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# Welding of copper and 304L stainless steel with continuous electron beam

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The electron beam welding (EBW) is one of the few technologies that allow welding of materials with different thermophysical characteristics. This paper presents the results of the study of the structure and the mechanical properties of electron beam welded samples of copper and stainless steel. The samples were welded with different source power, changing the beam current. The specimens were examined by X-ray diffraction and scanning electron microscopy. They were also subjected to mechanical tests, such as hardness and tensile strength measurement. The welded zone is a solid solution of copper and γ-iron with inclusions of pure copper and a small amount of α-iron. Higher values of the beam power lead to finer microstructure of the weld. It was found that an increase in the beam power leads to improvement in the mechanical properties.

**Keywords:** electron beam welding, dissimilar materials, copper, stainless steel

Many methods and techniques were developed for joining of similar materials [1-3]. However, more and more often in practice there is a need for welding of dissimilar materials. Heavy all-steel structures are being replaced by lighter ones containing welded steel parts with copper, aluminium, titanium, etc., leading to energy savings and improved mechanical properties. Complex joints of different materials are used in a number of industries such as automotive, shipping and aerospace [4]. Obtaining a strong compound of two materials with very different thermophysical properties and behavior is a difficult task and a real challenge for scientists and engineers.

Studies of welds of copper and stainless steel produced *via* explosion welding [5, 6], laser welding [7-9], and electron beam welding [10, 11] are reported. The authors of [5] summarized the possibilities of joining the similar and dissimilar materials by explosive welding. They discussed the joining of copper to steel with respect to the technological conditions. The intermetallic phases were not found in the investigations [6]. The analysis shows that diffusion did not take place between bonding plates, and diffusion was observed after annealing of the bonded samples [5, 6]. The laser welding is widely studied and used in practice. It allows joining of materials with tiny geometry and different optical and thermal properties. The authors of [8] investigated the influence of the laser process conditions on the properties of the copper-stainless steel welds. The joining mode was transformed to welding-brazing from fusion welding. The welding-brazing mode joins liquid stainless steel to solid copper, whereas the fusion zone mode joins stainless steel and copper by melting and mixing both metals. The melting of the copper can be effectively suppressed by offsetting and inclining the laser beam to the stainless steel. The microstructure and the tensile characteristics of EBW and TIG welded samples of copper and stainless steel were compared in [9]. It is marked that the main advantages of EBW in the case of dissimilar metal joints are lack of fusion, lack of penetration and no heat loss which in turn improves the weld quality. EBW of copper and three kinds of austenitic stainless steel was presented in [10]. The authors reported a complex heterogeneous fusion zone with porosity and microfissures due to the process with rapid cooling and poor mixing of the materials and due to the geometry parameters. They draw the conclusion that dissimilar metal welding can be very critical and sound welds can be obtained only if an accurate optimisation of the process parameters is performed. EBW with beam oscillation improves the mechanical properties of the copper-stainless steel welds in comparison with non-oscillating beam [11]. This improvement is due to the adequate mixing of copper in the welded zone and the backfilling of the microcracks on stainless steel by copper.

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However, investigations of the structure and mechanical properties of EBW of copper and 304L stainless steel, as well as of the influence of the beam power on the discussed functional properties are currently less well investigated. Therefore, this paper presents the results of the study of the structure and the mechanical properties of electron beam welded samples of copper and 304L stainless steel. The results are discussed concerning the applied technological conditions of electron-beam welding procedure.

## EXPERIMENTAL

Three kinds of welded specimens of copper and AISI 304L stainless steel (SS) with the following chemical composition (wt %): 0.03% C; 2.0% Mn; 0.75% Si; 0.045% P; 0.030% S; 17.5 – 19.5% Cr; 8.0 – 12.0% Ni; 0.10% N, were examined. The samples were flat plates with sizes of 100 × 50 × 8 mm.

