Vol. 43, No. 1 (2021) 150-158, DOI: 10.24874/ti.1068.12.20.02

Tribology in Industry

www.tribology.rs

RESEARCH

Nano Identification and Tribo Testing of Explosive Welding Copper/Brass

B. Nedić[a,*], M.S. Lazarević[a], D. Džunić[a], J. Bogdanov[b], S. Đurić[a]

[a] *Faculty of engineering, University of Kragujevac, Sestre Janjić 6, Serbia,*
[b] *University of Defense in Belgrade, Military Academy, Belgrade, Serbia.*

Keywords:

Explosive welding
Copper/brass joint
Nano identer
Scratch test
Microhardness

* Corresponding author:

Bogdan Nedić

E-mail: nedic@kg.ac.rs

Received: 28 December 2020
Revised: 25 January 2021
Accepted: 22 February 2021

A B S T R A C T

Bimetallic materials are construction materials that are increasingly used in many industries: in the graphic industry, tobacco processing industry for various cutting knives, in the chemical industry for various plants and vessels, food industry, military industry, etc. In the production of ships, their use becomes dominant, primarily as a combination of cheap construction materials highly resistant to corrosion, at a price closer to construction materials. The appearance of plating with the help of explosion energy has significantly increased the range and quality of available multilayer metals. Although stainless steels and aluminum are the most commonly used material for bimetallic and clad materials, materials such as titanium, zirconium or tantalum are increasingly used.

The paper analyzes the process of explosion welding and the results of exploration of the explosion of a welded joint of copper and brass. The microhardness of the material in the welded joint, tribological characteristics and scratch test joint were analyzed.

1. INTRODUCTION

Processing of new materials with classical procedures is very complex, often impossible. Therefore, new processes are being introduced, which are more progressive, enabling higher productivity and economy of metal processing. These processes include high-energy joining and deformation processes, such as explosion and magnetic pulse processing [1, 5, 10].

In the field of metal joining, the industrial application of explosives in the world began in the 50s of the last century and very quickly spread to other processes of metal processing by plastic deformation. Nowadays, the number of operations that use energy obtained by explosion is increasing [7].

Numerous tests in the field of new technologies with impulse loads have shown that the energy of explosion can be successfully used in processes such as:

- metal joining operations (welding, ie cladding of flat, curved and cylindrical surfaces),

- hardening of metals,
- sheet metal processing by deformation (with or without perforation),
- riveting,
- calibration,
- polishing,
- pressing of metal powders and plating,
- injection molding; cleaning of castings,
- application of metal powder on worn surfaces,
- obtaining complex shapes from pipes, etc.

Explosion welding of different and very specific materials makes this process more and more relevant. Joining steel and copper gives a material of good electrical conductivity and good mechanical properties, joining aluminum and steel reduces the weight of the product (eg cars), joining copper and brass gives a material good mechanical properties, high electrical conductivity intended for work in corrosive environments [8]. Many materials are very sensitive to elevated temperatures, have different coefficients of thermal expansion and melting temperature, or are chemically active at elevated temperatures (e.g. Ti). Zinc evaporates during welding and forms a porous joint during welding, etc. [6].

Copper and its alloys have a very wide application as mechanical and construction materials. They are used in all branches of industry, in microelectronics, in process equipment, in large construction plants, etc. Their advantage over other materials is reflected in high corrosion resistance, they have relatively high strength and have good thermal and electrical conductivity. All known joining techniques are used for their joining [2]. Brass, as a very commonly used copper alloy, has very good mechanical properties, high machinability, high corrosion resistance and wear resistance and therefore has a wide range of applications [4].

2. EXPLOSION WELDING

Multilayer materials usually consist of two or more interconnected different metals. In the case of multilayer materials, the layers, as a rule, fulfill different functions, and in accordance with that, clad materials, bimetals or multilayer materials can be used. In the case of clad materials, there are basic (clad) and cladding layers. The base layer has the function of a supporting element, is significantly thicker than the cladding layer and is made of a material that has a lower price.

The cladding layer, depending on the requirements, has specific properties such as high corrosion resistance, fire resistance, wear resistance, electrical conductivity, decorativeness, etc., is usually less thick and is made of more expensive material [11].

The basis of the technological process of obtaining multilayer materials is the process of pressure welding.

