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BRAZE WELDING OF COPPER USED IN MEANS OF TRANSPORT

Summary. The joining of multiple components in engineering applications, including copper parts in automotive, aircraft, and locomotive components, requires the development of efficient and cost-effective manufacturing processes. Copper and copper alloys are low-melting-point metals that, when brazed, present the problem of cracking, and the frequent failures of these joints in the transport sector have not yet been satisfactorily resolved. This article presents advances in brazing techniques applied to copper joints in the automotive industry, enabling cost savings. Copper has high electrical conductivity and good resistance to atmospheric corrosion; although joining is possible, it is not considered an easily weldable metal. The influence of three types of copper electron beam wires (containing aluminum, tin, and silicon) and brazing welding parameters such as current intensity, arc voltage, and brazing speed were tested for joints used in locomotive cooling systems. NDT tests, tensile strength, and hardness tests were used to analyze the effects of these different parameters on the properties. The CuSi3 electrode wire with a brazing current of 180 A, arc voltage of 18 V and a speed of 230 mm/min, achieved high joint quality and a straight line between the base material and the braze weld, allowing for superior UTS with a slight increase in hardness (from 95 to 103 HV), which is desirable to minimize stress concentration.

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1. INTRODUCTION

Copper and Cu alloys are used in the structures of various means of transport. Copper is widely used in railway, aviation, and automotive industries because of its high electrical conductivity and corrosion resistance [1-3]. Copper has excellent plastic properties, that are important and useful in the construction of transport means. This does not mean that copper is a load-bearing structural material, but its ductility, flexibility, and formability are crucial in many components. The ability to join copper and its alloys plays a significant role. In addition to classic welding methods, braze welding is also gaining importance. Examples of the use of copper in the welding construction in the automotive sector are as follows [4-5]:

- joining copper tubes in compressors or evaporators,
- repairs to pipes and heat exchangers if they are made of copper,
- components of catalysts,
- suspension elements,
- internal and external decorative elements,
- air conditioning and cooling system,
- electrical installations in special vehicles,
- connecting copper busbars,
- internal and external decorative elements.

Copper and copper welding connections are widely used in rail transport. The most important examples related to rail transport include [6-9]:

- electrical system components,
- connecting large-diameter copper wires,
- connector and control system regeneration,
- cooling and hydraulic systems,
- terminals and contacts where strong, conductive connections are required,
- compressor repairs,
- busbar regeneration,
- connecting copper busbars,
- internal and external decorative elements.

Thanks to their good thermal conductivity and their high mechanical stability, heat exchangers made from copper/ brass are commonly used for air-conditioning systems in utility vehicles, for radiators in construction machinery, or for industrial cooling equipment and in other automotive elements. In table 1 are presented the limitations and advantages of copper braze-welding processes in the automotive industry (tabl.1).

Copper connectors are also used in the aviation industry, both in the construction and repair of various types of equipment. Typical applications for copper connectors in aviation include [5-6]:

- refrigeration system components,
- air conditioning and cooling systems,
- hydraulic and pneumatic systems,
- where high thermal or electrical conductivity is required.

Tab. 1

Application of braze-welding in means of transport

Application / Area:	Example Issue / Limitation	Advantages of Brazing/ braze-welding	Ref.
Heat exchangers / radiators in vehicles (e.g., cooling systems, HVAC cores)	Brazing processes must tightly control temperature profile and joint gap to avoid defects (e.g., voids or weak joints at interface). (General brazing metallurgy limitation in brazed joints)	Strong, durable joints maintained at high temperature. Reliable performance under vibration / pressure.	[10]
Automotive / commercial brake lines using copper-nickel alloy tubes	Corrosion resistance issues in certain alloys (e.g., Bundy tube corrosion in salty environments) required alloy design changes.	Good corrosion resistance in CuNi alloys compared to older steel tubing.	[11-12]
Brazed cooling fluid lines / heat transfer networks (including intercoolers, turbo cooling circuits, oil coolers)	Joint quality depends on fill-out and metallurgy of filler metal; poor penetration can reduce leak tightness. (Common issue in brazing process research).	High thermal conductivity and good joint integrity.	[13]
HVAC and battery cooling systems in electric vehicles (brazed copper cores)	Brazing of dissimilar metals (e.g., copper to stainless steel) may pose challenges due to thermal distortion and brittle phase formation (e.g., recent induction brazing review).	Allows compact, high-performance heat transfer components with fewer joints	[14-15]

Copper has a low melting point of 1085°C, but braze welding requires care to avoid melting edges of the joined components. The braze welding method is very practical because the connection is made similarly to soldering without melting the sheet metal edges. This avoids the significant welding challenges associated with traditional copper welding [16-17]. In the vast majority of cases, when welding copper structures, preheating to approximately 600°C should be used. This is a time-consuming and expensive procedure.

