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Weldability of AISI 316L Stainless Steel and Carbidic Austempered Ductile Iron Using Electron Beam Welding Technology

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***Abstract*— The aim of this study is to determine the weldability of different materials - AISI 316L stainless steel and carbidic austempered ductile iron (CADI) by electron beam welding (EBW). Welding is performed with different beam current (I_b) of 10 mA and 20 mA, welding speed (V) of 400 mm/min and 1000 mm/min with an offset relative to the stainless steel of 0.2 mm at a constant frequency deviation (Freq). Vickers microhardness is measured in the fusion zone (FZ) and in the heat affected zones (HAZ). The most suitable welding mode is determined in terms of higher microhardness in the FZ with the presence of defects in the weld seam.**

Keywords*— *carbidic austempered ductile iron, electron beam welding, stainless steel, weldability.

I. Introduction

In recent years, the need to create new materials and designs has arisen. Electron beam processing and, in particular, electron beam welding (EBW) is among those technologies by which monolithic joints are obtained, both between similar and dissimilar metals and their alloys, as well as non-metallic materials [1], [2], [3].

There are publications [4], which describe the application of electron beam processing. This publication indicates the possible combinations of different metals and their alloys depending on any dependence. Weglowski [5] generally presents possible combinations of electron beam weldable materials with the inclusion of some steels and non-ferrous metals.

A trend in agriculture [7], [8] is the effect of Carbidic austempered ductile irons (CADI). Compared to other cast irons, they have greater wear resistance and high toughness at the expense of their high brittleness [9].

Due to the high carbon content of cast irons, their welding is difficult, but not impossible. In practice, conventional welding methods with preheating of cast iron are recommended to reduce residual stresses and deformations [10], [11], [12], [13].

An advantage of electron beam welding is the presence of a concentrated thermal energy effect with a high density, and the vacuum environment allows obtaining a quality weld seam with chemically active and hard-to-melt metals and alloys [14].

In addition to the availability of a suitable machine, it is necessary for the materials to possess the complex characteristic of weldability, which is related to:

- The suitability of the metal for welding, depending on chemical composition, metallurgical method of production, way of making the details, the heat treatment of the metal before the welding process;
- The technological possibilities of welding, expressed by the factors: method of welding; of the parameters of the welding mode; the general technological plan of welding; thermal mode of welding; need for preliminary or accompanying heat treatment; the need for subsequent heat treatment of the joint or the entire welded structure.
- Structural reliability of the welded joint, which is a function of the thickness of the welded material; the shape of the welded joint; the manner and preparation of the joined ends.

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Weldability is determined by using quantitative and qualitative indicators in terms of whether the welding material is suitable for a specific welded structure, whether the specific parameters of the welding mode are selected and assessing the reliability of the resulting monolithic joint [10], [15], [16].

The aim of the present research is to create a monolithic welded joint between dissimilar materials austenitic stainless steel AISI 316L and CADI by means of EBW. The reason why this combination of materials was chosen is that the chemical composition of 316L austenitic steel contains nickel in the order of 10.0-14.0%. It is known that pure nickel electrodes are used in arc welding of cast iron. This is due to the fact that it takes a significant amount of carbon without changing its properties.

II. MATERIALS AND METHODS

A. Materials

The CADI blanks were obtained according to the methodology proposed in [17]. Castings were obtained using the method of casting from fused patterns, which were then subjected to isothermal quenching in salt baths. Those made of austenitic stainless steel AISI 316L were pre-turned and ground. The chemical composition of the two materials is listed in Table 1.

TABLE 1 CHEMICAL COMPOSITION OF THE USED MATERIALS

Mat.	**C, %**	**Si, %**	**Mg, %**	**B, %**	**Mn, %**	**Cr, %**	**Mo, %**	**Ni, %**
CADI	3,5	2,3	0,03	0,13	-	-	-	-
316L	0,03	0,75	-	-	2,0	16,0 - 18,0	2,0 - 3,0	10,0 - 14,0

Fig. 1 shows the dimensions of the blanks used for both materials.

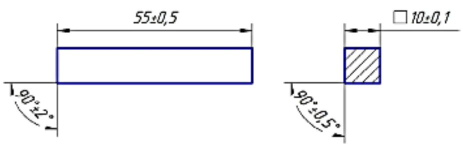

Fig. 1 Geometric dimensions of blanks from CADI and austenitic stainless steel AISI 316L.

B. Electron beam welding

EBW was performed with an Evobeam Cube 400 welding unit manufactured by Evobeam, which has the parameters specified in Table 2.

Various companies that deal with welding cast iron, [19] recommend preliminary cleaning and preheating of the cast iron.

According to [10] the best way to control the cooling rate during welding is to apply preliminary and concomitant heating. Depending on the temperature of the preheating, the following main methods of welding cast iron are distinguished:

- hot welding, with a heating temperature of 600-650 °C;
- semi-hot welding, with a heating temperature of 300-400 °C;
- cold welding - without preheating.