Explosion welding of metals is an ultra fast oblique collision of metals under the action of detonation products, relatively high velocities of plates that join with the appearance of high dynamic pressure and plastic deformations in waveform at the joint boundary and adiabatic local heating of metal surface layers [9].
The criteria that must be met in the process of such a merger are:

1. The collision speed must be high enough to provide a collision pressure that is greater than the critical pressure,
2. The speed of the point of impact must be less than the local speed of sound in the joining metals,
3. The kinetic energy of the pushed plate must be sufficient to cause plastic deformations in the surface layers of the metal,
4. The upper limit of energy is determined by the effect of destruction and
5. The initial distance must be greater than half the thickness of the pushed plate, due to the required acceleration on the free path.

The joining process consists of placing the welded plates in parallel at a certain distance or at a certain angle at a given distance. An appropriate amount of explosives is placed on the plate to be pushed. Initiation is performed from the bottom to the top. After initiation, the detonation process develops and a very high pressure is created by pushing the upper plate which collides with the lower plate at high speed (Fig. 1 and 2).

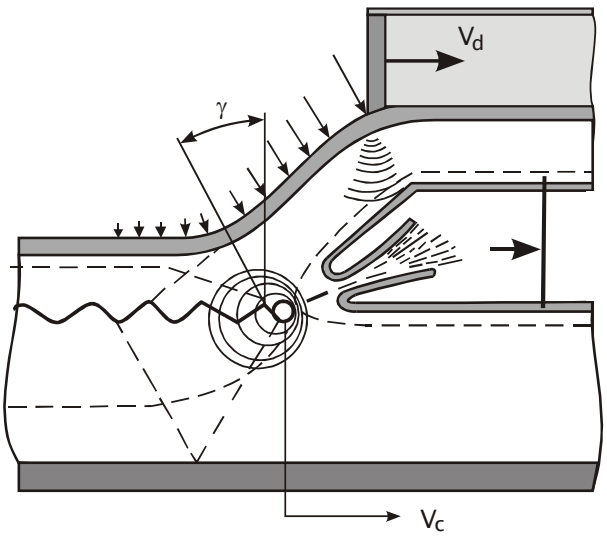


Fig. 1. Schematic representation of the mechanism of metal cladding by explosion, Vc - contact point speed; γ - dynamic angle of impact; Vd - detonation speed.

The collision is performed gradually, during which the plate rotates and creates conditions for the appearance of "surface" cumulative current, and the surface of the plate turns into a quasi-liquid state. In the collision zone, metal particles are brought to the distance by the action of interatomic forces. At the same time, a tangential component of the collision velocity appears in the direction of propagation of the detonation wave, which during the plastic deformation makes the metal joint zone wavy.

Difficulties occur when joining dissimilar metals due to differences in structure, coefficients of linear expansion, thermal conductivity, electrical conductivity, chemical resistance, melting temperature, solubility in liquid and solid state and the like. Therefore, a pair of dissimilar metals that are joined must meet some of the conditions such as:

- the same type of crystal lattice,
- small difference of electro-chemical properties, etc.

These conditions are met by metals from the same group of the periodic table of elements [3]. The first studies of the mechanism of formation of a metal compound by explosion were Abrahamson's studies in the boundary layer of colliding surfaces of two metals connected by explosion [9, 13]. He tried to explain the appearance of waves from the position of the hydrodynamic theory of an ideal (incompressible) fluid, according to which any solid body can be replaced by an ideal incompressible fluid if the collision pressure is far greater than the strength of the material itself. At the boundary of the collided surfaces of both metals, in any collision, a wavy shape does not always appear.

The conditions for the appearance of waves are defined by a number of criteria. When a small change in any collision parameter results in the formation of a wavy shape of the joint, such a regime is called critical.

The most important criteria for creating a wavy shape of the boundary joint of two metals are:

- minimum collision pressure and
- collision point velocity.

In addition to the above basic criteria, the character of waves and the size of their parameters are also affected by:

- amount of explosive charge,
- detonation charge of explosive charge (Vd),
- initial distance between plates (h),
- properties of joining metals, etc.

