

## WELD EVALUATION OF EUTECTIC HIGH-ENTROPY ALLOY AND AUSTENITIC STEEL FORMED BY EBW

Ján RONČÁK, Patrik JOZEFOVIČ, Martin ZOBAČ

*Institute of Scientific Instruments of the CAS, Brno, Czech Republic, EU, [roncak@isibrno.cz](mailto:roncak@isibrno.cz)*

<https://doi.org/10.37904/metal.2024.4905>

### Abstract

AlCoCrFeNi<sub>2.1</sub> alloy belongs to a group of materials called eutectic high-entropy alloys (EHEAs). These have gained attention due to the fact that there is no so-called "strength ductility trade-off". At the same time, the material properties are stable over a wide temperature range due to the high entropy state of the eutectic structure. The generally good castability of eutectic alloys, which prevents segregation of the major chemical elements and precipitation of new phases, also extends the possibilities for future applications. Based on the above, AlCoCrFeNi<sub>2.1</sub> alloy could be applied in critical structural locations subjected to severe conditions in terms of elevated temperatures and mechanical stresses. Alloy could replace, for example, austenitic steels with high ductility but lower tensile strength values. In order to make full use of a given material, its behaviour must be verified in bonding technologies with commercially used materials. Therefore, the following research deals with heterogeneous weld joints of AlCoCrFeNi<sub>2.1</sub> with austenitic steel EN 1.4571 formed by electron beam welding. The evaluation of the weld consisted of observation of the resulting microstructure, determination of the chemical concentration of the elements in the fusion zone, phase analysis followed by mechanical properties testing in the form of Vickers hardness test and tensile test.

**Keywords:** AlCoCrFeNi<sub>2.1</sub>, eutectic high-entropy alloy, austenitic steel, electron beam welding

### 1. INTRODUCTION

Eutectic high-entropy alloys (EHEAs), popularised by Lu et al. [1] in 2014, were intended to extend the existing family of high-entropy alloys (HEAs). This is because the pre-existing alloys, in most cases, contained a single-phase structure guaranteeing high strength or ductility without the possibility of combining them. At the same time, the aim was to take advantage of the good castability of eutectic alloys in general and thus expand the possibilities of their future applicability. Together with the concept of EHEAs, the alloy AlCoCrFeNi<sub>2.1</sub> was introduced. The complex name is derived from the atomic ratio of the chemical elements. Its microstructure is formed by a lamellar eutectic containing a strength guaranteeing B2 phase (containing mostly Al and Ni) and a ductile FCC L<sub>12</sub> phase (enriched primarily in Co, Cr, Fe and also Ni). As a result, it is possible to achieve a tensile strength of 944 MPa with a ductility of 25,6 % at room temperature. The high entropy of the system should keep the microstructure and associated properties stable over a wide temperature range [2–4].

The limitation of the application of AlCoCrFeNi<sub>2.1</sub> alloy in large series production or larger volumes is the high cost of the elements needed to achieve the desired mechanical properties. The alloy can therefore be part of the thermally and mechanically stressed parts of the structure instead of forming the whole volume. To do this, it is necessary to verify how AlCoCrFeNi<sub>2.1</sub> behaves when bonded to commercially used materials. Previous research on HEAs in joining [5, 6] has focused on austenitic steels characterised by their high ductility but low strength. One of the steels, whose strength and microstructural stability at elevated temperatures is enhanced by alloying titanium, is 1.4571. Titanium reacts with carbon and nitrogen, which in turn stabilises the matrix formed by austenite and prevents intergranular corrosion [7].

Technologies used to form joints include electron beam welding. The technology involves accelerating electrons incident on the surface of the material to be welded, converting kinetic energy into thermal energy and forming a non-separable fusion joint. It is characterised by low heat input, small heat affected area and high variability in terms of weld depth [8, 9].

The paper deals with the electron beam welding of EHEA AlCoCrFeNi2.1 alloy with austenitic steel 1.4571 and the evaluation of the selected weld joints by materials engineering methods.

