Tribology and Materials
Vol. x, No. x, 202x, pp. xx-xx
ISSN 2812-9717
https://doi.org/10.46793/tribomat.2024.006

Cavitation resistance of explosively welded aluminium/steel joint

Miloš LAZAREVIĆ [1], Danica M. BAJIĆ [2,3,*], Jelena MARINKOVIĆ [2], Ana ALIL [4]

[1] University of Kragujevac, Faculty of Engineering, Kragujevac, Serbia
[2] Military Technical Institute, Belgrade, Serbia
[3] University of Defence in Belgrade, Military Academy, Belgrade, Serbia
[3] University of Belgrade, Institute of Chemistry, Technology and Metallurgy, Belgrade, Serbia
*Corresponding author: danica.bajic@mod.gov.rs

Keywords
explosive welding
ultrasonic cavitation
aluminium
steel
cavitation wear

History
Received: 24-03-2024
Revised: 07-05-2024
Accepted: 12-05-2024

Abstract
Explosion welding is an unconventional method of joining two dissimilar metal materials, mostly used to clad dissimilar materials or when some unusual geometries need to be joined. Some of the bimetal joints obtained this way have applications in special cutting tools, transition joints, propellers and turbine blades, and therefore it is important to know the wear resistance of welded joints. In this research, explosive *Demex*, based on ammonium nitrate and trinitrotoluene, was used to weld plates of aluminium alloy AW-2024 and steel 1.0216. The welding procedure was carried out in the configuration of parallel plates. The quality of the welded joint was inspected on samples cut out from the welded plate by the method of microscopic analysis on the cross-section and by an ultrasonic cavitation test. Materials erosion in the zone of the welded joint after each of 4 cavitation cycles was observed using an optical microscope and by monitoring the mass loss. The wear resistance of the created bimetal was analysed from the aspects of further exploitation.

1. Introduction

Explosive welding is a unique process that involves usage of the explosive energy to join two dissimilar metals together. This method is particularly useful when traditional welding techniques are not feasible due to the significant differences in the properties of the materials being joined. By utilising explosive energy, the atoms of the two materials are forced to intermix at the interface, creating a strong metallurgical bond. Explosive welding is often applied in the production of corrosion resistant vessels and pipes, in specialised cutting tools, turbine blades, transition joints, antenna masts, propeller blades, ballistic protection of vehicles and other specific applications where the combined properties of two dissimilar materials are desired and where two larger surfaces of metal plates are cladded one onto another [1-7]. It is often used to create bimetal plates consisting of one more expensive material of specific properties and the other cheaper material, as a carrier of the construction [3,8-10]. The process of explosion welding is carried out as follows: the flyer (cladding) metal plate is positioned parallel or inclined to the base plate, the explosive is evenly applied over the cladding metal, and when the detonation takes place the cladding plate collides with the base plate. In this fast collision, the welded joint is created, most often in the shape of waves at the interface [1,5,9].

A quality inspection of the welded joint is essential to guarantee the structural integrity and reliability of the joint. Visual inspection of the obtained bimetal plate is often the first step, followed by more advanced non-destructive testing methods such as ultrasonic testing, radiographic testing and chemical penetrant testing. These techniques help identify defects, cracks, or discontinuities in the welded joint that could lead to failure in the exploitation [11,12].

Besides the mentioned methods of quality inspection of the welded joints, one unusual method can be performed on the welded joint cross-section – the cavitation wear test, especially on those bimetal joints intended for use as cutting tools, propellers, or turbine blades and other applications where the joint is exposed to rapid pressure changes. This test involves exposing of the welded joint to high-velocity liquid flow, which creates bubbles that can cause cavitation erosion. Ultrasonic cavitation is a phenomenon where high-frequency sound waves are used to create cavitation bubbles in a liquid. This process can be utilised for various applications, to clean surfaces, enhance chemical reactions, disperse particles, or even modify materials.