TABLE 2 SPECIFICATION OF ELECTRON BEAM WELDING MACHINE [18]

Elements	**Description**
Vacuum chamber	300 x 300 x 300 mm
Chamber pumping system	High Vacuum Turbo-Molecular-pumpset
Electron Beam gun system	High Vacuum Turbo-Molecular-pumpset
Manipulation system	3 mechanical CNC axes: X, Y and C all interpolated; 4 virtual CNC-Axes: IX, IY, IB und IL
Gun vacuum	5.10^{-4} mbar
Accelerating Voltage (U_a)	60 kV
Beam Current (I_f)	0-100 mA
Welding speed (V)	0-2500 mm/min

For this reason, two types of welding of dissimilar materials have been made: without and with preheating of the workpieces.

The main parameters in the EBW mode are classified into three main categories [18], [20] are:

- The parameters characteristic to the Electron Beam are Accelerating Voltage (U_a), Beam Current (I_f), Focusing Current (F), Depth of Penetration (H) and Beam Focal Diameter (d_{fo});
- The parameters characteristic to the Welding Joint Features are Welding Speed (v), Welding Width (B), Focal Distance (d_t), Vacuum Pressure (P_s) and Preheating Temperature (T_{pr});
- Other parameters involve Material Type, Thermo-physical and Chemical features of the material and Workpiece Thickness. These parameters do not constitute as being a part of Process Parameters.

Table 3 shows the selected parameters of EBW for the first type of workpieces (without preheating), and in table 4 - for the second type of workpieces (with preheating).

TABLE 3 TECHNOLOGICAL PARAMETERS OF EBW FOR WORCKPIECES WITHAUT PREHEATING

Accelerating voltage U, kV	**Welding speed V, mm/min**	**Beam current I_b, mA**	**offset**	**Focusing current I_f,mA**
60	1000	10	0,20 (steel)	1530
				1510 (surface)
				1490
60	1000	20	0,20 (steel)	1510 (surface)
60	600	1	0,20 (steel)	1510 (surface)
60	600	2	0,20 (steel)	1510 (surface)

TABLE 4 TECHNOLOGICAL PARAMETERS OF EBW FOR WORCKPIECES WITH PREHEATING

Sample	Accelerating Voltage U, kV	Focusing current I_f, mA	Welding speed V, mm/min	Beam current, I_b, mA	Offset mm	Radius of oscillation r_{osc}, mm
1	60	1510 (surface)	400	10	0,2 (steel)	0
2			400	20		0
3			400	10		0,15
4			400	20		0,15

The pre-heating of the blanks was carried out in a PEK-4 chamber furnace with the heating mode specified in table 5.

TABLE 5 HEATING MODE FOR CADI AND 316L BLANKS

Preheating, t°C	Retention time in the vacuum chamber after EBW, min	Removal temperature, °C
340	5	90

C. Microstructure analysis

To carry out a qualitative and quantitative analysis regarding the monolithic compound created after EBW, a microstructural analysis was carried out, including making a macro- and micro-analysis. For this purpose, all welded samples were cut along the cross-section of the seam and microsections were made using a standard methodology. They were sanded manually using sandpapers of different sizes from 500 to 2500 mm, then polished with DiaMax diamond paste and developed with 4% solution of picric acid in ethyl alcohol. Then an electron microscope was used to determine the depth of the resulting weld seam and the presence of defects. The Vickers microhardness of some of the samples was determined with DURAMIN-40 AC3.

III. RESULTS AND DISCUSSION

A. For samples without preheating before EBW

After welding this group of samples and using the modes indicated in Table 3, the following observations were made: for the samples with a current of 1 and 2 mA, no monolithic joint was obtained, and for the remaining samples with a current of 10 mA and 20 mA, a monolithic joint was obtained, but it was of a small depth ranging from 3-5 mm regardless of whether the Focusing current If was above, along and below the surface of the workpiece. This confirms the fact that it is advisable to preheat dissimilar materials before EBW. For these reasons, the need to determine the microhardness of this group of samples is eliminated.

B. For samples with preheating before EBW

In the second group of samples, which were subjected to preheating after electron beam welding, a monolithic joint was obtained. After cutting them in cross-section, the expected greatest depth of the weld seam was measured in samples with numbers №2 and №4, for which the magnitude of Beam current was I_b=20mA.

Vickers microhardness was measured near the surface of the weld on all specimens in this group with a loading force of 0.1N (Figure 3). The results obtained are grouped in two figures, as follows: Figure 4 - results of the measured microhardness of welded materials with a Beam current of I_b=10mA and Figure 5 - results of the measured microhardness of welded materials with a Beam current of I_b=20mA.