Electron beam welding (EBW) was carried out on the EvoBeam Cube 400 welding machine. Fig. 1 shows the scheme of the process. The technological conditions of the EBW process were the following: accelerating voltage $U$ = 60 kV; welding speed $v$ = 0.5 cm/s; beam current $I_1$ = 30 mA (sample 1), $I_2$ = 40 mA (sample 2), and $I_3$ = 50 mA (sample 3), corresponding to a beam power of $P_1$ = 1800 W, $P_2$ = 2400 W, and $P_3$ = 3000 W, respectively. A stationary electron beam without deflection was used.

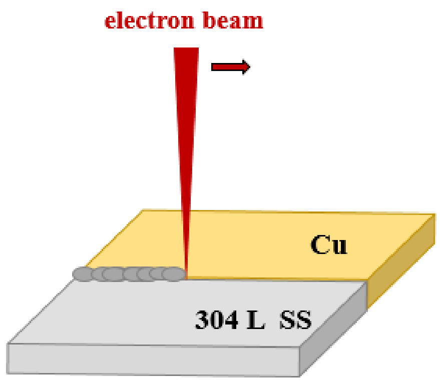


**Figure 1.** Scheme of the experiment of EBW of copper and stainless steel AISI 304L.

The phase analysis was conducted on a X-ray diffractometer "Bruker D8 Advance". The used method was "Coupled Two Theta", using Co Kα radiation with wavelength 1.78897 Å and line focus orientation. The range of the research was from 40° to 120°, the X-ray generator current was 40 mA and the used voltage was 35 kV. Other characteristics of the test were 0.05° step size and 0.25 s time for the step. The standard database used to identify diffraction peaks was Crystallography Open Database (COD).

Scanning electron microscopy (SEM) was used for the investigation of the structure of the welded specimens. Secondary electrons were employed. The distribution of chemical elements in the fusion zone and near the fusion zone was analysed by energy-dispersive X-ray spectroscopy (EDX).

The mechanical properties were investigated by a machine for static and dynamic tests ZWICK Vibrophore 100. Tensile specimens were tested, which were welded at a different power of the beam. The test was performed in accordance with the requirements of ISO 6892-1 Method B. Also, samples made of pure copper and 304 L SS were investigated for comparison.

The microhardness experiment was performed on a semi-automatic microhardness tester ZWICK/Indentec - ZHVμ-S. Metallographic cross-sections of specimens were made of welded materials in the transverse direction of the weld. The line along which the microhardness was measured was located in the middle of the weld seam. A load force of 0.49 N was used for all experimental points.

## RESULTS AND DISCUSSION

The application of the technological conditions of sample 1 lead to partial joint penetration weld, while the use of the conditions related to the specimens 2 and 3 lead to complete joint penetration depth.

In Fig. 2 the X-ray diffraction patterns of the investigated samples are shown. The XRD phase exhibits a solid solution of copper and γ-iron in the form of face-centred cubic (fcc), as well as α-iron with body-centred cubic structure (bcc). Additionally, considering the welds formed by a beam current of 30 and 40 mA, peaks corresponding to pure Cu were detected. This means that at these specimens, the copper has not been completely dissolved into the steel matrix. Prerequisites for the formation of a solid solution are the close atomic radii and the same crystal lattice of copper and γ-iron (fcc crystal structure), which is in agreement with the results obtained in the present study. The α-iron phase is formed due to the high temperature in the EBW process. The bcc phase is metastable at room temperature, and can be formed at 1200 °C. Obviously, this temperature has been obtained during the welding process, meaning that the bcc structure has been successfully formed. Also, at the electron-beam welding process, the thermal cycling gradient is very high, and the solidification behaviour is non-equilibrium. This means that metastable phases, such as the bcc structure of α-iron, can be obtained [12, 13]. It is clear that the peak corresponding to bcc phase has a different height at different technological conditions. It is highest for the sample welded by a beam c/urrent of 50 mA, and consequently this sample has the highest amount of α-iron. This could be attributed to the highest cooling rate at the EBW process. The highest value of electron beam power leads to the greatest temperature gradient. Therefore, these statements are consistent with the results obtained in our study.