In the context of inspection of the quality of the explosively welded joint, ultrasonic cavitation can be employed to analyse the cavitation wear resistance of the metals at the joining area, the difference in their erosion, and possibly reveal any hidden defects that may not be visible through traditional inspection methods. This new approach could be helpful in the validation of welded joint integrity.

In this research, explosive *Demex* was used to weld plates of two typical dissimilar metals, aluminium and steel. The resistance of the welded joint cross-section to cavitation wear was examined by ultrasonic cavitation. This aluminium-steel bimetal could have potential use for connecting aluminium roofs, masts and antennas to steel structures, to obtain reduced weight and increased stability of the structure, as well as in shipbuilding in the construction of ship's formwork or propellers.

2. Materials and experimental methods

2.1 Materials

For the experimental procedure of welding, an explosive with the trademark *Demex* (Trayal Corporation) was used. This explosive has a powdery consistency and its main ingredients are ammonium nitrate (~ 95.5 wt. %) and trinitrotoluene (~ 2 wt. %), with the addition of small amounts of several inert ingredients. The detonation velocity of the explosive, determined using optical probes and an oscilloscope, was 2450.2 m/s and its bulk density was 761.8 g/dm^3. The quantity of the explosive was calculated according to the properties of the plates to ensure the joining of the two selected metals [1,13-15] and the needed equivalent mass of this explosive was 530 g.

Plate surfaces of aluminium alloy AW-2024 (dimensions 200 × 150 × 3 mm) and steel 1.0216 (dimensions 200 × 150 × 10 mm) were prepared for the welding procedure by polishing and cleaning.

2.2 Explosive welding procedure

The metal plates were placed parallel to each other, parallel to the ground, with small spacers in the corners of the plates which provided a 4 mm distance between the plates to be welded. The steel plate was the base plate and the thinner one, the aluminium plate, was the flyer plate, i.e. the cladding plate. Powdery explosive *Demex* in the required quantity was poured on top of the upper plate. It is necessary to prevent uneven distribution or dissipation of the explosive powder over the edges of the metal plates, therefore a wooden frame was used of defined height to ensure that the layer of the explosive material is uniform and thick enough. Figure 1 depicts the scheme of the explosive welding procedure.

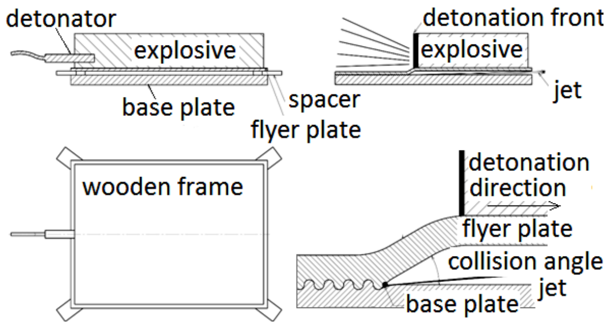

Figure 1. Explosive welding set-up scheme

2.3 Microstructural inspection

After metallographic preparation (by grinding and polishing, with a grinder and sandpaper), samples were etched in a 3 % solution of nitric acid. Microstructure was examined on the Leica M205 A stereo microscope and the Leitz Metalloplan optical microscope equipped with a DFC295 camera and LAS 4.3.1 image processing software. Microscopic analyses were performed before the cavitation test and after each cycle.

2.4 Microhardness

The microhardness of the welded joint zone was tested by the Vickers hardness method on the Wilson DiaMet device. There were 4 indents made on each side of the welded joint and the distance between the indents was 50 μm. The normal load was 0.1 kgf (0.98 N).

