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Electron Beam Brazing of Austenitic Stainless Steel AISI 304

Abstract: Electron beam brazing is a joining technology combining the advantages of a precisely controlled heat source and those of vacuum brazing process. The oxide layer decomposes in high-temperature vacuum conditions, which improves the wetting process and, consequently, leads to the obtainment of more favourable properties of the brazed joint. In comparison with brazing in vacuum furnaces, the electron beam brazing process enables the precise heating of selected areas without the necessity of heating the entire element, which, in turn, results in smaller structural changes in the brazed material and the lower consumption of energy. During tests discussed in this article, sheets made of stainless steel AISI 304 were brazed using various copper and silver filler metals. Brazed joints were subjected to microstructural tests and shear strength tests. The results revealed the high efficiency of the electron beam brazing of corrosion-resistant steel sheets using filler metals.

Keywords: stainless steel, brazing, electron beam, metallographic tests, shear strength of brazed joints

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Introduction

Presently, the development of industry necessitates the making of joints using materials characterised by significantly varying physicochemical properties. However, in some cases, the joining of such materials is accompanied by many problems. Improperly adjusted parameters could lead to the generation of excessive stresses and the formation of cracks. In addition, joints made using the aforesaid parameters could be characterised by high brittleness. To prevent this, joints can be made using brazing methods, characterised by relatively low process temperature, a low heat input and, consequently, limited unfavourable structural changes and deformations. Brazing also enables the making of joints using dissimilar materials, which are difficult or impossible to join using other methods [1–3].

The use of the electron beam with appropriately adjusted parameters including current, accelerating voltage, control over beam focus or splitting enables (within a wide range) to control a heat input to elements being joined. The performance of the process under high vacuum conditions not only offers high precision but also limits the formation of oxides on the surface of brazed materials, thus improving brazing metal wettability and, consequently, the quality of brazes. However, it should be noted that the use of the electron beam method also has its disadvantages. The method cannot be

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used to joint metals and metal alloys containing components easily evaporating in vacuum (e.g. zinc, phosphorus), which could create certain difficulties when selecting brazing metals as most filler metals, particularly those applied in flux brazing, cannot be used in the electron beam brazing technology [1–6].

The article presents issues accompanying the fabrication of new effective tools using advanced superhard materials (SHM – superhard materials) based on cubic boron nitride (CBN) and polycrystalline diamond. It was ascertained that an optimum method enabling the obtainment of joints was brazing involving the use of adhesive-active brazing metals. Related tests concerned the making of SHM–steel joints (or hard tungsten carbide-based alloys) involving the use of the electron beam. The tests included the investigation of chemical and physical reactions taking place during the brazing of SHM to the base material. It was found that the CBN–braze system was characterised by the active physicochemical effect resulting from the diffusion of components of the solid and liquid phases and the formation of chemical elements on the joint boundary. Theoretical and experimental tests made it possible to launch unique ceramic machining tools. Publication [8] (by a team of researchers from the Technological Institute from Harbin (China)) discusses the braze welding of hard WC-Co alloys with steel SAE1045 (having a carbon content of 0.45 % by weight). At the first stage, the authors made a welded joint using the electron beam only. Welds obtained in the aforesaid process were characterised by numerous cracks starting in the w HAZ of the WC-Co alloy and propagating towards the weld and the base material. The primary problems which accompanied the joining of the above-named materials included their significantly varying properties as regards thermal conductivity and expansion. The subsequent stage involved making a joint using an Fe-Ni interlayer. The joints obtained using the aforesaid method were characterised by high quality and significantly lower hardness than those obtained using the traditional electron beam welding process (EBW) (Fig. 1).

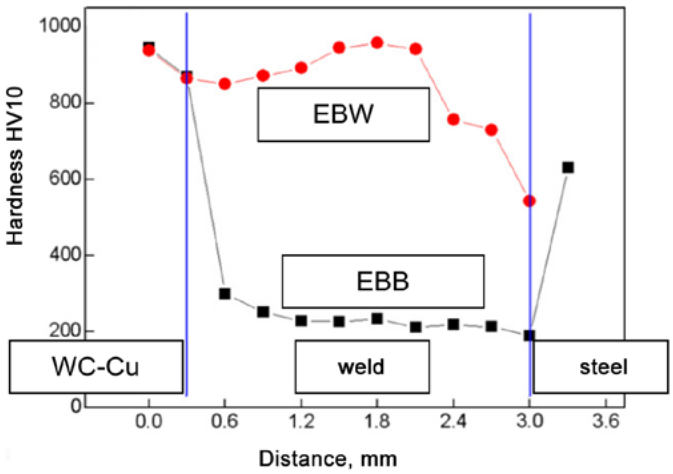

Fig. 1. Comparison of hardness measurement results obtained in relation to electron beam welded (EBW) and electron beam brazed (EBB) joints [8]

