ELECTRON BEAM WELDING of AlCoCrFeNi2.1 EUTECTIC HIGH-ENTROPY ALLOY

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Abstract

Eutectic high-entropy alloys have become a significantly studied type of material due to their combination of strength and ductility. However, previous research has focused primarily on manufacture, solidification behaviour and mechanical properties. Only a small part of the research has been devoted to welding. This paper is focused on evaluating the weldability of eutectic high-entropy alloy AlCoCrFeNi2.1 in the as-cast state without further heat treatment. The electron beam welding process was performed twice at the same parameters, except for the beam current. Properties such as the depth of the remelted layer, the formation of the heat-affected zone, and the presence of undesirable defects in the welded joints were observed using light and electron microscopy. At the same time, material properties in the form of microstructural stability, chemical composition, and hardness of the welded joints were evaluated.

Keywords: AlCoCrFeNi2.1, electron beam welding, eutectic high-entropy alloys, microstructure

1. INTRODUCTION

High-entropy alloys (HEAs) have gained increased attention from the scientific community in recent years because of their improved selected properties compared to conventionally produced alloys. The original intention was to create a single-phase alloy composed of five or more elements with a predefined amount (5-35 at%), in which intermetallic compounds would not be formed due to favourable configurational entropy. However, the concept has proven to be challenging, as single-phase HEAs exhibit the presence of more than one phase after heat treatment or mechanical stress at elevated temperatures. This fact does not have to be taken as negative, as the presence of another phase may, under certain conditions, mean an additional improvement in the properties of the material. Multiphase alloys include, but are not limited to, eutectic high-entropy alloys (EHEAs) [1,2].

Eutectic high-entropy alloys are promising materials combining increased mechanical properties and sufficient ductility of the material. They contain primary transition metals Co, Cr, Cu, Fe, and Mn supplemented by additional substitution or interstitial chemical elements. In addition to the increased mechanical properties at a wide range of temperatures [3, 4], they are also characterized by excellent castability, which increases their potential in terms of future applications in industry. One of these alloys is AlCoCrFeNi2.1, whose eutectic consists of a lamellar structure of ductile FCC and hard B2 phases [1,2].

One of the other criteria to judge whether a new alloy is suitable for industrial use is weldability [5,6]. Electron beam welding is a progressive technology that uses a high energy density of electrons accelerated by high voltage. The beam power can be estimated as the product of the beam acceleration voltage and the beam current. The entire welding process takes place in a vacuum chamber, which ensures that the high energy density of the beam is maintained and at the same time prevents the chemical reaction of the welded piece with the atmosphere at elevated temperature. It is used primarily in industries with increased demands on the homogeneity of the welded joint, mechanical properties and the absence of defects. Therefore, this method is also suitable for the material we have chosen [7,8].

The aim of the study was an evaluation of the weldability of the eutectic alloy AlCoCrFeNi2.1, using:

- observation of macroscopic parameters such as the depth of remelting at given process parameters, the formation of a heat-affected zone or the presence of defects,
- determination of the resulting microstructure and mechanical properties based on the selected welding parameters.

2. MATERIALS AND RESEARCH METHODOLOGY

The AlCoCrFeNi2.1 alloy was produced by remelting different type of alloy with the primary content of four basic elements Co, Cr, Fe and Ni with the highest proportion of chromium. Therefore, the other elements, together with the aluminium, were doped as needed. The melting took place in a miniature induction furnace Indutherm MC 15 under reduced pressure in a chamber filled with argon. The ideal and final composition of the alloy in at% are shown in **Table 1**. The presence of silicon in the base material is due to the remelting of the recycled alloy described in the previous lines. The casting resulted in a cylindrical ingot which, after machining, acquired a diameter of 14 mm and a height of 28 mm.