2.5 Ultrasonic cavitation test

The resistance of the welded materials in the zone of the welded joint to cavitation wear was examined using an ultrasonic processor Sonopuls HD 4100 (BANDELIN electronic). Three samples cut from the bimetal plates were exposed to ultrasonic cavitation in distilled water, placing the sample fixed at 0.5 mm from the sonotrode. The test was performed in 4 cycles of 60 minutes, at room temperature (20 – 22 °C). The sonotrode (ultrasonic probe) was solid, 12.7 mm in diameter. Samples that were subjected to this test were not cut perfectly even, their approximate dimensions were: 18 – 20 mm (length), 10 mm (width) and 13 mm (thickness). The size of the affected zone was somewhat smaller than the sonotrode diameter since the aim was to encompass both materials and the welded joint interface to be most affected by the cavitation. The same pieces were tested in all 4 cycles. The ultrasonicator was set to 20 kHz, 60 W of power. The experimental set-up is shown in Figure 2.

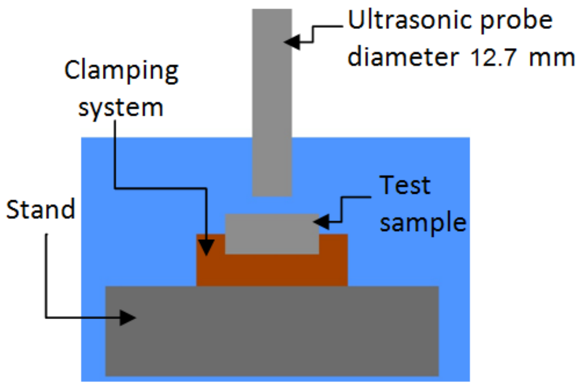

Figure 2. Scheme of ultrasonic cavitation test set-up

After each cycle of cavitation, the samples were dried to a constant mass and the mass loss was measured. The appearance of damage in the welded joint interface of the material was observed using a Leica M205 A stereo microscope.

3. Results and discussion

3.1 Microstructure

The appearance of the obtained welded joint is shown in Figure 3. The characteristic wavy shape can be observed. Precisely, small curled waves were observed, with certain intermediate material – intermetallic zone. Similar observations were reported by other authors [9]. An intermetallic zone is formed during the joining or interaction between two or more metals, as an area where the melting occurs, as well as the formation of alloys or compounds between these metals. This zone can be narrow or wide, depending on the welding process and the types of metals involved. It often has different mechanical, chemical or thermal properties compared to the metals included in it. Here, most probably a small extent of aluminium underwent melting in this zone due to lower melting temperature (detail shown in Fig. 3), and also probably there could be formed Fe_4Al_{13} and Fe_2Al_5 at the interface [9]. The formation of a liquid phase on the interface surface is typical for high-speed impact welding. When the surfaces of the two metals being explosively welded are exposed to the shock-compressed gas flow in front of the contact point (with temperatures of several thousand degrees), the colliding surfaces can be heated up to several hundred degrees [16], leading to the melting of the metals on the contact layers. When welding different materials, it is often noticed that twisting in a wavy shape occurs within these areas, so such melting zones are often called vortices [14,17]. This vorticity is attributed to the local plastic deformation of surface materials by the cumulative jet generated as a result of the collision. Specific vorticity can be seen by observing the plastic deformation of ferritic grains in the vicinity of the vortices (Fig. 3).