The authors of publication [9] discussed the effect of electron beam current on the microstructure and the mechanical properties of joints of aluminium with austenitic steel 304. The aforesaid authors made braze welded joints using various values of accelerating voltage. In the summary, the authors stated that the EBB joints were characterised by high quality and a shear strength of 93 MPa. The quality of the joints was significantly affected by the appropriate adjustment of braze welding parameters. It was observed that excessively high current triggered the formation of cracks in the joint.

The electron beam braze welding process is also used in various joining technologies related to outer space applications. Article [10] presents the possibilities of using spot brazing in vacuum to repair such elements as telescopes, aerials or power supply sources. The author [10] stated that electron beam brazed joints were characterised by high quality and resistance to conditions present in outer space (vacuum, radiation).

The above-presented examples justify the conclusion that the appropriate adjustment of electron beam parameters enables the control of a heat input to a joint and, consequently, the obtainment of joints characterised by high quality and mechanical strength.

Objective and scope of research work

The research work aimed to appropriately adjust and optimise electron beam brazing parameters when making stainless steel joints. The scientific objective of the study was to identify the effect of the filler (brazing) metal and of the primary parameters of electron beam brazing on the geometry and quality of joints.

In turn, the practical goal was to develop the technological conditions of the electron beam welding of elements made of steel sheets, enabling the obtainment of the highest quality and mechanical properties of joints. The scope of the tests involved:

- selection of filler metals and the performance of electron beam brazing tests,
- examination of the quality and strength of joints,
- identification of conditions and technological parameters enabling the obtainment of the optimum quality and mechanical properties of joints as well as the development of an electron beam brazing technology.

Tests

The first stage of the tests involved the analysis of the possibility of performing electron beam-based welding process. The tests material was steel grade X5CrNi18-10-1.4301 (AISI 304) in the form of sheets (150 mm × 50 mm × 1.5 mm). To more accurately identify materials used in the tests it was necessary to perform the analysis of the chemical composition of the base material. The obtained results are presented in Table 1. The analysis of the chemical composition was performed using a Q4 TASMAN spark emission spectrometer (Bruker).

Filler metals were in the form of strips, thicknesses was which restricted within the range of 0.2 mm to 0.5 mm. Before brazing, all of the specimens were subjected to cleaning and degreasing (by means of acetone); the specimens were not subjected to etching. The brazing process was performed under high vacuum conditions (10^{-4} mbar), using an XW150:30/756 electron beam welding and surface processing device (Fig. 2). The brazing tests, consisting in the making of overlap joints (Fig. 3), were performed in accordance with the scope of the work. The cleaned and degreased elements were

Table 1. Results of the analysis of the chemical composition of steel AISI 304

Material	Contents of chemical elements, % by weight							
	C	Si	Mn	P	S	Cr	Ni	Fe
1.4301 in accordance with PN-EN 10088-1 [11]	≤0.07	≤1.0	≤2.0	≤0.045	≤0.03	17.5÷19.5	8.0÷10.5	bal.
1.4301 used in the tests	0.06	0.45	1.01	0.03	0.009	18.42	8.53	bal.

Table 2. Filler metals used in the tests (in accordance with PN-EN 17672:2016-12 [12])

Brazing metal grade in accordance with PN-EN ISO: 2016-12	Contents of chemical elements, % by weight							Temperature (solidus), °C
	Ag	Cu	Zn	Mn	Ni	Sn	Ni	
Ag 449	49.0	16.0	23	7.5	4.5	-	-	680
Ag 272	72.0	28.0	-	-	-	-	-	780
Ag 463	63.0	28.5	-	-	-	6.0	2.5	690
Cu 773	-	48.0	-	<0.1	10.0	-	-	890
Cu 595	-	71.5	-	12.0	2.0	-	-	965

placed (in accordance with specified configuration) in previously prepared fixtures.

