissible limit. To start with, the metal plates were milled and cleaned with emery paper for evacuation of oxide layers and contaminations. The welding edges were prepared to limit the gaps between (less than 0.05 mm) the plates prior to welding. In addition to this, a fixture arrangement was also kept to hold the plates firmly to minimize the gap between the plates and distortion. Butt welding of these plates was carried out using 80 kV-12 kW indigenously developed electron beam welding (EBW) setup located at Indian Institute of Technology (IIT), Kharagpur, India. The input welding parameters were selected based on plate thickness and machine constraints. Fig. 1 shows the photograph of the electron beam welding set-up used in this study. It consists of (i) electron beam gun chamber, (ii) electromagnetic (EM) focusing and deflection lens, (iii) work chamber, (iv) vacuum system for electron gun and work chambers, (v) electrical controls for power source, EM lenses and vacuum systems, (vi) beam viewing system, and others [15]. It is to be noted that a vacuum level of 5 × 10-5 mbar was maintained in the electron gun and work chambers during all the experimental runs. The welded samples were cooled in the vacuum chamber first for a few minutes to avoid oxidation and were then kept in air for further cooling. It is important to mention that the same cooling time was maintained for all the welded samples, as it has a significant influence on their microstructures and properties.

Table 1
Chemical composition of Cu-Cr-Zr alloy.

Element	Cr	Zr	Si	S	Al	Impurities	Cu
Wt. %	0.83	0.07	0.53	0.56	0.30	≤ 0.13	Balance

The primary welding parameters for EBW are accelerating voltage, beam current and welding speed, which have significant influence on the heat input to the weld. Although there are various secondary parameters (namely beam oscillation, focusing distance, and others), which have some influence on the weld but not so significant [4,15], these were not considered in the present study. Here, the primary welding parameters were considered for the study. The input parameters with their maximum and minimum limits are given in Table 2. These experiments were conducted according to the full-factorial Taguchi L8 orthogonal array design (refer to Table 3), where two levels of each input parameters were considered [16]. Eight numbers of experiments had been performed without any aging for mechanical and metallurgical characterization. In addition to the base metal had been characterized by conducting the same test as weld specimens, Moreover, in order to make a comparative study between the weld and base metal, similar types of tests were carried out on the base metal. Tensile strength and microhardness of weld joint had been considered as the mechanical responses. Then, a few welded samples were chosen at random along with the base metal for conducting the metallurgical study keeping in mind that the selected weld schedules were free of cracking.

The transverse tensile (perpendicular to welding direction) specimens were prepared according to ASTM E8-E8M standard [17] from the welded samples using wire-EDM. The schematic view of the transverse tensile specimen is given in Fig. 2. The tensile test was conducted in a 100 kN (Instron, model-8862) tensile testing machine with a crosshead speed of 1 $mm.min^{-1}$. Ultimate tensile strength and Yield stress of all the welded specimens and parent metal had been determined for the study. The fracture surfaces of the damaged joints were studied under SEM to get an indication of failure behavior.

Microhardness values were also measured according to ASTM standard E384-11 [18] of the welded joint using a Vickers microhardness test machine (Leco: Model-LM700) under a load 50 gf / 15 s (load / dwell time). The specimens considered here had the dimensions of 10 mm X 10 mm X 5 mm. Microhardness value was measured after the surface preparation using the papers of various grits and diamond polishing. Measurements were taken in the horizontal direction for the parent metal regions, heat affected zone (HAZ) and fusion zone (FZ) to identify the effect of microstructural heterogeneity. In addition to that, microhardness was also measured along the vertical direction to observe its variation along the top, middle and bottom zones of FZ.