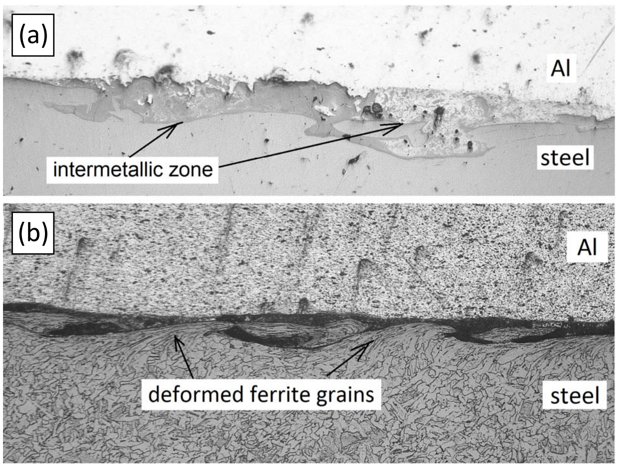

Figure 3. Welded joint: (a) polished and (b) etched

3.2 Microhardness

Results of the Vickers microhardness measurement are presented in Figure 4. As observed, there is a slight increase in the hardness on the side of the steel plate right before the welded joint line. On the side of aluminium, the hardness is more uniform, with a slight increase in the hardness near the interface (joint line). There was no decrease in hardness in the zone of the joint line, which means that there is no typical heat-affected zone of the welded joint that appears when conventional welding methods are used [18].

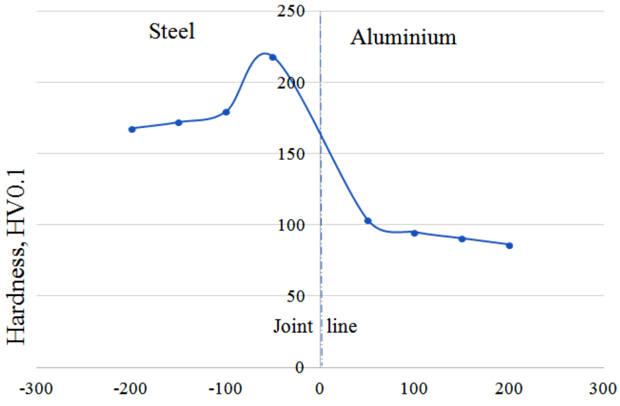

Figure 4. Vickers hardness in the vicinity of the welded joint

3.3 Cavitation wear

The values of mass loss of the examined samples, taken from the welded plate, registered after each of four 60-minute cycles of ultrasonic cavitation, are given in Table 1. The cumulative curves of the mass loss, i.e. wear curves are shown in Figure 5.

Table 1. Cavitation wear resistance – mass loss

Sample	Δm_1, mg	Δm_2, mg	Δm_3, mg	Δm_4, mg	Total, mg
1	20.2	6.8	4.6	1.6	33.2
2	19.4	3.5	3.7	1.3	30.1
3	18.9	5.9	3.9	1.4	27.9
Average	19.5	5.4	4.1	1.4	30.4
SD	0.7	1.7	0.5	0.2	2.7

SD – standard deviation

The examined samples had total mass losses in the range of 27.9 to 33.2 mg. All three obtained cavitation wear curves have very similar trends, confirming the repeatability of the test method. There can be noted one significant difference in mass losses at the end of 2nd cycle, where for the three samples, the measured mass losses were: 6.8, 3.5 and 5.9 mg. The most probable reason for this difference may be that, at the beginning of the cavitation wear process, the erosion of the material is most pronounced, while later on it becomes more uniform and less invasive.

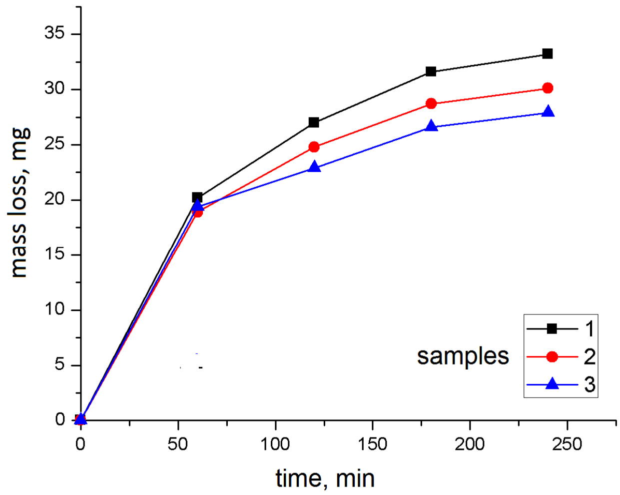

Figure 5. Wear curves for the examined samples

The appearance of the treated zone of the welded joint after four cycles of cavitation, recorded by a stereo microscope, is shown in Figures 6 to 9. In the following figures, the upper metal is aluminium and the lower material is steel. The ultrasonic probe had a circular cross-section, so the trace of cavitation wear is in the shape of a part of the circle. The wear traces are not complete circles as the sonotrode has a diameter of 12.7 mm and the thickness of the sample is somewhat below 13 mm (after grinding and sending which were done to obtain flat plates after the explosion welding).