Fig. 2. Electron beam brazing device; model XW150:30/756

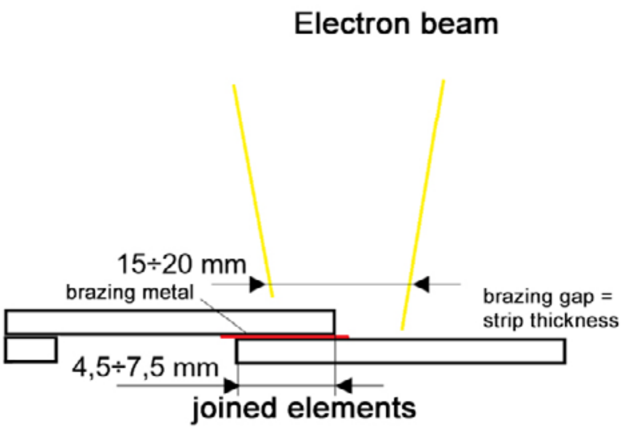

Fig. 3. Preparation of specimens used in electron beam brazing tests

The first stage of the tests was focused on the determination of the optimum method of guiding the electron beam on materials being joined. It was important to adjust process parameters so that the electron beam would only appropriately heat the material but did not melt it. The experimental tests enabled the selection of a brazing method where the electron beam was split and struck both sheets at the same time (Fig. 3). The aforesaid solution enabled the more uniform heating and, consequently, wetting of the elements subjected to brazing. To obtain high-quality joints, the beam was not only split but also set into oscillating motion using a cyclometric function. The subsequent stage involved the making of a test series of joints using various brazing (filler) metals. Table 3 presents brazing metals used in the tests.

The brazed joints were subjected to mechanical tests (shear tensile tests) as well as macro and microscopic metallographic tests, aimed to verify the quality of brazed elements.

Microstructural tests

The metallographic tests were performed in accordance with the requirements of the PN-EN 17639:2013-12 standard [13]. The specimens were subjected to grinding followed by polishing. The tests were performed using an Eclipse MA 200 metallographic inverted microscope (Nikon). The results in the form of macro and microstructures are presented in Figures 4–8.

Static shear tests

The static shear tensile tests of the brazed joints (Fig. 9) were performed using an MTS Criterion C45 testing machine using a transverse beam travel rate of 5 mm/min, within a range of up to 100 kN, (in accordance with the requirements of the PN-EN 12797:2002 standard) [14].

Table 3. Parameters used in the making of test joints using various brazing metals

No.	Brazing metal grade in accordance with PN-EN ISO 17672: 2016-12	Accelerating voltage, kV	Electron beam current, mA	Linear brazing rate mm/min	Focal length, mm
1	Ag 449	60	14	135	402
2	Ag 272	60	13	120	402
3	Ag 463	60	17	150	402
4	Cu 773	60	15	100	402
5	Cu 595	60	18	150	402

The results obtained in the tests are presented in Table 4 and in Figure 10.

Discussion

The objective of the research work discussed in the article was to verify the possibility of using the electron beam in the brazing of steel AISI 304. To do so, it was necessary to carry out numerous brazing tests aimed to identify the usability of the aforesaid method. The selection of an appropriate method to heat the test material was followed by the initial brazing tests involving steel AISI 304 and various brazing metals. The metallographic tests revealed that the similar brazed joints made of steel AISI 304 using all the brazing metals were characterised by high quality. The macrostructures did not reveal the presence of brazing imperfections (Figures 4 through 8). The mechanical tests revealed that the joints were characterised by high shear strength. The most favourable results were obtained in relation to the joints made using copper-based brazing metals, i.e. Cu 773 (average shear strength amounted to 141.9 MPa) and Cu 595 (average shear strength amounted to 131.1 MPa). The most favourable results in terms of the joints made using silver-based brazing metals were obtained in relation to Ag 463 (average shear strength amounted to 129.8 MPa). In turn, the lowest shear strength among all of the tested joints was characteristic of the joint made using Ag 449 (average shear strength amounted to 108.5 MPa).

Because of its highest melting point, brazing metal Cu 595 required the application of a lower processing rate and higher (in comparison with other brazing metals) electron beam current.

The above-presented brazing tests confirmed the usability of the electron beam as the heat source in the brazing process. The process performed under vacuum

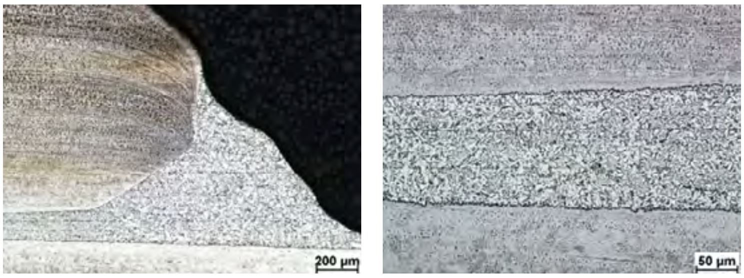

Fig. 4. Microstructure of the joint made of steel grade AISI 304 using the electron beam brazing process and brazing metal Ag 449; chemical etching in Nital., a) mag. 50×, b) mag. 200×