Table 1 Comparison of the ideal and final chemical composition of the AlCoCrFeNi2.1 alloy

Composition	**Elements (at%)**					
	Al	**Co**	**Cr**	**Fe**	**Ni**	**Si**
Ideal	16.4	16.4	16.4	16.4	34.4	-
Final	17.6	16.5	14.7	16.6	33.6	1.2

The main part of the experiment consisted of remelting sample using a micro electron beam welder MEBW-60/2-E. Despite the fact that it is a remelting of the material, the term welding is also used in the following text. The reason is the similarity in shape with the welded joint and the associated simplification of the issue. The device has a fully digital control with a maximum beam power of 2 kW and an accelerating voltage of 60 kV. The sample manipulation has two degrees of freedom: linear movement along the vertical axis and rotation about the same axis. This is suitable for welding cylindrical parts similar in shape to our cast samples. The working pressure was better than 4×10^{-4} Pa during the welding process. In total, the alloy was remelted twice in separate circuits and the parameters are shown in **Table 2.**

Table 2 Parameters of AlCoCrFeNi2.1 electron beam welding

Process label	**Parameters of welding**				
	Beam current (mA)	**Accelerating voltage (kV)**	**Welding speed (mm/s)**	**Focus current (mA)**	**Heat input (J/mm)**
FZ 1	5	55	10	750	27.5
FZ 2	10	55	10	750	55

The processed sample microstructure was then observed and evaluated. The sample was cut with a metallographic saw and prepared by grinding and polishing processes. An etchant containing 15 ml of H_2O, 4 ml of HF, and 1 ml of HNO_3 was used to etch the resulting microstructure. The sample was soaked in the etchant for about 5 seconds. A light microscope (Zeiss Axio Observer 7) was used to observe the macro- and microstructure, followed by observation and chemical analysis in an electron microscope (FEG SEM Zeiss Ultra Plus). Mechanical properties were verified by a Vickers hardness test (Qness Q10A) with a load of 0.2 kg and an indentation time of 10 s.

3. RESULTS AND DISCUSSION

The experiments in this paper were carried out to evaluate selected parameters and projected functionality of welded joints with materials engineering methods that include macroscopical and microscopical observation, hardness of fusion welded metal, and its chemical composition.

In **Figure 1**, we can see the macroscopic image of the sample FZ 1 (5 mA) with the hardness measurement path indicated at the top of the area. The remelted area has a cross-section shape typical for e-beam welding, visibly surrounded by a heat-affected zone highlighted by effective etching. The width of the remelted area is approximately 1.6 mm wide and 1.55 mm deep. The microstructure consists of an equiaxial fine-grained structure leading to the centre. However, in terms of functionality, the mechanical properties of the eventual weld will be affected by a pore located in the centre. The presence of the defect is probably caused by the trapped gas from the root of the joint. After the material has been melted and partially evaporated, the evaporated gases in the area behind the passing electron beam escape towards the surface and at the same time the molten material solidifies. If the solidification rate is too high, certain gas particles do not have enough time to move to the surface and will remain trapped in the cooled structure of the weld. Therefore, whether a given defect occurs in the welded joint can be partially influenced by the process parameters which will be part of the future experiments.

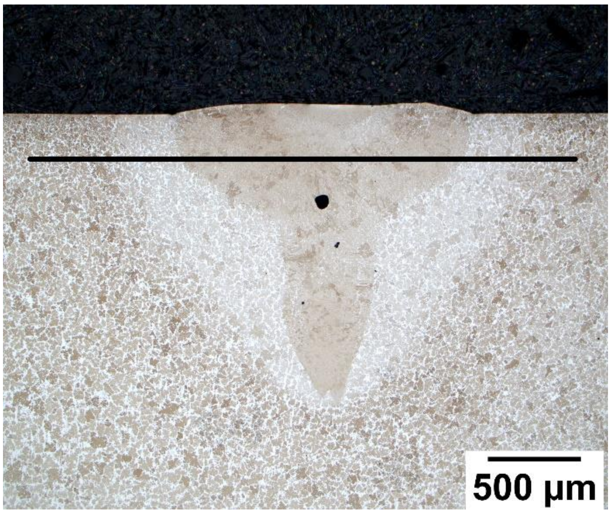

Figure 1 Welding joint FZ 1

Figure 2 Welding joint FZ 2

The sample marked as FZ 2 (10 mA) with a marked hardness measurement path is shown in **Figure 2**. It is clear from the figure that remelted area has a similar shape as the previous sample, together with a heat-affected zone and a fine-grained structure facing the centre of the weld. However, the upper part of the weld joint is visibly formed by dendrites similar to the base material. Due to the higher power of the beam, a welded joint was formed with a width in the upper area of 1.8 mm and a depth of the remelted layer of 3.9 mm. The measured geometric dimensions and the size of the heat-affected zone FZ 1 and FZ 2 therefore prove a nonlinear dependence between the welding parameters and the dimensions of the welded joint. At the same time, it can be stated that the high-entropy alloy proved from a macroscopic point of view a good degree of weldability and the correctness of selected parameters in the case of the welded joint FZ 2.