Braze welding requires focusing on good substrate wettability and process parameters to avoid melting the base material [18]. Copper wires containing 6% tin or solders containing 8% aluminum are typically used for this purpose. Equilibrium diagrams show that the addition of these elements significantly lowers the liquidus curve, causing the melting temperature of the electron wire to be approximately 1010°C, which is 75°C below the melting temperature of

copper. This paper explores the feasibility of using silicon-containing wire, which is less commonly used in braze welding. Even a small addition of approximately 2% reduces the melting temperature of copper even more significantly, by approximately 130°C. This is due to the steeply sloping nature of the solidus curve, which is more steeply sloping than the liquidus curve in the Cu-Sn and Cu-Al equilibrium diagrams. At about 800°C, the Cu_3Sn phase may be formed, which can lead to excessive tensile and hardness of the braze weld. When using the popular CuAl_8 wire, the presence of the theta phase (Al_2Cu) can be expected, which will also improve the mechanical properties of the braze. The authors of the article assume that the precipitating epsilon phase $\text{Cu}_{65}\text{Si}_{11}$ will cause a similar strengthening of the brazed joint (Fig. 1).

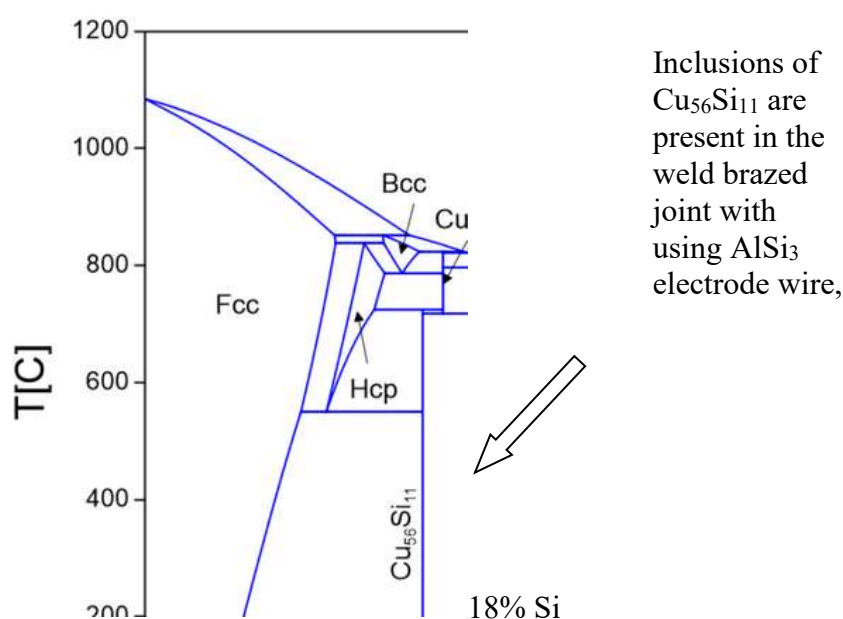


Fig. 1. Part of the diagram Cu-Si from the Cu side (adapted from [19])

The theta phase (Al_2Cu) is formed at 550°C and the epsilon phase $\text{Cu}_{65}\text{Si}_{11}$ is formed at 750°C i.e., at a lower temperature than the Cu_3Sn phase, which might be advantageous in the brazing process.

2. RESEARCH MATERIALS AND METHODS

High purity copper CW004A (99,9% Cu) sheet was used for the investigation (EN 1412 – Copper and copper alloys). This is the main standard that formally defines the designation CW004A). Parameters of CW004A are shown in Table 2.