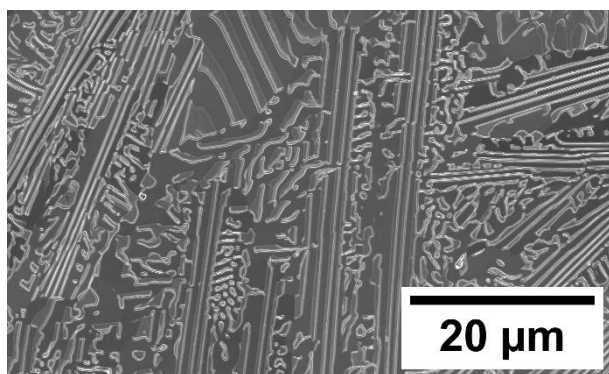
## 2. MATERIALS

The AlCoCrFeNi2.1 alloy was produced using an Indutherm MC15 vacuum induction furnace. The inside of the chamber was filled with argon in order to limit oxidation of the melt. Pure metals were used for fabrication with the weight ratios listed in **Table 1**. Despite the name of the alloy being derived from the atomic ratio of the elements represented, the indication of the elements in wt% follows the established methodology in metallurgy and also simplifies the comparison with commercially used austenitic steel. Other results are also interpreted using wt%.

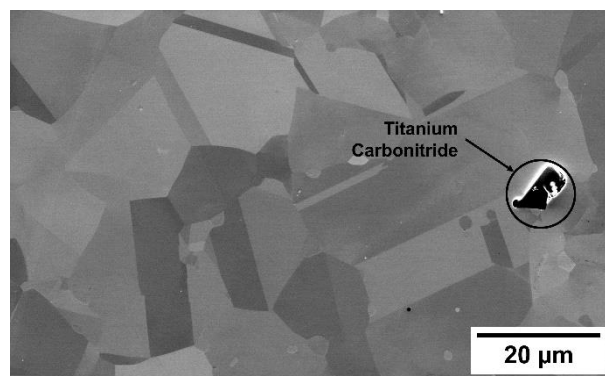
**Table 1** Chemical composition of AlCoCrFeNi2.1 EHEA and 1.4571 austenitic steel

Alloy	Chemical elements (wt%)							
	Al	Co	Cr	Fe	Ni	Ti	Mo	Mn
AlCoCrFeNi2.1	8.7	18.0	17.7	17.1	38.7	-	-	-
1.4571	-	0.2	16.8	Balance	10.6	0.3	2.0	2.0

The microstructure of AlCoCrFeNi2.1 (**Figure 1**) is formed by a lamellar eutectic containing FCC (Co, Cr and Fe rich) and BCC (Al, Ni rich) phases confirmed by EBSD measurements. In terms of microstructure (**Figure 2**), steel 1.4571 is formed by FCC austenitic grains and titanium carbonitrides enhancing corrosion resistance at high temperatures.



**Figure 1** Microstructure of AlCoCrFeNi2.1



**Figure 2** Microstructure of 1.4571

## 3. WELDING PARAMETERS AND METHODOLOGY

The base materials were machined into a cylindrical shape with a diameter of 14 mm. By creating a pin on the eutectic alloy and a hole on the austenitic steel, it was possible to coaxially align the samples. Subsequently, a circumferential weld was formed at their interface. The welding was carried out in the vacuum chamber of an electron beam welding machine with a maximum power of 2 kW at an accelerating voltage of 60 kV. The working pressure was kept below  $4 \times 10^{-2}$  Pa throughout the process. To comprehensively evaluate the behavior of the heterogeneous joints, welds were performed using several parameters differing primarily in welding current and welding speed (**Table 2**). All joints exhibited similar chemical and phase compositions.

The difference was in the mechanical properties, where fracture occurred outside the joint using parameters marked FZ 1. The paper therefore discusses the properties associated with the aforementioned welded joint.

