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Effect of electron beam welding current variations on the microstructure and mechanical properties of Nb-1Zr advanced alloy

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ABSTRACT

The effect of electron beam welding current changes on the microstructure and mechanical properties of the Nb-based alloy has been investigated. The electron beam welding was applied with 4 different values for electric current 20, 24, 30 and 35 mA on 3 mm thick plates. The aspects including different welding regions, geometry and depth of welding penetration, as well as the effect of heat input on the mechanical properties are investigated. The mechanical properties including tensile and microhardness values of the weld was measured. The results show that in a sample with a 30 mA welding current, the optimum conditions for the depth of penetration, microstructure, mechanical properties and the geometry of the weld are obtained. The welds showed a cellular structure, and intercellular dendrites in the central region of the weld have been caused due to microsegregations created between the cells. In heat-affected zone (HAZ), severe recrystallization and grain growth has occurred. Because of the high thermal conductivity of niobium, the HAZ size is relatively large. Based on the 3D Rosenthal's equation, the recrystallization temperature of alloy was calculated as 713 °C. It is observed that as G × R increases, the grain size in the central line of the weld decreases. The hardness profile shows that the hardness of the weld zone and the HAZ is significantly less than that of the base metal due to elimination of work hardening effect. The tensile strength of the weld for a sample with a current of 30 mA was 281 MPa, which is 53% of the tensile strength of the base metal and the weld was broken in the HAZ.
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1. Introduction

1.1. Niobium

Niobium is a refractory metal with a melting point of 2477 °C, and a boiling point of 4741 °C [1]. It has the chemical symbol of Nb and atomic number of 41 [2]. Niobium and its alloys have excellent high temperature properties, including high melting points and good creep properties. These alloys have good workability and also have the lowest density among refractory metals [3–6]. Nowadays, pure niobium and Nb-1Zr alloy are widely used in aerospace industries for high temperature applications [7]. Niobium products are used in the manufacturing of corrosion resistant equipment, including reaction vessels, columns, bayonet heaters, shell and tube heat exchangers, rupture diaphragms and orifices [8]. High-purity niobium is also used for many accelerator projects using superconducting technology [9]. The rate of niobium creep is very low by adding 1% of the zirconium, and the high temperature properties of are very good [1]. The Nb-1Zr alloy is used in sodium steam lamps or for the investigation of molten alkali metals in nuclear reactors, because it has low neutron absorption properties, high corrosion resistance and good resistance to radiation damage [10,11]. A very fine-grained niobium-zirconium alloy is also considered as a new biomedical substance [12]. The welding of niobium alloys by conventional GTAW, and modern electron beam (EBW) and laser beam (LBW) is under consideration [13].

1.2. The electron beam welding of Nb-based alloys

Due to the increasing demand for high speed and low distortion in welding, electron beam welding has become a useful method in jointing engineering pieces [14]. The main advantages of this welding method are the high ratio of depth to width, lack of defects, small HAZ and high efficiency [15]. Unlike other welding methods, this method also maintains the purity of the metal in the melting region and HAZ [16]. The main applications of this high-efficiency welding process are automotive, nuclear, electrical engineering,

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aerospace and mechanical engineering [17]. The study of the physical and chemical properties of electron beam welding on refractory metals was carried out by Budkin [18]. He studied the weldability of these metals under different welding conditions and studied the dependence of the thickness of the intermetallic compounds created on the welding strength [18]. Budkin also developed the physical-mathematical model of the electron beam welding process for refractory metal welding to steel [19]. Demyanov and Kaniukov considered the superconducting properties of ultra-pure electron beam welding [16]. They found that the superconducting properties of the welded specimens were reduced, which is due to an increase in the concentration of impurities in the melting area. M.J.Torkamany et al. also studied the properties of laser welding of pure niobium with two conduction and keyhole modes. They also paid attention to a dissimilar welding of niobium to Ti-6Al-4V alloy [20].

By reviewing the references in this field, it has been concluded that limited research on the welding of niobium alloys have been conducted. In spite of Nb-1Zr alloy important applications in advanced industries such as aerospace, nuclear and military, very few articles and research reports have been published on its electron beam welding so far. In this study, it is tried to study the effect of electron beam welding current on microstructure, weld penetration and mechanical properties of Nb-1Zr alloy.