Three electrode wires (for braze welding) containing three different alloying elements (6% tin, 8% aluminum, or 3% silicon) were selected for the tests: CuSn_6 , CuAl_8 , CuSi_3 . These wires for braze welding have different values on the liquidus and solidus curves. When analyzing the equilibrium diagrams, the values on the liquidus and solidus curves were assumed, as summarized in Table 3.

Tab. 2

Mechanical properties

Material	Yield strength (YS) [MPa]	Tensile strength (UTS) [MPa]	Hardness [HV]
CW004A	150	360	95

Tab. 3

Mechanical properties

Electrode wire	Liquidus [°C]	Solidus [°C]	The difference between both values, [°C]
CuAl8	1035	1020	15
CuSn6	1020	830	190
CuSi3	960	930	30

The table shows that CuSi3 wire has the lowest melting temperature, which seems to be the most advantageous in the braze welding process, as it prevents copper, which has a melting point closer to 1085°C, from melting more than its alloys. The Cu-Sn and Cu-Si equilibrium diagrams have steeply sloping liquidus and solidus curves, which means that small additions of Al or Sn effectively lower the wire's melting temperature. The Cu-Al equilibrium diagram has a less steeply sloping character, which is why the melting temperature of CuAl8 wire is the highest of the three compared. On the other hand, it seems that the smallest distance between the liquidus and solidus curves for the CuAl8 wire can be very advantageous in the brazing process, although there is a concern that the melting temperature of this wire is too high (1035°C).

The braze welded joints were made from CW004A pure copper with a thickness of 4 mm. The joint was a cross joint. Two smaller sheets measuring 60 mm x 30 mm were soldered to a horizontal copper sheet (60 mm x 60 mm). After brazing, the ends of the sheets were cut off to form a cross joint with both arms 40 mm long. Argon was used as a shielding gas. The diameter of the tested 3 wires (CuAl8, CuSn6, Cu Si3) was always 1 mm. The most important welding parameters are:

- I – braze welding current (was changing twice: 160 A and 170 A),
- U – arc voltage (was changing twice: 18 V and 20 V),
- v – braze welding speed (was changing twice: 230 mm/min and 330 mm/min),
- type of current/polarity (+),
- gas flow rate (argon) was at the level of 13.5 dm³/min.

Weld brazing with all three various electrode wires was carried out. The process was realized without preheating. After making the MIG braze welded joints, visual tests (VT) were made. The VT tests were extended with other non-destructive tests: penetrant and ultrasonic. The NDT (nondestructive tests) were carried out to verify the tightness and quality of the braze. Thus, the following NDT tests were realized:

- VT, visual test (keeping the PN-EN 970 from 1999),
- PT, penetrant (keeping the standard PN-EN 14273 from 2016),

- UT, ultrasonic (keeping PN-EN 1714 from 2002).

After NDT tests, the focus was on DT (destructive tests):

- tensile strength keeping the standard PN-EN ISO 6892-1 from 2020,
- hardness test keeping the standard PN-EN ISO 6507-1 from 2018-05,
- light microscope observation keeping the standard EN ISO 2624 („Copper and copper alloys – estimation of average grain size) from 1990.

Figure 2 shows weld-brazed joints prepared for NDT and DT measuring.



Fig. 2. Preparing weld braze samples

3. RESULTS

The current, arc voltage, and brazing speed were varied twice using three different electrode wires. Twenty-four different samples were obtained, designated D1 to D24. The weld brazed joints were carefully observed. NDT tests were carried out correctly (visual, penetrative,) according to standards (PN-EN 970; PN-EN 14273). The results of the NDT are presented in the below Table 4.

Tab. 4

NDT results

Sample symbol	Electrode wire	Braze welding current [A]	Arc voltage [V]	Speed [mm/min]	NDT observations
D1	CuAl8	160	18	230	Poor spreading of the filler metal in the soldered joint