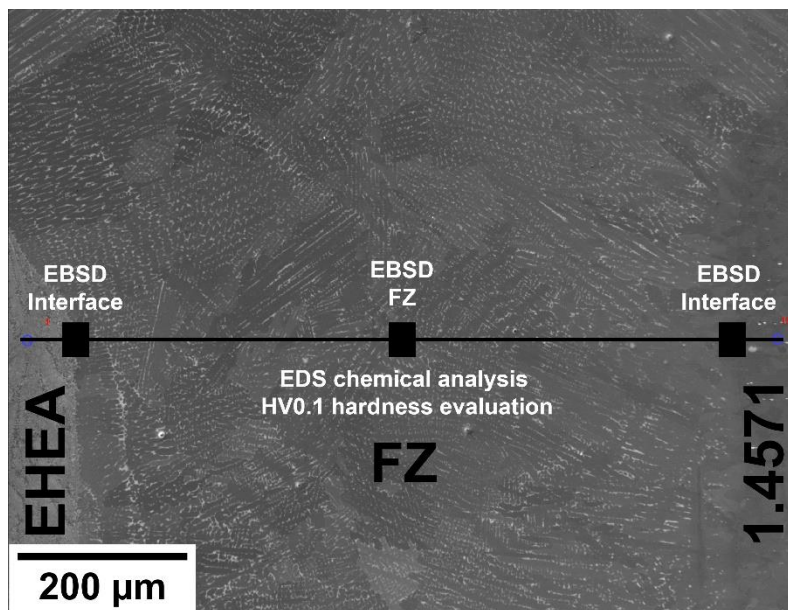
**Table 2** Parameters of AlCoCrFeNi2.1 and 1.4571 electron beam welding

Process label	Parameters of welding				
	Beam current (mA)	Accelerating voltage (kV)	Welding speed (mm/s)	Focus current (mA)	Heat input (J/mm)
FZ 1	13	55	10	738	71.5
FZ 2	17	55	20	743	46.8
FZ 3	25	55	30	747	45.8

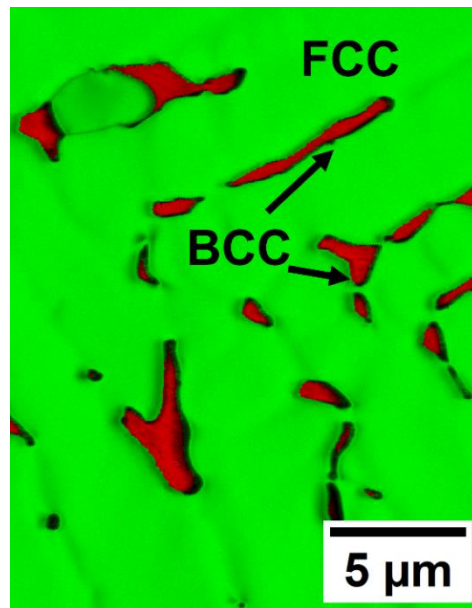
The welds were processed in a metallographic laboratory and electrolytically polished using a commercially available etchant A2 from Struers. Microstructure observations were performed using a Magellan 400 electron microscope (Thermofisher Scientific) along with line EDX analyses and EBSD phase compositions. The hardness of the material was measured by the Vickers test with a load of 0.1 kg for 10 s. The tensile strength is determined for a 5 mm diameter, 40 mm long body as a function of the stress on the displacement of the crosshead.

#### 4. RESULTS AND DISCUSSION

**Figure 3** shows the upper part of the weld area created using the FZ 1 parameters. The figure also shows the approximate locations of the phase analysis, in-line chemical analysis and hardness measurement HV0.1. Remelted region is dominated by dendritic grains (darker areas) with the FCC crystalline lattice extending from the base material to the centre of the weld. The inter-dendritic regions formed by the phase with BCC crystalline lattice (light areas) fill the rest of the volume. The proportion of the FCC phase depicted by the green colour in **Figure 4** is approximately 96 % (the rest is created by the BCC phase). Observation of the weld did not reveal the presence of macroscopic defects.