The next step was electron microscope observation and subsequent chemical analysis, to which selected areas of the weld FZ 1 (**Figure 3**) and FZ 2 (**Figure 4**) were subjected. The analysis confirmed the presence of a dual-phase dendritic structure, where one phase contains an increased amount of chemical elements Al and Ni, and the other phase has an increased amount of Co, Cr, Fe and Ni. At the same time, the presence of Si was detected evenly distributed on the entire surface of the studied area. Its presence has already been confirmed in a previous chemical analysis of the base material. The influence of silicon on the weldability of a given alloy has not been investigated due to the broad scope of the topic. However, due to its widespread use in metallurgy and its likely presence in remelted materials used for casting high-entropy alloys, it opens up a new area for future research.

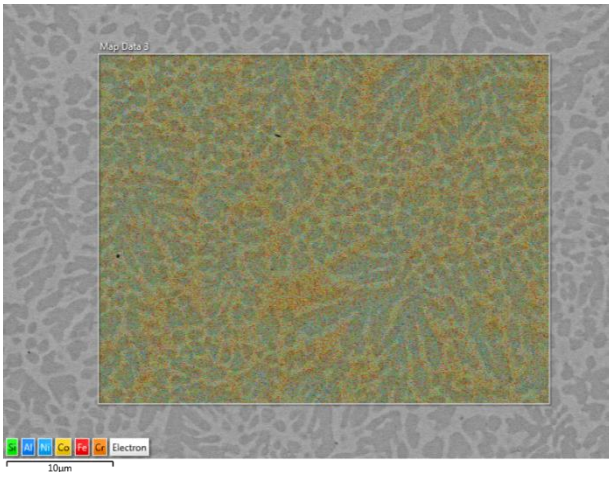

Figure 3 Chemical analysis of sample FZ 1

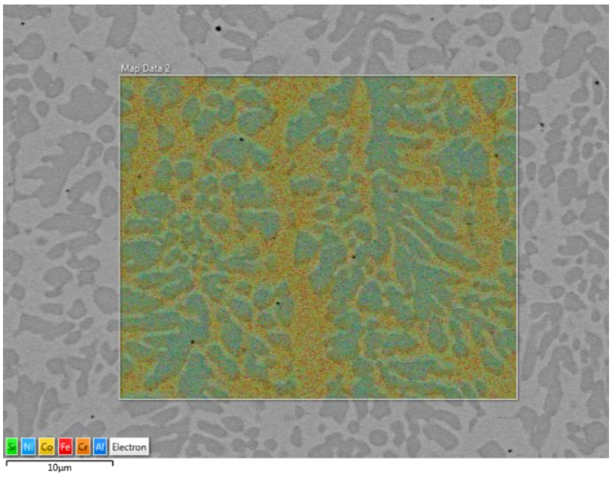

Figure 4 Chemical analysis of sample FZ 2

Subsequent point analysis performed at several places of both mentioned phases not only confirmed the presence of elements, but also quantified their amount in at%. Individual values of representation in FZ 1 and FZ 2 are written as average values of several experimental measurements (**Table 3**).

Table 3 Chemical composition of the phases present in the weld

Chemical elements	**Phase 1 (Al, Ni rich)**		**Phase 2 (Co, Cr, Fe, Ni rich)**	
	FZ 1 (at%)	**FZ 2 (at%)**	**FZ 1 (at%)**	**FZ 2 (at%)**
Al	21.7	21.8	11.1	11.6
Co	15.7	15.6	18.4	18.4
Cr	11.8	11.5	18.2	17.8
Fe	14.7	14.5	20.0	19.6
Ni	35.0	35.5	31.1	31.4
Si	1.1	1.1	1.2	1.2

Overall chemical analysis shows that the AlCoCrFeNi2.1 alloy meets the conditions for good weldability. The microstructure of both welded joints consists primarily of two phases with a maximum difference of 0.5 at% in case of identical phases. At the same time, compared to the base material, there was no visible precipitation of the chromium-based phase due to the rapid cooling of the remelted material.