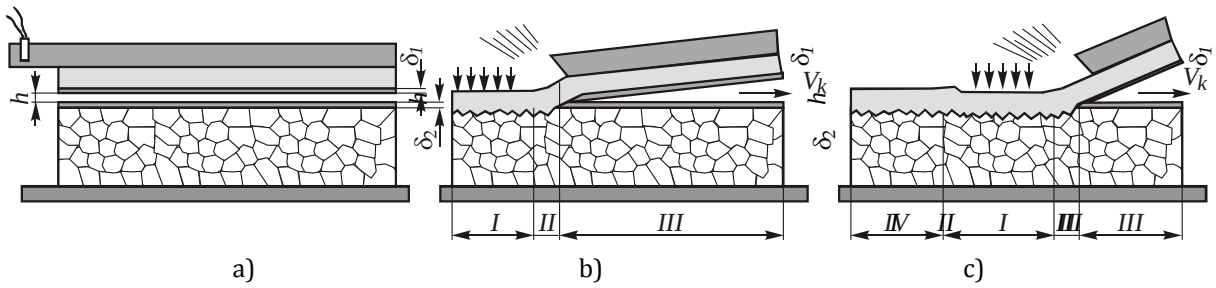


Fig. 2. Stages (a, b, c) of joint formation during explosion welding, I - zone of intensive compaction, II - zone of intense plastic shear, III - zone of action of cumulative current, IV - zone of elastic relief, h - gap between plates before welding, δ1, δ2 - thickness of oxide layers before welding, Vk - direction of cumulative current movement.

As the formation of the wavy shape of the joint is, first of all, the process of plastic deformations of the metal on the collision surface, the collision pressure must be higher than the dynamic strength of the collided materials:

$$P_S > P_{kr} \quad (1)$$

where:

Ps - collision pressure caused by the shock wave of the explosive mixture,

Pkr - critical pressure that depends on the type of collided materials.

The results of experimental tests of collided surfaces show that not only high pressure but also the joint speed (collision point speed) is sufficient, ie that the corrugated joint occurs only at the collision speed which is less than the local sound speed of the collided materials:

$$V_{ts} > V_Z \quad (2)$$

where:

Vts - collision point speed,

Vz- local speed of sound of collided materials.

This expression represents the criterion of the collision speed for the appearance of a wavy shape at the boundary of the collided metal surfaces. The collision parameters (thrust plate velocity, collision point velocity, angle, critical pressure, collision plate thickness, etc.) affect the wave geometry differently.

In the joint zone, due to large plastic deformations, heat is released which can cause local melting of metals in the joint zone. Due to the high values of the parameters, vortices usually appear in the collision, so mutual inclusions of one metal in another are possible (Fig. 3) [10].

Vortexing can have a negative effect on the strength of the joint. Wave parameters (length, amplitude, shape) change depending on the initial conditions of metal joining, and above all the initial angle between the plates, whose increase, the wave parameters increase to a certain value. Therefore, for the analysis of the waveform creation process, corrections related to the amplitude, length and waveform are introduced.

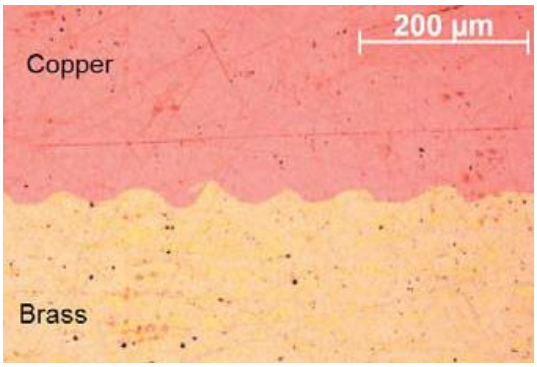


Fig. 3. Image of Cu - brass joint [10].

The metal merges in a millionth of a second, when under the action of high dynamic pressure, created by the explosive mixture, the formation of surface cumulative currents and the quasi-liquid state of the surfaces occurs, Figure 4 [12, 14].

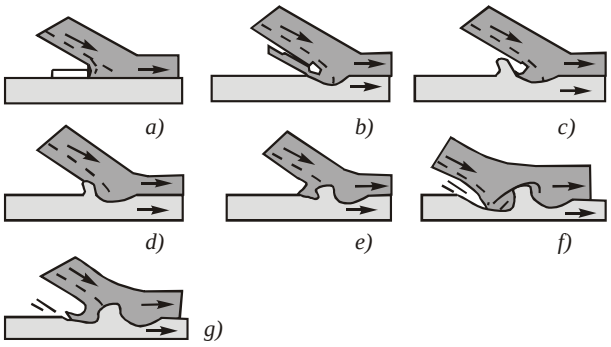


Fig. 4. The mechanism of wave formation in the collision zone: a) moment of deformation start, b) allowing for velocity of the parent plate, c) hump interfering with jet, d) formation of tall, e) formation of forward trunk, f) formation of front vortex, g) completion of process.