The figures show that the nature of the microhardness distribution is almost the same. As expected in the HAZ (in green in the figures) the measured microhardness is higher than that of the materials. The heterogeneous measured values are from the CADI side and are due to its composition. The reason for the nature of the microhardness distribution is that the appearance of brittle intermetallic compounds in the HAZ and FZ of the weld seam is possible. The measured maximum values are: for Sample 1 – 450 $HV_{0,1}$, Sample 2 - 422 $HV_{0,1}$, Sample 3 - 360 $HV_{0,1}$ and Sample 4 - 460 $HV_{0,1}$.

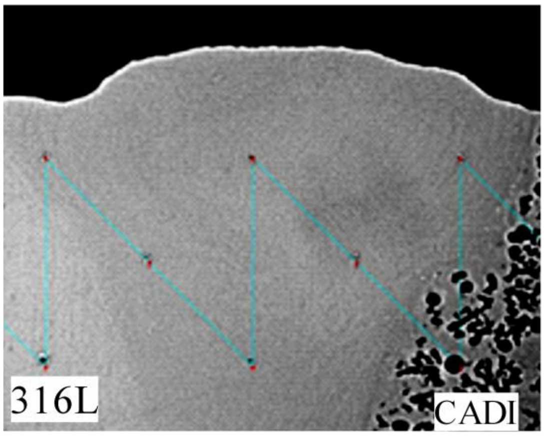

Fig. 2 Vickers microhardness measurement of specimen No. 4.

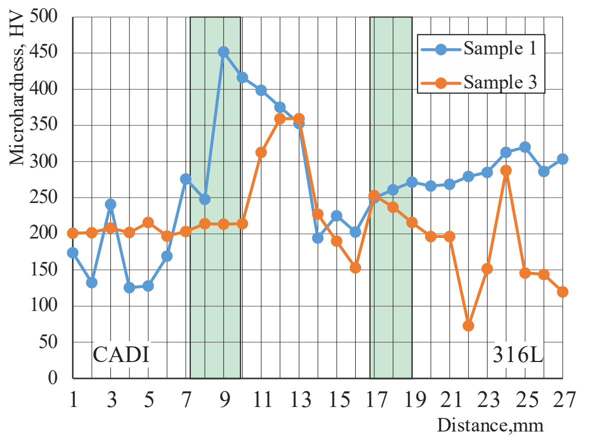

Fig. 3 Measured microhardness of electron beam welded samples with Beam current I_b=10mA.

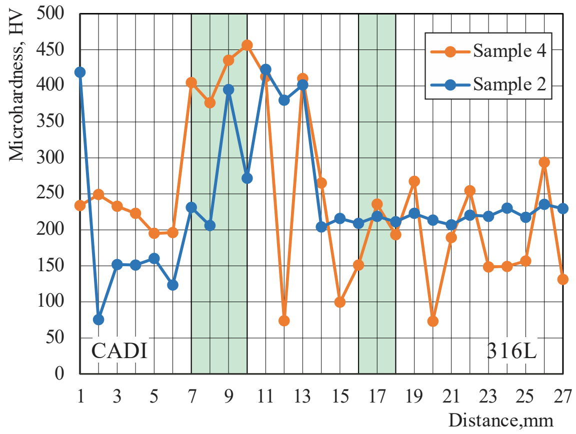

Fig. 4 Measured microhardness of electron beam welded samples with Beam current I_b=20mA.

From the macro analysis made regarding the presence of defects, defects were found only in the form of hollows, which are located near the root of the seam. The Depth of Penetration (H) of the seam was measured, with the largest being 10mm in sample No. 4, which was welded with a Beam current of I_b=20mA but also had oscillation with Radius of oscillation r_{osc}=0.15mm.

IV. Conclusions

Electron beam welding of dissimilar materials austenitic stainless steel AISI 316L and Carbidic austempered ductile irons (CADI) was performed. Two cases of welding were selected - with and without preheating the workpieces. EBW is performed with different magnitude of Beam current.

The following conclusions and recommendations can be made from the obtained results for electron beam welding of dissimilar materials:

- Despite the fact that a large part of the literature recommends that welding of cast iron be performed with a combination of preheating and the use of conventional welding methods with pure nickel electrodes, a defect-free monolithic joint is obtained, albeit with a small seam depth of penetration H=5 mm at a beam current I_b= 20 mA;
- When preheating the blanks, a monolithic joint is obtained in cases where a oscillation radius r_{osc}=0.15mm is used at beam current of I_b=10mA and I_b=20mA. A maximum depth of penetration 10 mm of the weld seam was achieved at a current of 20 mA.
- In some of the welds obtained in the second case of electron beam welding, a incomplete penetration was formed at the end of the weld. The probable reasons for this are both poor pressing of the parts against each other and insufficient preheating temperature.
- The Vickers microhardness of all samples was measured in both heat affected zones (HAZ) and fusion zone (FZ). In the HAZ it has an average value of 214 $HV_{0,1}$ to 423 $HV_{0,1}$ for CADI and from 257 $HV_{0,1}$ to 274 $HV_{0,1}$ for 316L, and in the FZ - from 336 $HV_{0,1}$ to 401 $HV_{0,1}$.

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