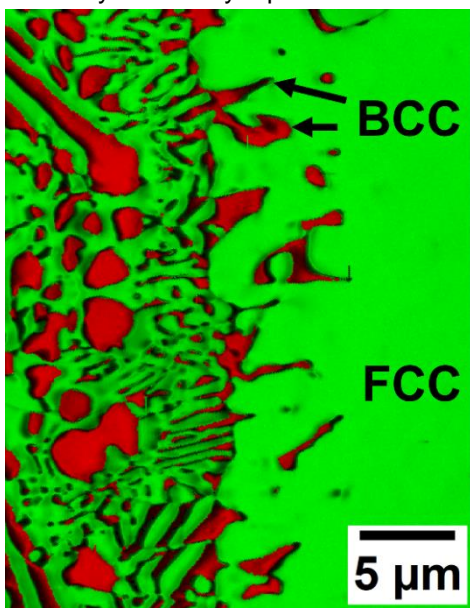


**Figure 3** Macrostructure of the welded joint with marked areas of analyses

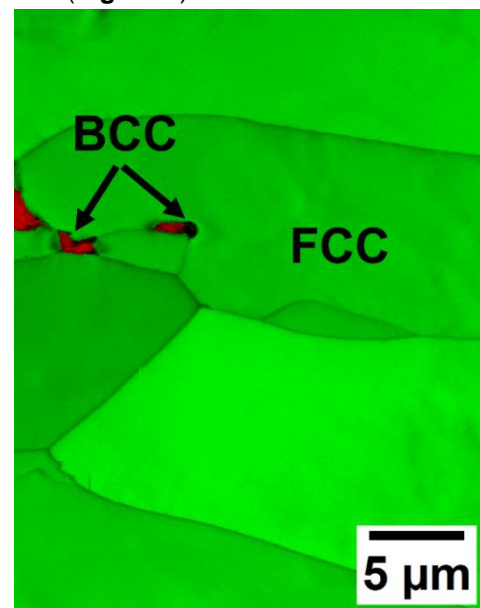


**Figure 4** Phase composition of the welded joint

The interfaces between the base materials and the weld joint differ not only from each other, but also compared to the inside of the remelted area. The interface at AlCoCrFeNi<sub>2.1</sub> consists of fine-grained lamellae pointing into the welded joint (**Figure 5**). On the opposite side, the transition between the austenitic steel and the weld joint is smoothly formed by a phase with FCC crystalline structure (**Figure 6**).