The elements of the plate volume gain speed due to the action of the impulse and thus prepared, they collide with the elements of the plate plates at a certain angle. The joint is realized with metal connections due to plastic deformations and in conditions of high speed and pressure. The short coupling time disables the diffusion process or minimizes it.

3. EXPERIMENTAL TESTS

The dimensions of the copper and brass plates, as bimetal plates, were 150×100×2mm. In this experiment, a copper plate with explosives on it was tilted at an angle of 20o, Figure 5. The minimum mutual distance of a copper cladding plate from a clad (basic) brass plate was 5mm.

The explosive charge was initiated by placing an electric detonator (KDE) in the middle of the shorter side of the plate. Plastic pentrite explosive PEP-500, density 1.50 g/cm with a detonation velocity of 7400 m/s, was used as an explosive charge. The thickness of the explosive charge placed on the cladding brass plate is 3 mm. The experiment was performed at the Technical Repair Institute in Kragujevac.

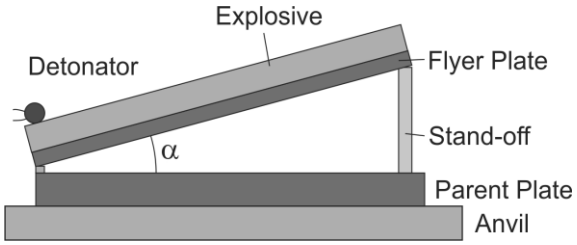


Fig. 5. Position of plates in an explosive welding experiment.

The quality of the brass-copper welded joint included tests of the welded joint:

- surface topography,
- chemical composition,
- microhardness,
- scratch test, i
- tribological characteristics.

All tests were performed at the Center for Tribology, Faculty of Engineering, University of Kragujevac. Before testing the welded brass-copper joint, in the company Valjaonica Bakra, Sevojno, samples were prepared: cutting to dimensions 10x7x4 mm, pouring into plastic and polishing. The cutting was performed so that the examined surface is in the direction of propagation of the shock wave, Figure 6.

a) b)

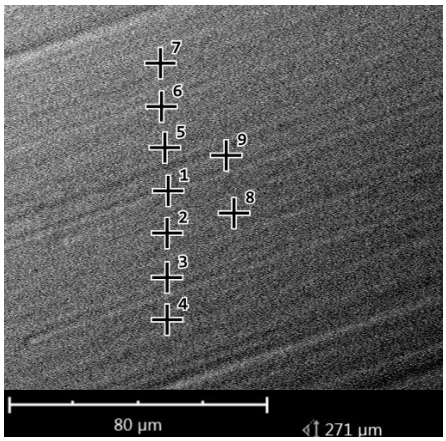
Fig. 6. Samples with welded copper-brass joint; a) after cutting, b) embedded in a resin and polished.

Fig. 7. Optical microscopy - Appearance of a welded joint.

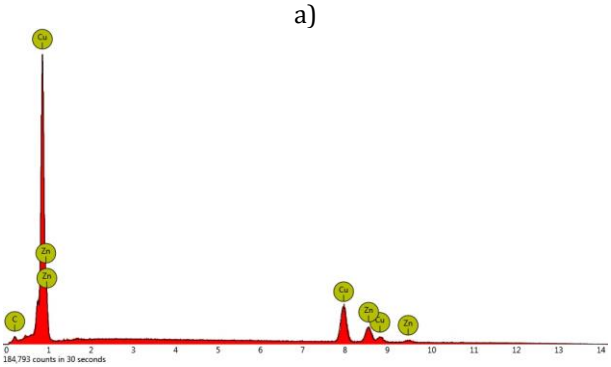
Figure 7 shows the boundary of the welded joint, where the greenish color represents the brass layer and the light brown the copper layer.

3.1 Chemical composition

Tests of a brass-copper weld on a SEM ProX Desktop Phenom scanning microscope include the determination of its chemical composition in the weld zone. The chemical composition of the copper and brass samples was determined in three places, while the chemical composition (Table 1) in the welded joint zone was determined in 9 places according to the matrix in Figure 8.



a)



b)

Fig. 8. Measurement of the chemical composition in the weld zone a) Scanning electron microscopy, position of the measurement point and b) spectral analysis at 8 points of the weld.