As it may be observed, there is a step-by-step erosion after each cycle and, as expected, the aluminium side of the welded joint suffered from severe wear damage, far more pronounced than in the case of the steel side. Due to differences in electrochemical potential between aluminium alloy and steel, cavitation erosion is more intensive on the side of aluminium and the damage on the side of the aluminium surface covers an even larger area, wider than the cross-section of the sonotrode. After the 1st cycle a limited cavitation pitting occurred, and in the following cycles pits enlarged and appeared all over the treated area of the metal surface.

The appearance of corrosion (denoted with arrows in Fig. 8) may be noticed on the steel side, as the characteristic dark red-brown colouration of the surface. However, the welded joint itself has preserved its integrity, since these corrosion islands and pits are evenly distributed all over the treated surface, not concentrated near the joint line. Corrosion-related features of this kind of welded joints will certainly be an interesting perspective for further research.

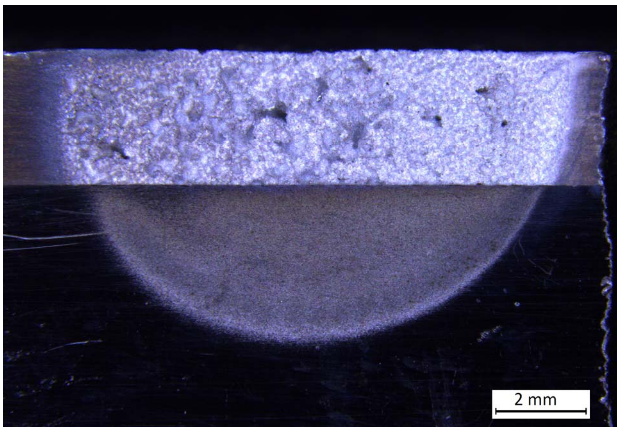

Figure 6. Sample after 1st cycle of cavitation

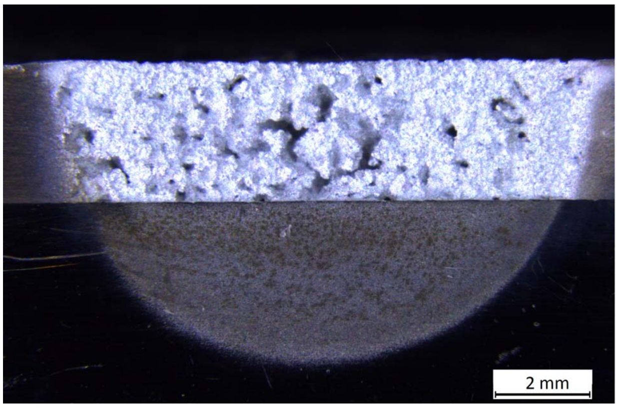

Figure 7. Sample after 2nd cycle of cavitation

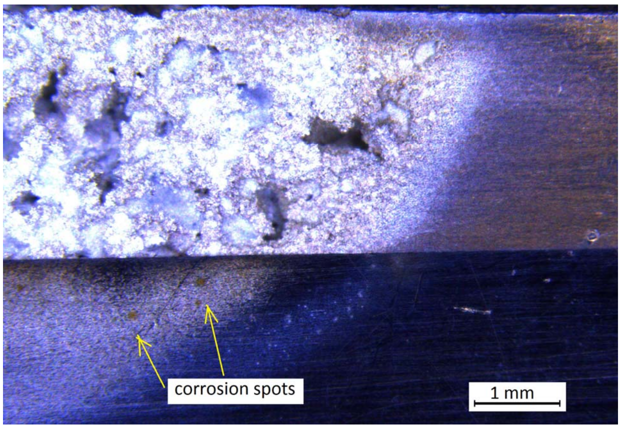

Figure 8. Sample after 3rd cycle of cavitation

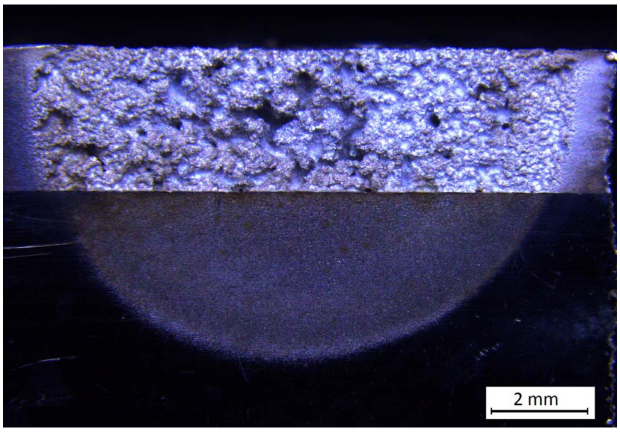

Figure 9. Sample after 4th cycle of cavitation

4. Conclusions

Explosively welded joints of aluminium alloy and steel were examined. Microscopic analyses have revealed that the welding procedure was successful – the welded joint with the expected wavy shape was obtained, with the appearance of a small amount of molten metal in the vortices of the waves, as an intermetallic zone. Microhardness in the vicinity of the welded joints is somewhat higher than in the base plate or the cladding material and no decrease in hardness is observed in this zone.