D2	CuSn6	160	18	230	Poor spreading of the filler metal in the soldered joint cold solders, porosity.
D3	CuSi3	160	18	230	Correct joint
D4	CuAl8	180	18	230	Correct joint
D5	CuSn6	180	18	230	Correct joint
D6	CuSi3	180	18	230	Correct joint
D7	CuAl8	160	20	230	Cold solders, porosity.
D8	CuSn6	160	20	230	Correct joint
D9	CuSi3	160	20	230	Correct joint
D10	CuAl8	180	20	230	Cold solders, porosity.
D11	CuSn6	180	20	230	Cold solders, porosity.
D12	CuSi3	180	20	230	Correct joint
D13	CuAl8	160	18	330	Poor spreading of the filler metal in the soldered joint
D14	CuSn6	160	18	330	Poor spreading of the filler metal in the soldered joint cold solders, porosity.
D15	CuSi3	160	18	330	Correct joint
D16	CuAl8	180	18	330	Weak capillarity
D17	CuSn6	180	18	330	Correct joint
D18	CuSi3	180	18	330	Correct joint
D19	CuAl8	160	20	330	Weak capillarity
D20	CuSn6	160	20	330	Weak capillarity
D21	CuSi3	160	20	330	Correct joint
D22	CuAl8	180	20	330	Poor spreading of the filler metal in the soldered joint cold solders, porosity. weak capillarity

D23	CuSn6	180	20	330	Weak capillarity
D24	CuSi3	180	20	330	Weak capillarity

Based on the table data, it can be concluded that the correctness of the weld-brazed joint is influenced by many factors and process parameters. It was observed that the best technological properties can be obtained using the CuSi3 electrode wire. The CuSi3 filler wire provides the most stable and highest-quality joints; in most parameter combinations, a correct joint was obtained, regardless of current, voltage, and travel speed. Copper electrode wires containing tin (CuSn5) or aluminum (CuAl8) can also be used to make a correct joint, but it is much more difficult to determine the correct process parameters. CuAl8 filler wire is the most sensitive to changes in process parameters and frequently results in defects such as poor filler metal spreading, cold solder joints, and weak capillary action.

It can be observed that the CuSn6 electrode wire produces correct joints only within a narrow range of parameters; unfavorable settings lead to porosity and cold solder joints.

It was noted, that increasing the brazing current from 160 A to 180 A, at 18 V and a travel speed of 230 mm/min, improves joint quality for all three filler wires.

The analysis of the data (table 4) shows, that higher arc voltage (20 V) promotes the formation of defects (cold solder joints and porosity), particularly when using CuAl8 and CuSn6 filler wires. During the increasing the travel speeds to 330 mm/min negatively affects filler metal spreading and capillary action, especially for CuAl8 and CuSn6.

It can be concluded that, the most favorable process conditions were obtained using CuSi3 filler wire, a current of 160-180 A, an arc voltage of 18 V, and a travel speed of 230 mm/min.

It is interesting to note, that weak capillary action occurs mainly at higher braze-welding speed (330 mm/min), indicating insufficient heat input and too short a thermal interaction time.

For the D22 sample we can observe porosity and cold solder joints occur more frequently when low current is combined with higher arc voltage, suggesting unstable wetting conditions.

It was noted that the selection of all process parameters was crucial. Small changes in parameters can result in a perfectly correct joint or one with defects. It was decided to collect the observations regarding the influence of each parameter in table 5. The table shows that more than half of the joints contained welding defects. Regardless of this, the influence of arc voltage, current intensity, and welding speed was observed, which can be presented (table 5).

The data in table 5 show that the selection of the filler material has a greater influence on joint quality than arc voltage variations within the investigated range.

The next part of the investigation was associated with the tensile strength tests. The tests were realized on the ZWICK 100N5A machine. Only those joints that passed the NDT tests (D3, D4, D5, D6, D8, D9, D12, D15, D17, D18, D 21) were stretched (average of 3 measurements). Results of tensile strength are presented in the Table 6.

The results of the tensile tests are treated as positive. All joints are characterized by good tensile strength above the recommended value of 140 MPa. Tensile strength above the recommended value of 140 MPa. It was noted that the highest tensile strength can be achieved using a copper electrode wire containing silicon. Copper wires containing tin or aluminum do not allow for equally high tensile strength. The selection of process parameters is crucial. Depending on the current intensity, arc voltage, and brazing speed, the tensile strength will vary. It was observed that the most important parameter is the one that provides higher current intensity while simultaneously reducing arc voltage and brazing speed. The best results were observed for sample D6, and a light microscopy image was taken for this sample (Fig. 3).