Table 1. Chemical composition of the joint

Measurement point	%		
	Carbon	Zinc	Copper
7	6,3	-	93,7
6	6,4	-	93,6
5	5,9	-	94,1
9	6,5	-	93,5
1	6,3	30,8	62,9
8	6,2	35,3	58,5
2	6,4	33,9	59,7
3	6,5	34,6	58,9
4	6,8	34,5	58,7

The appearance of carbon in spectral analysis can be due to several reasons:

- contamination of the vacuum chamber due to inadequate cleaning of the sample,
- inadequate sample preparation for SEM microscope measurement, sample polishing, etc.
- the existence of materials that are close to carbon in the spectrum or misidentification of materials, etc.

3.2 Micro hardness of the welded joint

Mechanical tests were performed using a Micro Scratch Tester & Nano Hardness Tester Anton Paar NHT2. Mechanical tests included the determination of micro / nano hardness and modulus of elasticity of the layers of test materials. These tests of mechanical characteristics involved the penetration of the indentator in the form of a regular three - sided diamond Berkovic pyramid into the surface of the material whose characteristics are determined, Figure 9.

The first brass/copper test was performed with a 1×21 matrix, where the embossing step was 100 μm, ie the total test length ± 1.0 mm in relation to the welded joint (Figure 10, blue line). The second brass/copper test was performed with a 1×25 matrix, where the embossing step was 25 μm, ie the total test width ± 0.3 mm in relation to the welded joint (Figure 10, red line). The injection force was 50 mN.

In Figures 7 and 9, the boundary of the welded joint can be seen, with the greenish color representing the brass layer and the light brown the copper layer. When pressing the three-sided pyramid into brass, an impression of approximately 5 μm was achieved, while when pressing into copper, an impression of about 7 μm was achieved.

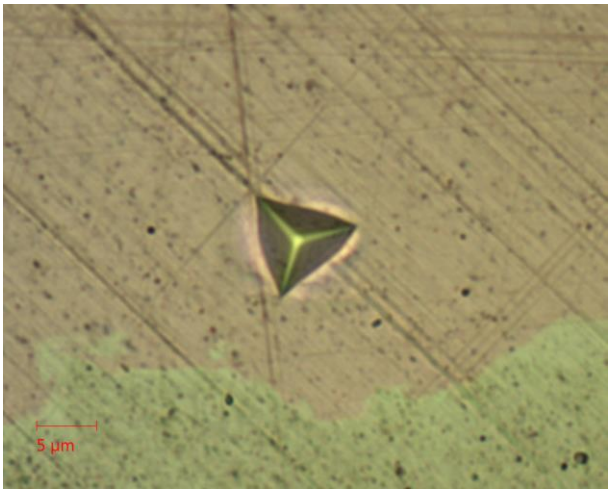


Fig. 9. Optical microscopy - Imprint of the Berkovic pyramid in copper immediately near the welded joint.

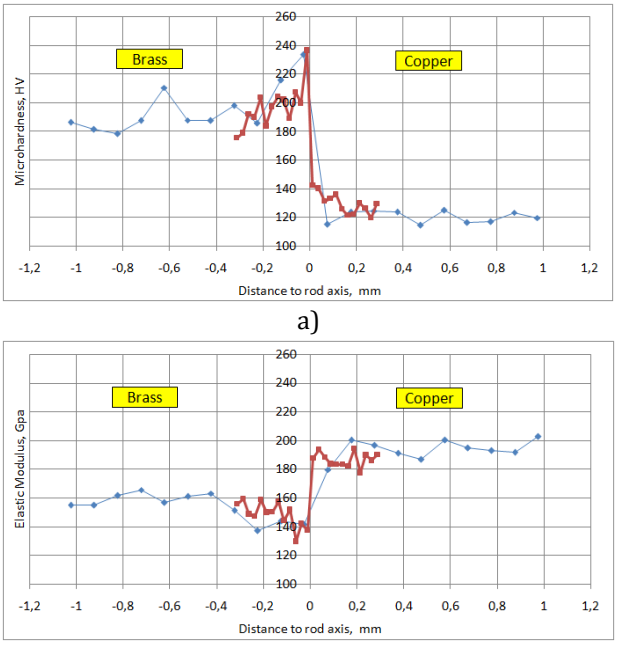


Fig. 10. Diagrams of microhardness and modulus of elasticity in the zone of welded joint brass/copper: a) microhardness and b) elastic modulus.