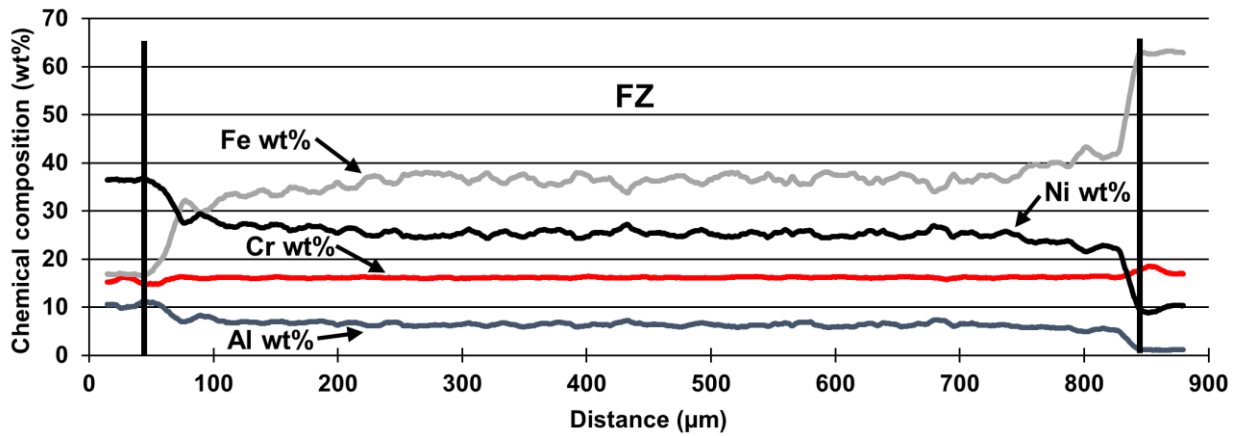


**Figure 5** Phase composition of the EHEA/FZ interface



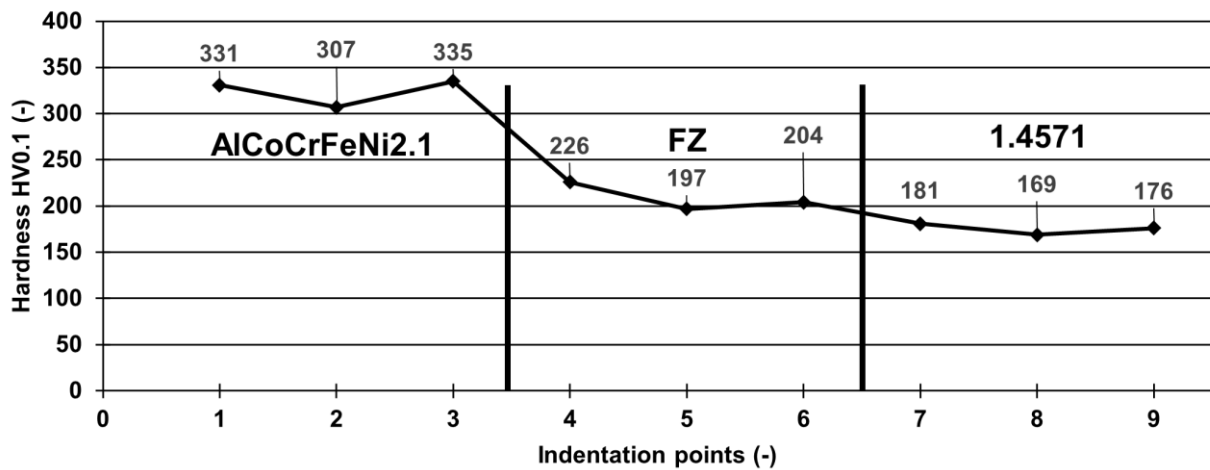
**Figure 6** Phase composition of the 1.4571/FZ interface

The narrow region formed by the FCC phase can be further observed in the remelted area near the interface. EDS line analysis (**Figure 7**) proved significant changes in the concentration of chemical elements at the locations. Thus, the FCC region in the welded joint from both sides is the result of line mixing of materials with complex chemical element contents. In terms of chemical composition, chromium is homogeneously distributed from one interface to the other. On the contrary, concentration of nickel and aluminium decreases in locations with elevated iron concentrations and vice versa. A similar phenomenon takes place in the base material AlCoCrFeNi<sub>2.1</sub>, where the BCC phase is enriched in Al and Ni due to the favourable mixing enthalpy of the elements [2].



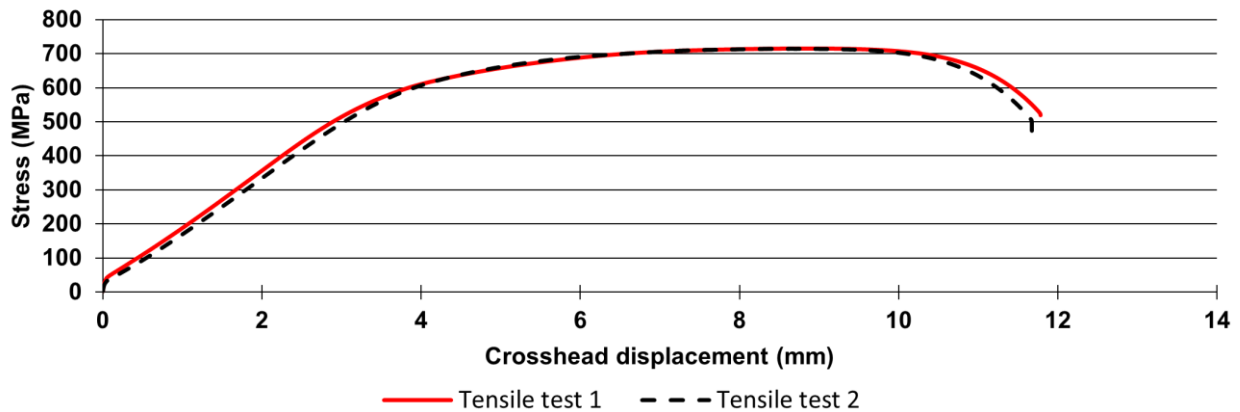
**Figure 7** EDS line chemical analysis indicated in **Figure 4**

The resulting hardness of HV0.1 is shown in **Figure 8**. The hardness of the welded joint is within the range of values of the base materials, outperforming austenitic steel. The increased hardness is probably due to the presence of a BCC phase strengthening the weld joint.