Tab. 5

Influence of the main process parameters on the NDT observations

Parameter	Observation
The role of arc voltage	Effect of arc length: • higher voltage → longer arc, larger heat affected zone, • lower voltage → shorter arc, more concentrated heat. In braze welding, a short, stable arc is desired to avoid overheating the copper. Effect on heat distribution: • too high a voltage causes a large heated zone, which can lead to surface oxidation and uncontrolled filler metal spillage, • too low a voltage destabilizes the arc and causes spatter.
The role of current	Effect on heat distribution: Current directly affects the arc temperature and the electrode wire's deposition rate. • higher current → faster wire melting, risk of over-melting the base material (which is undesirable in brazing), deeper penetration (which is not beneficial in weld brazing), • lower current → poor filler metal flow, cold solder joints, porosity. Effect on capillarity → proper wetting of the copper, capillary penetration of the filler metal, uniform braze joint.
The role of speed	Effect on heat distribution: • lower speed → excessive heating of the base material, risk of local melting of copper (undesirable in brazing), larger heat-affected zone (HAZ), • higher speed → too little heat to wet the surface, poor capillarity of the filler metal, the wire melts slower than the torch moves. Effect on joint defects: • lower speed → solder spreading, reduced capillarity – the solder is not "drawn" into the joint, possible burn-through, discoloration, and increased oxidation, reduced mechanical and aesthetic properties, • higher speed → cold solder joints (insufficient flow), porosity, lack of capillary fusion, lack of partial fusion on the walls, lack of bonding, intermittent face structure, filler metal "deposited" on the surface instead of penetrating into the gap.

Tab. 6

Mechanical properties of the tested joints

Sample symbol	Electrode wire	UTS [MPa]
D3	CuSi3	167 ± 2,00
D4	CuAl8	144± 0,58
D5	CuSn6	172± 1,26
D6	CuSi3	191± 0,76
D8	CuSn6	163± 0,29
D9	CuSi3	173± 2,52
D12	CuSi3	168± 0,29
D15	CuSi3	174± 2,00
D17	CuSn6	145± 1,00
D18	CuSi3	151± 1,26
D21	CuSi3	142± 0,58

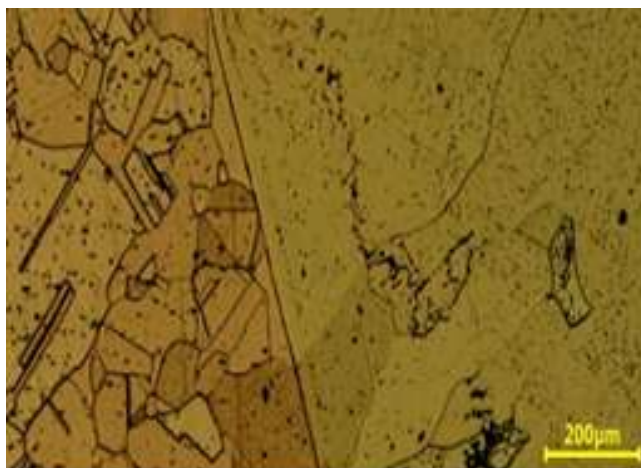


Fig. 3. Weld brazed joint near the contact line (ammonium persulfate etching)

The figure shows the nature of the joint in which the base material, copper, did not melt. No grain growth of the base material occurred. The solder, silicon bronze (sample D6), is visible on the right. The rectilinear nature of the contact line clearly indicates that the process parameters were correctly selected. The high image quality was achieved thanks to the carefully selected medium (ammonium persulfate etching).

The last part of the article was HV hardness measurement in the copper weld braze joint. The tests were carried out for the D6 sample only, which has obtained the most favorable results in all tests. The hardness in the base material (BM), and the braze weld (BW) was carried out. The hardness test results, the average of 5 measurements, are shown in Tab. 7.

Tab. 7

Hardness distribution in the braze weld

Sample	BM [HV]	BW [HV]
D6	$95 \pm 1,5$	103 ± 2

The hardness measurement is very satisfactory. A small difference was observed between the base material and the weld braze. This is important because similar hardness levels in both measured zones will not cause material stresses or weld cracks.

4. CONCLUSION

Welding processes play a significant role in the construction of various types of transportation, including rail, automotive, and aircraft. These joints are often made of difficult-to-weld materials. Creating increasingly modern and refined transportation requires the selection of new construction materials and new joining techniques. Copper remains an important material in the construction of various types of transportation. It was decided to test the weldability of copper elements of locomotive construction joining by brazing process. Three types of copper electron beam wires containing alloying elements such as aluminum (CuAl8), tin (CuSn5), or silicon (CuSi3) were tested. Meticulous measurements were performed to assess the performance of all three types of electron beam wires.