3.3 Scratch test of welded joint

After measuring the microhardness, a Micro Scratch test was performed. Figure 11 shows the obtained scratch mark, and Figure 12, the diagram of changes in the measured quantities. The sliding distance was 1.0 mm where the boundary of the joint of the two materials was

approximately in the middle of the scratch sliding distance. The scratch test was performed at a constant load force Fn = 0.5 N, a speed of 0.25 mm / min and a radius of the tip of a diamond Rackwell needle of 100 µm.

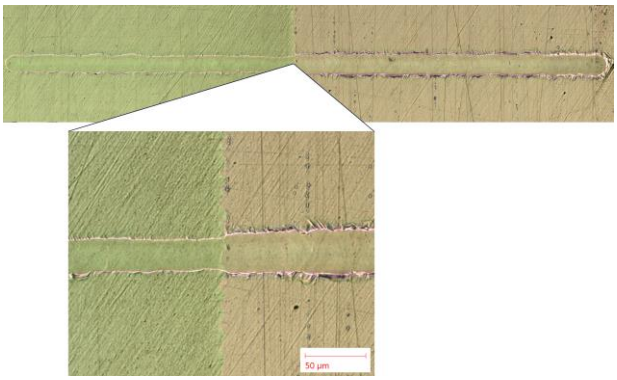
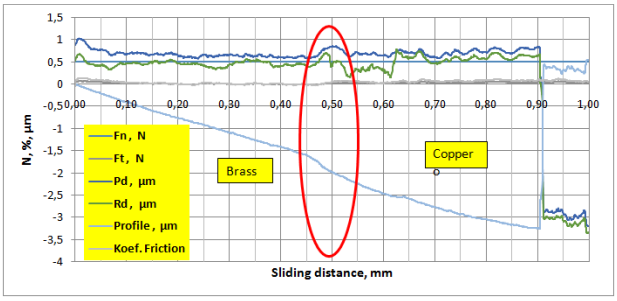
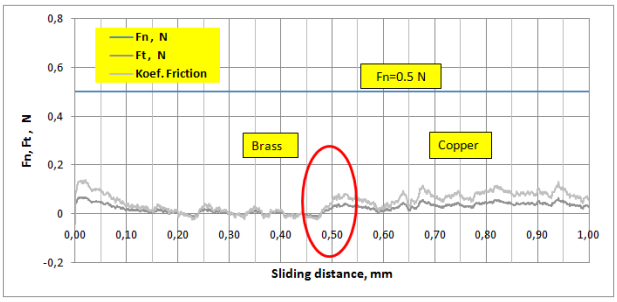


Fig. 11. Optical Microscopy - Micro Scratch wear track.



a)



b)

Fig. 12. Diagram of change of measured quantities in Scratch Test, *Fn* - Applied normal load (Fn=0.5 N), *Ft* - Friction force, *Pd* - Penetration depth during scratch, *Rd* - Residual depth after scratch.

A larger wear track width is observed in copper and greater extrusion of the material towards the edges of the wear track. No significant changes in the measured parameters are observed at the joint. Analysis of the force signal and friction coefficient, as well as other parameters can show the joint location. At the joint, there are changes in the measured parameters, but these changes are not large. The main reason is the different hardness of the material in the joint.

3.4 Topography of the welded joint surface

Measurement of the topography of the surface of the samples of copper, brass and brass/copper was performed on three samples in two places, in Table 2 are the mean values of the measured quantities. It can be concluded that there is no significant difference in surface roughness. Copper as the softest material has a higher roughness, while brass the least, as a material with higher hardness. Figure 13 shows the topography of the surface of the welded brass / copper joint in the transverse direction with respect to the joint line. Table 4 shows the values for Ra and Rmax for the tested samples after polishing.