The current manuscript provides a literature review on the welding of Nb alloys in Introduction. The materials and electron beam welding parameters used are presented in Experimental procedures, which include the base metal, the process parameters, metallographic examination, mechanical properties and the calculations. The results and discussion section includes the base metal evaluation, the weld sections, the results of calculations, and the mechanical properties. At the end, the most important results are summarized as Conclusions.

2. Experimental procedures

2.1. The base metal

In this study, a 3 mm sheet of advanced niobium alloy (Nb-1Zr) was used. To obtain the exact chemical composition of the alloy, an emission spectrometry method (EOS) was used; the results are given in Table 1. XRD analysis was used to determine the phases in this alloy, the XRD pattern is shown in Fig. 1. To do this, the Philips X'Pert MPD software is used.

In order to investigate the tensile properties of Nb-1Zr alloy, the sheets were cut by wire cut with smooth edges and prepared according to ASTM.E8/E8M standard, then tested by SANTAM single-axis tensioner, at strain rate 0.001 S^{-1}, at room temperature. The hardness of these two alloys was also measured by the Vickers hardness test method.

2.2. Electron beam welding process

The Nb-1Zr sheets were first cut into samples with dimensions of 50 mm × 15 mm by cutting machine. Then, they were cleaned by sandpaper, and they were placed in acetone solution for 5s. An electron beam welding (EBW) equipment with a maximum voltage of 85 kV, a maximum power of 20 kW and a vacuum level of 6×10^{-4} mbar has been used to produce bead-on-plate welds. The EBW equipment is an assembled product which is made by Electron Beam Application Development (EBAD) Company at 2014 a.m. in Iran. Samples were placed in a vacuum chamber after cleaning, and then a vacuum of 10^{-4} mbar was applied.

The parameters such as welding speed, current and voltage can affect the welding conditions. However, the previous studies showed that welding current has more effect on the penetration of weld, which is the most important aim of the present work. The applied welding current was in the range of 5–50 mA, at fixed voltage and welding speed. This current range was selected on the basis of preliminary tests for start the work, and data extracted from the related literature conducted on the stainless steels and nickel-based superalloys. Finally, the applied welding currents which showed more meaningful and different results were presented in Table 2.

According to Table 2, welding was carried out with four different values for current intensity of 20, 24, 30 and 35 mA on the samples. Other parameters such as voltage, filament current, focusing current, welding speed and focusing current on the surface were considered constant. The electron beam focus was considered on the surface due to the low thickness of the specimens. In high-thickness specimens, the electron beam focus is applied inside the sample.

2.3. Metallographic examination

To study the effect of current on the microstructure and size grading of different welding regions and changes in the geometry of the weld, the welded samples were cut from the cross section containing all of the weld regions. The samples were prepared on the basis of standard metallographic procedure. Samples were etched with a solution containing $4HF + 3H_2SO_4 + 1HNO_3 + 5H_2O$ at the optimum time of 45 s. The samples were first examined for the geometry and depth of penetration of the welds by the OLYMPUS SZX2-ILLB Stereo Microscope, and analyzed for more precision by optical microscope model BX51M manufactured by OLYMPUS company and scanning electron microscope manufactured by Philips Model XL30.

2.4. Mechanical properties

In order to investigate and compare the tensile properties of electron beam welded Nb-1Zr alloy with base metal, the welded specimens were prepared according to the ASTM E8/E8M standard, which is shown in Fig. 2. A tensile load of 15 ton and single axis of French MTS model at a strain rate of 0.001 S^{-1} was used. Also, the microhardness of the different weld regions was measured by the Buehler LTD for all of the welded samples and compared to each other.

3. Results and discussions

3.1. The base metal

According to the EOS analysis, it is observed that all the alloying elements present in this material are less than 1 wt%. Referring to the XRD pattern of this alloy in Fig. 1, it is seen that this material is

Table 1
Chemical composition of Nb-1Zr alloy.

Element	H	Ni	N	O	C	Fe	Hf	Mo	Ta	W	Zr	Nb
Wt.%	0.001	0.002	0.006	0.002	0.008	0.04	0.05	0.14	0.5	0.6	0.8	98.5

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