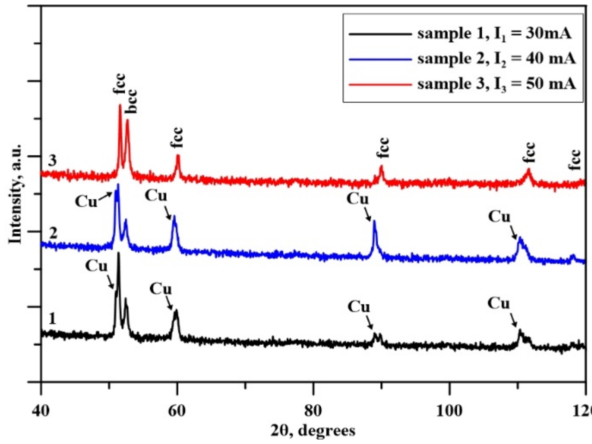


**Figure 2.** X-ray diffraction patterns of the welded joints.

In Fig. 3 cross-sectional SEM images of the welded specimen are shown. Fig. 3(a) shows the microstructure of the fusion zone of sample 1. Fig. 3 (b) presents the microstructure of the fusion zone of sample 2 and Fig. 3 (c) – the microstructure of the fusion zone of sample 3. According to the authors of [14], the increase in the beam current leads to the formation of finer microstructure of the weld. As already mentioned higher values of the discussed technological parameter cause a larger cooling rate. In the same time, the cooling rate is of significant importance for the formed weld structure, where larger values of the thermal cycling gradient lead to the formation of finer microstructure. Therefore, the highest value of the beam current leads to the largest cooling rate and the finest microstructure. These statements are completely in agreement with our results.

The results of the tensile test of welded samples of copper and steel are presented in Table 1. Tensile experiments were also carried out of pure copper and 304 L SS for comparison. As already mentioned, for sample 1 the beam power is not enough to form a complete joint penetration depth of the welded plates. This affects the mechanical properties, as the yield strength is by approximately 20% lower than that of the pure copper, the tensile strength is by 43% lower and the elongation is by 39% lower than these of copper.