Table 2. Ra and Rmax surface parameters

	Brass	Copper	Brass/Copper
Ra, µm	0.5	0,8	0.67
Rmax, µm	5.8	5,7	5.6

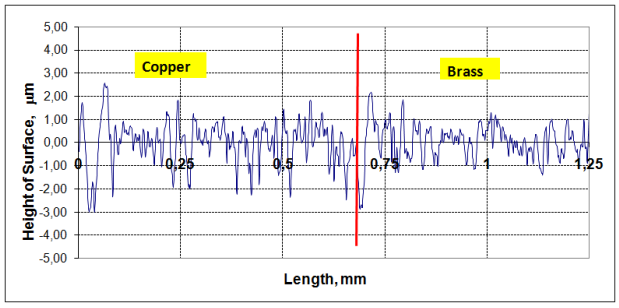


Fig 13. Brass/copper surface profile

3.5. Tribological tests

Tribological tests were performed in the Tribology Laboratory on the TPD-95 tribometer. Samples measuring 4x4x15 mm were made of brass/copper bimetal, using three sides of the test specimens. Normal load was 20 N, and slip speeds: 0.25; 0.5 and 0.75 m/s. The length of the test path was 50 m. The contact was without lubrication. The disc with a diameter of 35 mm and a width of 6.3 mm is made of 30CrNiMo8 steel, hardness 60-62 HRC.

Tribological tests were aimed at measuring the force and coefficient of friction of materials in the joint measurement and wear of bimetals.

Figure 14 shows the change in the coefficient of friction for the tested materials. It can be concluded that the lowest coefficient of friction in the brass samples is, while the coefficient of friction in the copper samples and the welded joint samples is approximately the same.

Figure 15 shows the change in the volume of the wear track on the sample with the welded joint. As the sliding speed increases, the width of the wear track increases, and thus its volume.

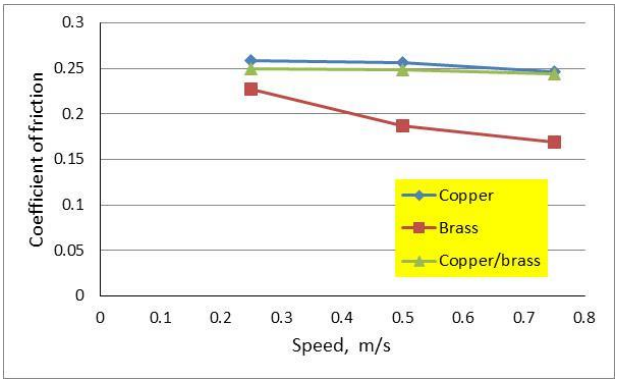


Fig. 14. Coefficient of friction

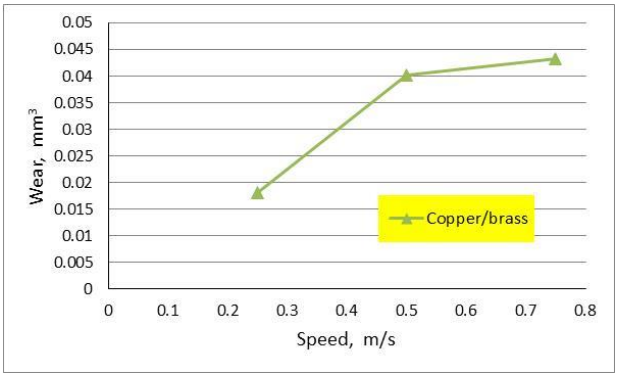


Fig. 15. The volume of the wear track in a sample with a welded joint

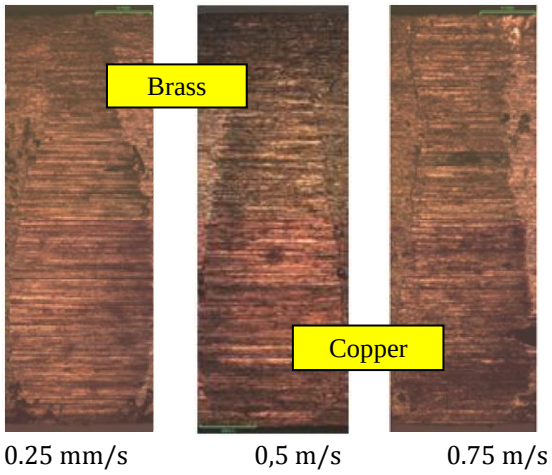


Fig. 16. Wear track in samples with brass/copper welds

4. CONCLUSION

Using microscopy, chemical analysis and SEM microscopy, it can be concluded that there is a clear boundary between explosively welded materials. There is a mixing of materials in the joint, which is manifested by the appearance of waves, while the spectral analysis did not show the diffusion of one material into another. A detailed analysis of the copper/brass joints did not show the melting of any material in the joint. The formed welded joint is with waves properly distributed, height 5-7 μm and length 20-25 μm. Microhardness measurements and the Scratch test did not show a significant change in the hardness or modulus of elasticity of the tested materials in the welded joint. Tribological tests have shown that the lowest coefficient of friction at the contact of the steel disc and the brass block, while the coefficient of friction in the samples of copper and samples with welded joints is approximately equal. The wear of the brocade with the welded joint was more intense on the copper side, as a softer material.