Variable process parameters were determined, including current intensity, arc voltage, and braze welding speed (Fig.4).

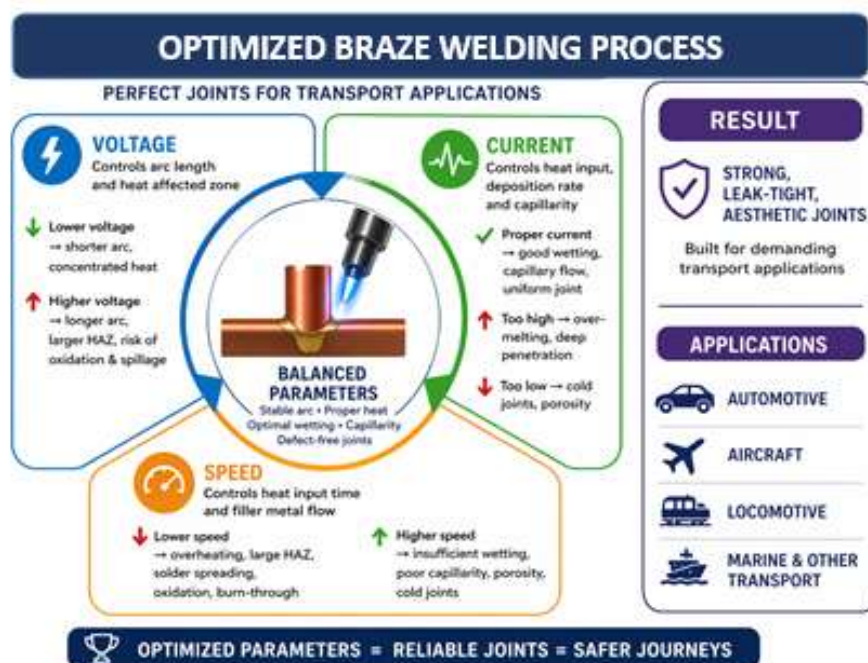


Fig. 4. Schematic of an optimized braze welding process to obtain connections for transportation applications

Variable process parameters were determined, including current intensity, arc voltage, and braze welding speed. Initially, the joints were subjected to NDT, and based on these observations, the selection of process parameters was noted to be crucial. Half of the joints were not made correctly; only those samples that passed NDT were used for further testing. Tensile strength measurements were performed on 11 different samples, revealing that sample D6, made with CuSi3 wire, had the highest tensile strength. Next, joint D6 was observed under a microscope. High joint quality and a straight line between the base material and braze weld were observed, indicating a lack of penetration of the base material. Additionally, a hardness measurement was performed on sample D6, confirming the joint's very high quality, as measured in this case by the comparable hardness of the base material and braze weld.