The cavitation resistance test showed that there was no grouping of cavitation pits at the joint, but they were evenly distributed over the surface. All the samples show a gradual mass loss with time under ultrasonic cavitation.

As a non-conventional method in this field, analysed together with the microstructure and microhardness results, the ultrasonic cavitation test is helpful from the point of a comprehensive approach to ensuring the reliability and durability of joints between aluminium alloy and steel plates in future exploitation in demanding industrial environments.

Acknowledgement

This work was supported by the Republic of Serbia, Ministry of Science, Technological Development and Innovation, contract no. 451-03-66/2024-01/200325 and 451-03-66/2024-03/200026, and University of Defence, Military Academy, project no. VA-TT/1/22-24.

References

[1] H. El-Sobky, Mechanics of explosive welding, in T.Z. Blazynski (Ed.), Explosive Welding, Forming and Compaction, Springer, Dordrecht, 2012, pp. 189-217, DOI: 10.1007/978-94-011-9751-9_6

[2] I. Krivtsun, V. Kvasnytskyi, V. Korzhyk, Solid-state welding, in F. Khoshnaw (Ed.), Welding of Metallic Materials, Elsevier, Amsterdam, 2023, pp. 149-195, DOI: 10.1016/B978-0-323-90552-7.00016-X

[3] B.B. Sherpa, R. Rani, Explosive welding process to clad materials with dissimilar metallurgical properties, in S. Kumar (Ed.), Material Flow Analysis, IntechOpen, Rijeka, 2021, ch. 2, DOI: 10.5772/intechopen.94448

[4] N. Becker, D. Gauthier, E.E. Vidal, Fatigue properties of steel to aluminum transition joints produced by explosion welding, International Journal of Fatigue, Vol. 139, 2020, Paper 105736, DOI: 10.1016/j.ijfatigue.2020.105736