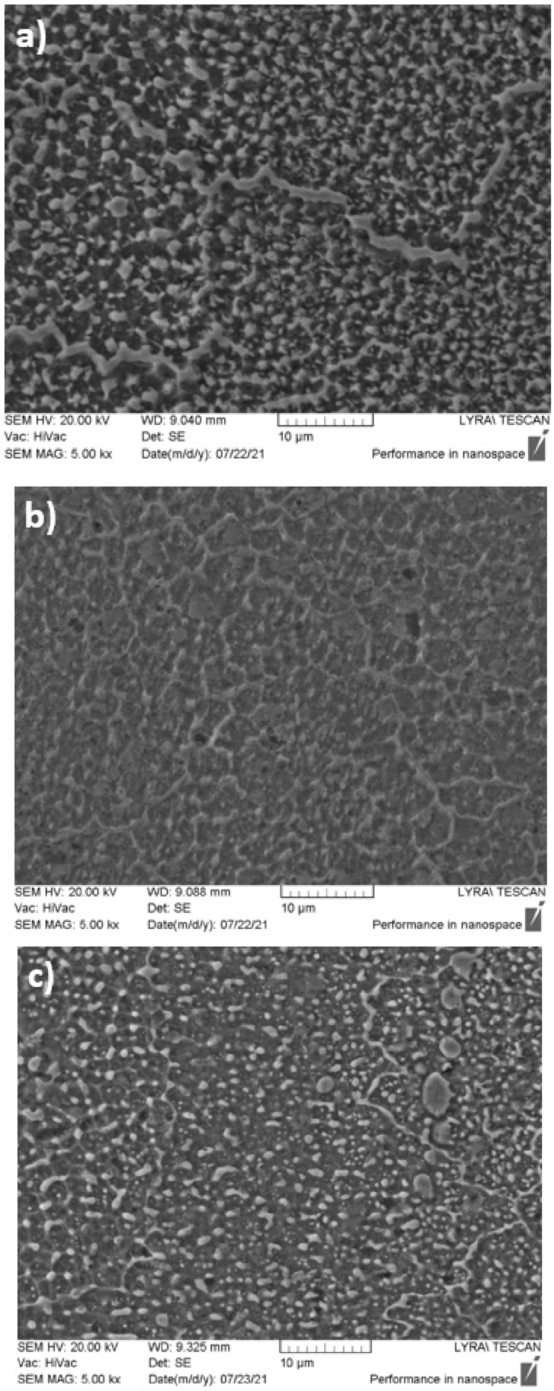


**Figure 3.** Cross-sectional SEM images of the fusion zone of sample 1 (a), sample 2 (b) and sample 3 (c).

As the electron beam current increases, a weld is available along the entire depth of the welded plates. The mechanical parameters also increase and for sample 3 they reach a tensile limit, a tensile strength and a relative elongation of 35%, 79%, and 87% of the values obtained for pure copper, respectively. As already mentioned, the presence of a larger amount of the bcc phase in sample 3 may explain its better mechanical properties.

**Table 1.** Results of the tensile test of welded dissimilar samples of copper and stainless steel and pure Cu and 304 L SS.

| Sample | Yield strength $R_{p0,2}$, MPa | Tensile strength $R_m$, MPa | Elongation $A_t$, % |
|---|---|---|---|
| Cu | 267 | 275 | 16.8 |
| AISI 304L | 298 | 608 | 35.8 |
| Sample 1 | 52 | 119 | 6.5 |
| Sample 2 | 78 | 137 | 7.7 |
| Sample 3 | 93 | 218 | 14.6 |

In Fig. 4 the results of the measured microhardness in a cross-section of the weld are shown. The microhardness of non heat-affected areas of the copper and the stainless steel is 60-100 μHV and 250-350 μHV, respectively. In the fusion zone there is no difference in the microhardness values for the three samples. In sample 1 a significant increase in microhardness is observed on approaching the welded zone, in contrast to the other two samples. In the heat-affected area on the side of the copper, a decrease in microhardness is observed compared to heat-unaffected pure copper. This decrease for samples 1 and 3 is approximately 35%, for sample 2 it is 3.2%. This reduction in the microhardness of the heat-affected zone at the Cu side could be a reason for the deteriorated mechanical parameters in the tensile test.

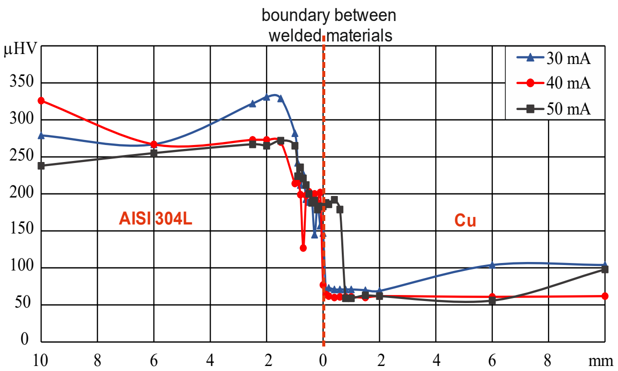


**Figure 4.** Distribution of the microhardness along the line perpendicular to the welding seam in the middle of the depth of the welded samples.

## CONCLUSIONS

1. Copper and 304L stainless steel specimens have been successfully welded using electron beam welding technology. A beam power of 1800 W is sufficient to weld 8 mm thick specimens in partial joint penetration weld. At a beam power of 2400 and 3000 W complete penetration weld has been formed at the same sample thickness.

2. The welded zone is a solid solution of copper and γ-iron with inclusions of pure copper and a small amount of α-iron. The technological conditions have a significant effect on the microstructure of the welded samples. Higher values of the beam power lead to finer microstructure of the weld.

3. Higher values of the beam power lead to better mechanical properties. In the sample welded with the highest power of 3000 W, the highest values of yield strength and tensile strength were measured - 93 MPa and 218 MPa, respectively.

4. There is no difference in the microhardness values for the three samples in the fusion zone. In the heat-affected area on the copper side, a decrease in microhardness is observed compared to heat-unaffected pure copper. It is the reduced microhardness in the heat affected zone on the copper side that is one of the reasons for the deteriorated mechanical parameters in the tensile test.

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