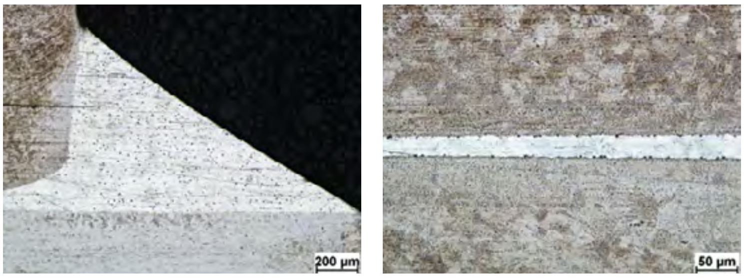

Fig. 5. Microstructure of the joint made of steel grade AISI 304 using the electron beam brazing process and brazing metal Ag 272; chemical etching in Nital., a) mag. 50×, b) mag. 200×

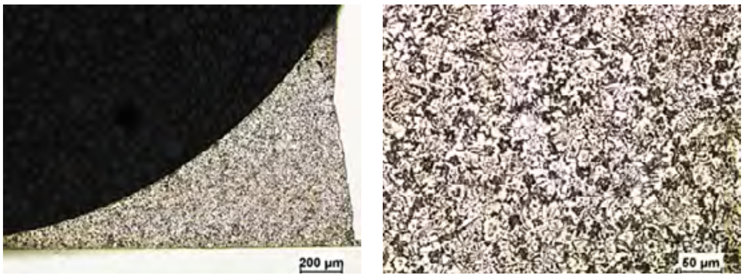

Fig. 6. Microstructure of the joint made of steel grade AISI 304 using the electron beam brazing process and brazing metal Ag 463; chemical etching in Nital., a) mag. 50×, b) mag. 200×

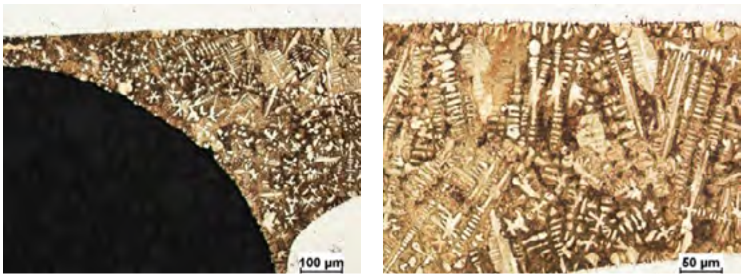

Fig. 7. Microstructure of the joint made of steel grade AISI 304 using the electron beam brazing process and brazing metal Cu 773; chemical etching in Nital., a) mag. 100×, b) mag. 200×

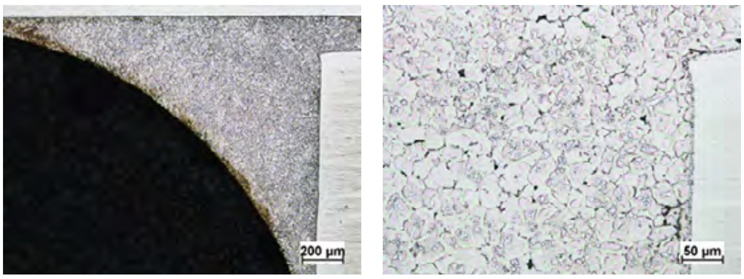

Fig. 8. Microstructure of the joint made of steel grade AISI 304 using the electron beam brazing process and brazing metal Cu 595; chemical etching in Nital., a) mag. 50×, b) mag. 200×