The last part of the experiment was to verify the hardness of both welded surfaces (FZ 1 and FZ 2) and the base material (BM). The hardness was measured at the top, middle, and bottom of the welds to ensure sufficient data and verification of hardness throughout the remelting depth. However, due to the fact that the measured areas do not differ significantly from each other, the resulting plot (**Figure 5**) includes values from the top of the remelted areas for better clarity. The individual measurement paths are indicated in **Figure 1** and **Figure 2**.

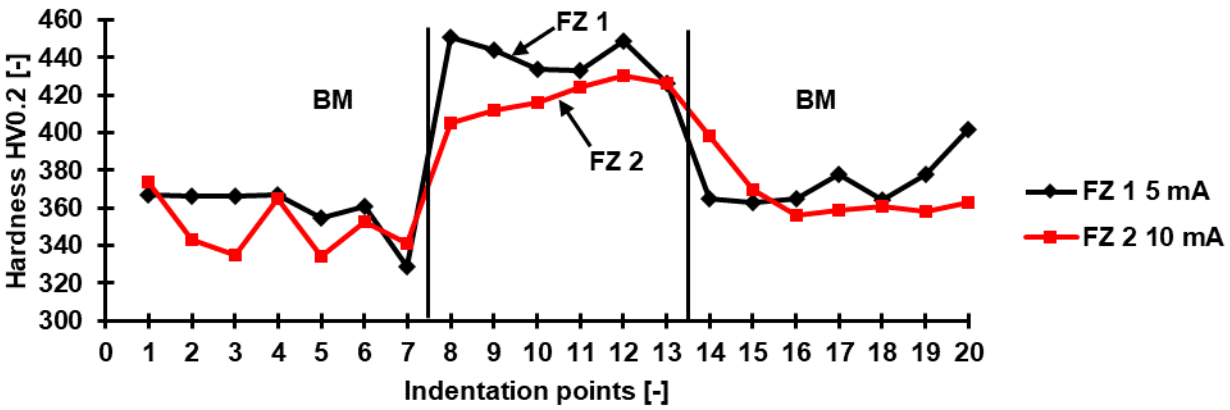

Figure 5 Hardness values of the base materials and the fusion zone

It is clear from the stated values that in both cases of remelting the hardness of the material increased. This fact confirms the appearance of fine-grained microstructure inside of welded joints. For a closer comparison, weld FZ 1 has the highest measured hardness values. Regarding the presence of the heat affected zone, the hardness values do not indicate a significant increase in the hardness of the material compared to the base material.

Because the hardness of the welded joints is compared with the hardness of the base material, it is necessary to verify whether the values obtained are close to the eutectic high-entropy alloys used in previous experiments. In [9], Wang et al. produced an alloy of AlCoCrFeNi2.1 and improved the mechanical properties through a friction stir processing. The hardness values of the cast and treated material ranged from 300 HV0.2 to 450 HV0.2, which confirms the correctness of the measured values in our case.

4. CONCLUSION

The weldability of the eutectic high-entropy alloy AlCoCrFeNi2.1 was evaluated using electron beam welding equipment and the functionality of the possible joint was verified using materials engineering methods with the following findings:

- The FZ 1 sample contains a defect in the form of a leaking gas pore.
- The microstructure of welded joints consists of two phases in the form of fine-grained particles.
- Remelted areas have higher hardness values HV0.2 compared to the base material.
- The hardness of the heat-affected zone does not differ significantly from the hardness values of the base material.

It follows from the above that the eutectic alloy AlCoCrFeNi2.1 can be evaluated as suitable for electron beam welding purposes. The sample FZ 2 does not contain defects and, at the same time, consists of a two-phase fine-grained structure. It thus confirms appropriately selected parameters and technological properties of the material. In the case of the FZ 1 sample, its functionality is limited by the pore contained in the remelted material. However, this fact can be partially conditioned by parameters selection, and therefore, it is necessary to verify the fact in the following tests.

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