[5] S.A.A. Akbari-Mousavi, L.M. Barrett, S.T.S. Al-Hassani, Explosive welding of metal plates, Journal of Materials Processing Technology, Vol. 202, No. 1-3, 2008, pp. 224-239, DOI: 10.1016/j.jmatprotec.2007.09.028
[6] G. Costanza, V. Crupi, E. Guglielmino, A. Sili, M.E. Tata, Metallurgical characterization of an explosion welded aluminum/steel joint, La Metallurgia Italiana, Vol. 108, No. 11, 2016, pp. 17-22.
[7] V. Philipchuk, F. Le Roy Bois, Explosive Welding, United States Patent Office, Patent No. 3,024,526, 1962.
[8] G.H.S.F.L. Carvalho, I. Galvão, R. Mendes, R.M. Leal, A. Loureiro, Explosive welding of aluminium to stainless steel, Journal of Materials Processing Technology, Vol. 262, 2018, pp. 340-349, DOI: 10.1016/j.jmatprotec.2018.06.042
[9] G.H.S.F.L. Carvalho, I. Galvão, R. Mendes, R.M. Leal, A. Loureiro, Aluminum-to-steel cladding by explosive welding, Metals, Vol. 10, No. 8, 2020, Paper 1062, DOI: 10.3390/met10081062
[10] T. Kovacs-Coskun, B. Volgyi, I. Sikari-Nagl, Investigation of aluminum-steel joint formed by explosion welding, Journal of Physics: Conference Series, Vol. 602, 2015, Paper 012026; DOI: 10.1088/1742-6596/602/1/012026
[11] B.B. Sherpa, S. Kumar, A. Upadhyay, P.D. Kumar, A. Aggrawal, S. Tyagi, Interface study of explosive welded Al-steel joint using ultrasonic phased array technique, in Proceedings of the 31st International Symposium on Ballistics, 04-08.11.2019, Hyderabad, India, pp. 2280-2290, DOI: 10.12783/ballistics2019/33266
[12] B.B. Sherpa, A. Upadhyay, S. Kumar, V. Mangla, P.D. Kumar, A. Agarwal, Examination of joint integrity in parallel plate configuration of explosive welded SS-Al combination, Materials Today: Proceedings, Vol. 4, No. 2, 2017, pp. 1260-1267, DOI: 10.1016/j.matpr.2017.01.146
[13] M. Tabatabaee Ghomi, Impact Wave Process Modeling and Optimization in High Energy Rate Explosive Welding, Licentiate theses, School of Sustainable Development of Society and Technology, Mälardalen University, Västerås, 2009.
[14] I.A. Bataev, S. Tanaka, Q. Zhou, D.V. Lazurenko, A.M. Jorge Junior, A.A. Bataev, K. Hokamoto, A. Mori, P. Chen, Towards better understanding of explosive welding by combination of numerical simulation and experimental study, Materials & Design, Vol. 169, 2019, Paper 107649, DOI: 10.1016/j.matdes.2019.107649
[15] B.B. Sherpa, P.D. Kumar, A. Upadhyay, S. Kumar, A. Agarwal, S. Tyagi, Low velocity of detonation explosive welding (LVEW) process for metal joining, Propellants, Explosives, Pyrotechnics, Vol. 45, No. 10, 2020, pp. 1554-1565, DOI: 10.1002/ prep.202000019
[16] S.V. Khaustov, S.V. Kuz'min, V.I. Lysak, V.V. Pai, Thermal processes in explosive welding, Combustion, Explosion, and Shock Waves, Vol. 50, No. 6, 2014, pp. 732-738, DOI: 10.1134/S0010508214060161
[17] X. Wu, C. Shi, K. Feng, L. Gao, W. Li, K. Qian, Experimental and numerical approach to titanium-aluminum explosive welding, Materials Research Express, Vol. 8, No. 9, 2021, Paper 096503, DOI: 10.1088/2053-1591/ac2017
[18] S.V. Khaustov, V.V. Pai, Y.L. Lukyanov, V.I. Lysak, S.V. Kuz'min, Simulation and experimental determination of temperature in the joint zone during explosive welding, Thermal Science and Engineering Progress, Vol. 30, 2022, Paper 101240, DOI: 10.1016/j.tsep.2022.101240