Table 4. Results of shear tests of similar joints made of steel AISI 304

Spec. no.	Overlap area, mm²	Shear force, kN	Shear strength, MPa	Remarks
Ag 449				
1	74.25	8.22	110.8	Rupture in the braze, mixed fracture
2	73.50	7.50	102.1	
3	73.26	7.65	104.4	
4	75.00	8.50	113.3	
5	74.50	8.33	111.8	
	Average value	8.04	108.5	
	Standard deviation	0.44	4.9	
Ag 272				
1	55.00	7.23	131.5	Rupture in the braze, mixed fracture
2	54.50	6.20	113.8	
3	56.00	7.19	128.3	
4	55.00	6.89	125.3	
5	55.50	6.27	113.0	
	Average value	6.76	122.4	
	Standard deviation	0.49	8.5	
Ag 463				
1	74.88	9.62	128.5	Rupture in the braze, mixed fracture
2	75.51	9.39	124.3	
3	74.49	9.44	126.7	
4	63.06	8.32	131.9	
5	63.97	8.80	137.6	
	Average value	9.11	129.8	
	Standard deviation	0.54	5.2	
Cu 773				
1	67.99	9.70	142.7	Rupture in the braze, mixed fracture
2	65.59	9.43	143.7	
3	67.50	9.51	140.9	
4	67.17	9.52	141.7	
5	69.76	9.79	140.3	
	Average value	9.59	141.9	
	Standard deviation	0.15	1.4	
Cu 595				
1	76.96	9.79	127.2	Rupture in the braze, mixed fracture
2	69.63	9.51	136.5	
3	77.63	9.81	126.4	
4	71.60	9.74	136.1	
5	75.00	9.70	129.3	
	Average value	9.71	131.1	
	Standard deviation	0.12	4.9	

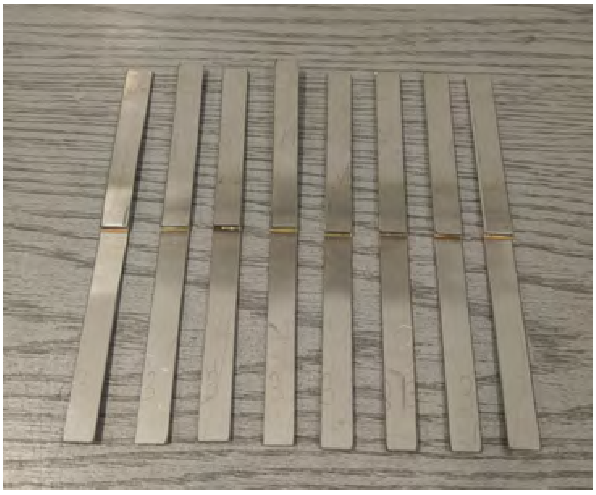

Fig. 9. Specimens prepared for the static shear tensile test (tension was preceded by the removal of excess braze metal)

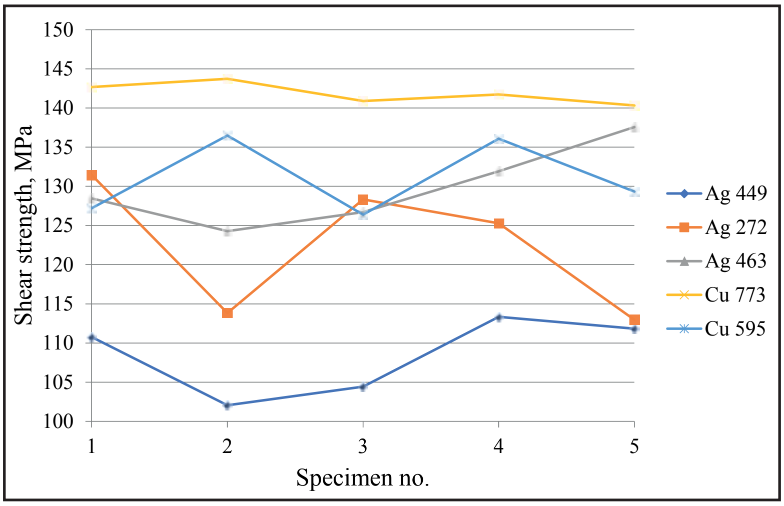

Fig. 10. Distribution of the shear strength of the electron beam brazed joints made of steel AISI 304 using various brazing metals

conditions enabled the maintaining of metallurgical purity. The metallurgical purity was also the result of the decomposition of oxide layers and the prevention of re-oxidation. During the brazing process carried out in vacuum, an important aspect was the chemical composition of brazing metals, which should not contain easily evaporating components. The current stage of research did not involve the analysis of the braze microstructure.

Conclusions

The above-presented tests justified the formulation of the following concluding remarks:

1. Brazed joints made using the split electron beam were characterised by high quality.
2. As regards the similar joints made of austenitic steel AISI 304, the most favourable results were obtained in relation to the joints made using brazing metal Cu 773 (average shear strength amounted to 141.9 MPa).
3. Because of its highest melting point, brazing metal Cu 595 required the application of a lower processing rate and higher (in comparison with other brazing metals) electron beam current.
4. The splitting of the electron beam on the surface of both sheets are the same time decreased the amount of supplied energy (heat input), enabled the more uniform heating and, consequently, the more favourable wetting of the elements subjected to brazing.

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