All realized tests have shown that from the aspect of metallurgical and mechanical and tribological properties, the newly obtained bimetallic material has retained the properties of the material from which it is made and that the joint has no new properties.

Acknowledgement

This paper is part of project TR35034 The research of modern non-conventional technologies application in manufacturing companies with the aim of increase efficiency of use, product quality, reduce of costs and save energy and materials, funded by the Ministry of Education, Science and Technological Development of Republic of Serbia.

REFERENCES

[1] K. Faes, T. Baaten, W. De Waele, N. Debroux, *Joining of Copper to Brass Using Magnetic Pulse Welding*, in 4th International Conference on High Speed Forming – ICHSF2010, 9-10 March, 2010, Ohio, The Ohio State University, USA, pp. 84-96.

[2] L. Brown, *Cost-Effective Manufacturing: Joining of Copper and Copper Alloys*, CDA Publication, UK, 1994.

[3] *Explosion Cladding by Vacuum Technology*, available at: https://smt-

holland.com/img/files/SMT_Brochure.pdf, accessed: 29.11.2020.

[4] A.G., Pantazopoulos, A.I. Toulfatzis, *Fracture Modes and Mechanical Characteristics of MachinableBrass Rods*, Metallography, Microstructure, and Analysis, vol. 1, pp. 106–114, 2012, doi: 10.1007/s13632-012-0019-7

[5] H. Wang, Y. Wang, *High-Velocity ImpactWelding Process: A Review*, Metals, vol. 9, iss. 2, pp. 1–18, 2019, doi: 10.3390/met9020144

[6] G. Pantazopoulos, A. Vazdirvanidis, *Characterization of the Microstructural Aspects of Machinable Alpha-Beta Phase Brass*, Microscopy and Analysis, vol. 22, no. 5. pp. 13-16, 2008.

[7] K. Faes, *Joining of Dissimilar Materials: Weldability of Copper to Brass and Aluminium to Steel using Magnetic Pulse Welding*, Belgian Welding Institute Nicolas Debroux CEWAC, pp. 1-17, 2010.

[8] F. Gharavi, I. Ebrahimzadeh, K. Amini, B. Sadeghi, P. Dariya, *Effect of Welding Heat Input on the Microstructure and Mechanical Properties of Dissimilar Friction Stir-Welded Copper/Brass Lap Joint*, Materials Research. vol. 22, no. 4, pp. 1-12, 2019, doi: 10.1590/1980-5373-MR-2018-0599

[9] T.Z. Blazynski, *Explosive Welding, Forming And Compaction*, Springer Netherlands, 1983.

[10] J. Verstraete, W. De Waele, K. Faes, *Magnetic Pulse Welding: Lessons To Be Learned From Explosive Welding*, in Conference: Sustainable Construction and Design, 16-17 February, 2011, Ghent University, Ghent, Belgium, pp. 458-464.

[11] V. Ghizdavu, N. Marin, *Explosive Forming – Economical Technology For Aerospace Structures*, INCAS BULLETIN, vol. 2, no. 4, pp. 107–117, 2010, doi: 10.13111/2066-8201.2010.2.4.15

[12] A.S. Bahrani, T.J. Black, Bernard Cossland, *The mechanics of wave formation in explosive welding*, Proceedings of the royal society, Series A, vol. 296, no. 1445, pp. 123–159, 1967, doi: 10.1098/rspa.1967.0010

[13] A.A. Ezra, *Principles and Practice of Explosive Metal Working*, London: Industrial Newspapers Limited, 1973.

[14] E.P. Carton, *Wave Forming Mechanisms in Explosive Welding*, Materials Science Forum, vols. 465-466, pp. 219–224, 2004, doi: 10.4028/www.scientific.net/MSF.465-466.219