References

1. Punzel E., F. Hugger, R. Dörringer, T.L. Dinkelbach, A. Bürger. 2020. "Comparison of different system technologies for continuous-wave laser beam welding of copper". *Procedia CIRP* 94. DOI: <https://doi.org/10.1016/j.procir.2020.09.081>.
2. Ciemiorek M., L. Morawiński, C. Jasiński, M. Orłowska, T. Chmielewski, L. Olejnik, M. Lewandowska. 2021. „Characterization of ultrafine-grained copper joints acquired by rotary friction welding”. *Archives of Civil and Mechanical Engineering* 22(1). DOI: <https://doi.org/10.1007/s43452-021-00326-z>.
3. Sairam C., S.G. Balaji, A.A. Menon, I. Manikandan. 2023. "Experimental Investigation on TIG Welded Copper B370 and Stainless Steel 434". *International Journal of Vehicle Structures and Systems* 15(6). DOI: <https://doi.org/10.4273/ijvss.15.6.17>.
4. Spiriyagin M.Wu., O. Polach, J. Thorburn, et al. 2022. "Problems, assumptions and solutions in locomotive design, traction and operational studies". *Railway Engineering Science* 30(3). DOI: <https://doi.org/10.1007/s40534-021-00263-w>.
5. Guo Y., J. Xie, Z. Fan, V. Markine, D.P. Connolly, G. Jing. 2022. "Railway ballast material selection and evaluation". *Construction and Building Materials* 344. DOI: <https://doi.org/10.1016/j.conbuildmat.2022.128218>.
6. Xavier T., D. Pant, J.R. Janaki. 2017. "Brazing of stainless steels using Cu-Ag-Mn-Zn braze filler: Studies on wettability, mechanical properties, and microstructural aspects". *Materials and Design* 121. DOI: <https://doi.org/10.1016/j.matdes.2017.02.057>.
7. Mannucci A., I. Tomashchuk, V. Vignal, P. Sallamand, M. Duband. 2018. "Parametric study of laser welding of copper to austenitic stainless steel". *Procedia CIRP* 74. DOI: <https://doi.org/10.1016/j.procir.2018.08.160>.
8. Golański D., T. Chmielewski, B. Skowrońska, D. Rochalski. 2018. "Advanced Applications of Microplasma Welding". *Biuletyn Instytutu Spawalnictwa w Gliwicach* 62(5): 53-63. DOI: <http://dx.doi.org/10.17729/ebis.2018.5/5>.
9. Szymański G., A. Patecki A., 1984. „Eddy current and temperature of the sheath in three-phase pipe sheathing system”. *IEEE Transaction of Magnetism* 20(5): 2004-2006. DOI: <http://dx.doi.org/10.1109/TMAG.1984.1063218>.
10. Nitin Kumar Sharma, Rangasayee Kannan, James Hogan, Gary Fisher & Leijun Li. 2021. "Progress in Improving Joint Strength of Brazed Cemented Carbides and Steels". *Science and Technology of Welding and Joining* 26(5): 420-437.
11. Lea A. 2003. "New brazing process uses anneal-resistant copper and brass alloys". *MTZ Worldw* 64: 14-17. DOI: <https://doi.org/10.1007/BF03228029>.

12. Shabtay Y.L., M. Ainali, A. Lea. 2004. "New brazing processes using anneal-resistant copper and brass alloys". *Materials and Design* 25(1). DOI: [https://doi.org/10.1016/S0261-3069\(03\)00162-6](https://doi.org/10.1016/S0261-3069(03)00162-6).
13. Hardwick L., P. Webb, R. Goodall. 2023. "Design of higher temperature copper brazing filler metals with reduced brittle phase content". *Materials Today Communications* 35. DOI: <https://doi.org/10.1016/j.mtcomm.2023.105524>.
14. Lemma E.A., J.M.S. Dias, A.A. Bastos, B. Mascate, A. Horovistiz. 2025. "Advances in induction brazing of copper and dissimilar metals: Challenges and emerging trends". *Journal of Advanced Joining Processes* 11. DOI: <https://doi.org/10.1016/j.jajp.2025.100302>.
15. Abnt Achouri M., G. Germain, P. Dal Santo, D. Saidane, T.T. Ajaal, R.W. Smith, S.J. Almeida. Altair University, April, N., Associação Brasileira de Normas Técnicas, Avci, A., İlkaya, N., Şimşir, M., Akdemir, A., Aweda, J. O., Adeyemi, M. B., Baffari, D., Buffa, G., Liang, B. 2009. "Fundamental Manufacturing Processes Study Guide, DV02PUB2". *Journal of Materials Processing Technology* 3.
16. Łabanowski J., D. Fydrych. 2021. "Advances In Materials Science Editorial On The Journal's 20th Anniversary". *Advances in Materials Science* 21(1). DOI: <https://doi.org/10.2478/adms-2021-0001>
17. Tarasiuk W., T. Szymczak, A. Borawski. 2020. "Investigation of surface after erosion using optical profilometry technique". *Metrology and Measurement Systems* 27(2): 265-273. DOI: <https://doi.org/10.24425/mms.2020.132773>.
18. Nosko O., Y. Tsybrii, W. Tarasiuk, A. Nosko. 2022. "Reliability of acicular grindable thermocouples for transient temperature measurements at sliding contacts *Measurement*". *Journal of the International Measurement Confederation Open Access* 19615. Article number 111270. DOI: <https://doi.org/10.1016/j.measurement.2022.111270>.
19. CompuTherm. "Cu-Si Phase Diagrams". Available at: <https://computherm.com/cu-si>.

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