**Figure 8** HV0.1 hardness measurement in the chemical analysis line

In the case of tensile properties of the material (**Figure 9**), the weld exhibited better tensile strength compared to 1.4571 in addition to increased hardness. Thus, in both cases there was a necking and subsequent fracture in the base material of 1.4571.



**Figure 9** Tensile test results of a heterogeneous joint

## 5. CONCLUSION

Electron beam welding of heterogeneous EHEA AlCoCrFeNi<sub>2.1</sub> and 1.4571 joints were performed using parameters varying in beam current and welding speed with the following findings:

- The weld joint is primarily formed by a dendritic structure with an FCC crystalline lattice. The remainder consists of a hard phase with a BCC lattice.
- The metallographic samples did not contain any macroscopic defects.
- Chemical analysis confirmed sufficient mixing of both base materials.
- The chemical composition gradients observed at the interface of the base material and the weld joint resulted in a narrow region formed by the FCC phase.
- In terms of mechanical properties, the welded joint achieved the best mechanical properties using a welding current of 13 mA and a welding speed of 10 mm/s.

Based on the experimental results, it can be concluded that with the selected parameters it is possible to weld the given combination of materials without complications. The welds formed differed only minimally in terms of microstructure, chemical concentration and phase composition. The main difference was thus achieved tensile strength. Further research will focus on the changes in microstructure and mechanical properties with long-term exposure to elevated temperatures.

## ACKNOWLEDGEMENTS

*The paper was created with the institutional support RVO:68081731.*

## REFERENCES

- [1] LU, Y., DONG, Y., JIANG, H., WANG, Z., CAO, Z., GUO, S., WANG, T., LI, T., LIAW, P.K. A promising new class of high-temperature alloys: Eutectic high-entropy alloys. *Scientific Reports*. 2014, vol. 4, DOI: 10.1038/srep06200
- [2] MURTY, B. S., YEH, J. W., RANGANATHAN, S., BHATTARCHARJEE, P. P. *High-entropy alloys*. Amsterdam: Elsevier, 2019. ISBN 978-012-816067-1.
- [3] JIAO, Z., YANG, T. *Advanced multicomponent alloys: From fundamentals to applications*. Singapore: Springer, 2022. ISBN 978-981-19-4743-8.
- [4] BAKER, I., WU, M., WANG, Z. Eutectic/eutectoid multi-principle component alloys: A review. *Materials Characterization*. 2019, vol. 147, pp. 545-557. <https://doi.org/10.1016/j.matchar.2018.07.030>.
- [5] OLIVEIRA, J. P., SHEN, J., ZENG, Z., PARK, J. M., CHOI, Y. T., SCHELL, N., MAAWAD, E., ZHOU, N., KIM, H. S. Dissimilar laser welding of a CoCrFeMnNi high entropy alloy to 316 stainless steel. *Scripta Materialia*. 2022, vol. 206. DOI: <https://doi.org/10.1016/j.scriptamat.2021.114219>.
- [6] SOKKALINGAM, R., MASTANAIAH, P., MUTHUPANDI, V., SIVAPRASAD, K., PRASHANTH, K. G. Electron-beam welding of high-entropy alloy and stainless steel: microstructure and mechanical properties. *Materials and Manufacturing Processes*. 2020. DOI: <https://doi.org/10.1080/10426914.2020.1802045>.
- [7] BRNIC, J., TURKALJ, G., CANADIJA, M., LANC, D. AISI 316Ti (1.4571) steel – Mechanical, creep and fracture properties versus temperature. *Journal of Constructional Steel Research*. 2011, vol. 67, pp. 1948-1952. DOI: 10.1016/j.jcsr.2011.06.011.
- [8] PATTERSON, J., HOCHANADEL, J., SUTTON, S., PANTON, B., LIPPOLD, J. A review of high energy density beam processes for welding and additive manufacturing applications. *Welding in the World*. 2021, vol. 65, pp. 1235-1306. DOI: <https://doi.org/10.1007/s40194-021-01116-0>.
- [9] WEGLOWSKI, M. ST., BLACHA, S., PHILLIPS, A. Electron beam welding – Techniques and trends – Review. *Vacuum*. 2016, vol. 130, pp. 72-92. DOI: <http://dx.doi.org/10.1016/j.vacuum.2016.05.004>.