

Original Article

Rotary friction welding of Al/Al₂O₃ Composites with Aluminium Alloys

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Abstract: Friction welding is one of the most economical process of joining solid-state materials. This technique allows to weld similar and dissimilar materials in a very short time. Friction welding of metal with composites gives new possibilities of application, due to the fact that materials have different physical and mechanical properties. In the study, aluminum alloy 44200 was friction welded to Al/Al₂O₃ composite. In addition, the following inspections were performed: optical microscopy, microhardness measurements and also tensile strength for all joints produced by friction welding. All of the studies were performed to evaluate the quality of connection between the 44200 alloy and the composites on the aluminum alloy matrix reinforced with ceramic phase of Al/Al₂O₃.

Keywords: friction welding; aluminium alloys; ceramics; Al composites

Introduction

The use of composite materials based on light alloys has a number of benefits. The group of composite materials based on aluminum alloys reinforced with the Al₂O₃ ceramic phase is of particular importance here. [1]

Composites based on Al alloys are increasingly used, especially in loaded structures [2], meeting high strength properties. In addition, they are characterized by corrosion resistance, higher wear resistance combined with a low density and a low coefficient of thermal expansion. More and more often they are used where it is important to reduce the weight of subassemblies, while maintaining mechanical parameters. The area of potential application of composite materials is the automotive industry [3].

Taking into account the requirements and the simultaneous reduction of production costs, it is crucial to develop new technologies for joining composites with other materials. One of such methods is friction welding [4,5].

The basic material used during the research was 44200 aluminum alloy, which is used in the automotive industry for components of internal combustion engines. The 44200 alloy, which was the matrix, was also used to produce composite materials from the Al/Al₂O₃ group. Ceramic alumina particles were used to reinforce the composite. Composite materials used in the work were produced by pressure infiltration of ceramic blocks with porosity of 70% and 80%.

Both the choice of alloy and composite materials used in the work was not accidental. Type 44200 aluminum alloy is one of the most commonly used in the automotive industry, and the composites used were developed as part of the KomCerMet project (POIG.01.03.01-00-013/08-00) precisely in order to improve the properties (important from the point of view of automotive applications) of the pure alloy [6]. The use of composites with two different contents of the ceramic phase was to show which of them would have the greater application potential. The share and morphology of the various phases of the composite significantly affect the weldability [7].

During the friction welding process, kinetic energy is converted into thermal energy due to friction. The whole process consists of joining two elements in solid-state, one of which is placed in a stationary holder, and the other is subjected to a rotational movement in relation to their axis. The materials are brought closer together, and then the friction resulting from the pressure force P_t is set (Fig. 1). Heat is generated by friction between the surfaces to be joined. The surfaces of the materials to be welded heat up to a high temperature, close to the melting point of metal, but do not exceed it. After the rotation is stopped, the materials are pressed with the force P_s , usually greater than the force P_t . The highly plasticized material from the friction zone moves to the flash, and the joined elements are shortened.

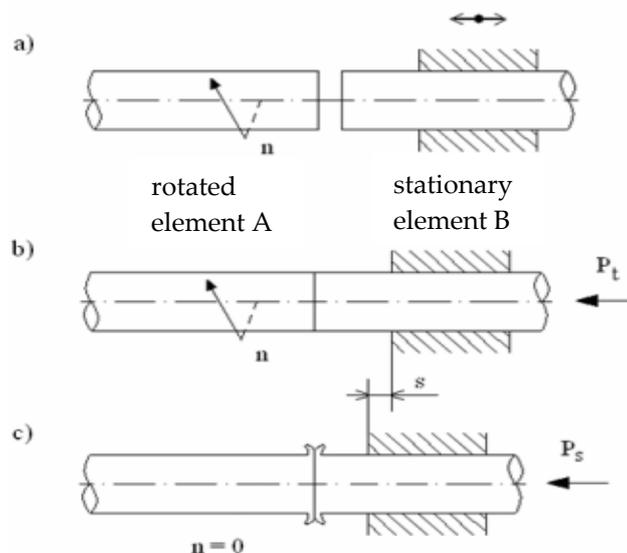


Fig. 1. The course of the friction welding process: a) setting the rotational speed n , b) pressure of the joined elements by the P_t force, c) increasing the pressure force after stopping the rotation

The main feature that must be characterized by composite-metal joints is usually high mechanical strength in conditions of significant temperature amplitudes. This problem is difficult due to the high hardness and brittleness of composite materials [8,9]. Thus, obtaining a high-quality metal-composite joint comes down to shaping an appropriate transition layer between these materials [10,11].

Additionally, when joining materials with different properties, problems arise due to differences in hardness, melting point, thermal conductivity and micro-structure [12]. Friction welding makes it possible to combine two dissimilar materials whose physicochemical properties are different. Thanks to the friction welding technique, very high-quality joints are obtained in a short time [13].

Friction welding of Al 44200 alloy with Al/Al₂O₃ composites

Characterization of materials

The starting material used in the works was 44200 aluminum alloy, containing the following alloying elements: Si, Fe, Cu, Mg and Ni (Table I). The material belongs to the group of eutectic alloys – high silicon content – 11%. Al-Si alloys form an eutectic with a composition of 11.7% Si, with a melting point of 577 °C, composed of crystals of a solid silicon solution in aluminum and a solid β solution of aluminum in silicon.

Table I. Chemical composition of 44200 alloy

Chemical composition						
Fe	Si	Mn	Ti	Cu	Zn	Others
max 0.55	10.5÷13.5	0.35	0.15	0.05	0.1	0.15

The alloy is characterized by very good casting properties (Table II). It is mainly used in the automotive industry, it is used for components of internal combustion engines (pistons, heads). Its microstructure is shown in Figure 2.

Table II. Selected physical properties of 44200 alloy

Material	Density [g/cm ³]	Cp [J/(g*K)]	$\alpha \cdot 10^{-6}$ [1/K]
Al	2.66	0.9	23.86
Al (44200) alloy	2.64	0.9	23.86

The hardness of 44200 alloy was measured by the Vickers method on a Struers Durascan 10. The average hardness of the alloy was 51 HV0.3.

For the welding tests with the EN AC-44200 aluminum alloy, composite materials were used, made on the basis of the 44200 cast aluminum alloy. The composites used in the work were produced by the Wrocław University of Science and Technology using the pressure infiltration technique of porous ceramic blocks made of Al₂O₃ particles with sizes in the range of 3÷6 μ m.

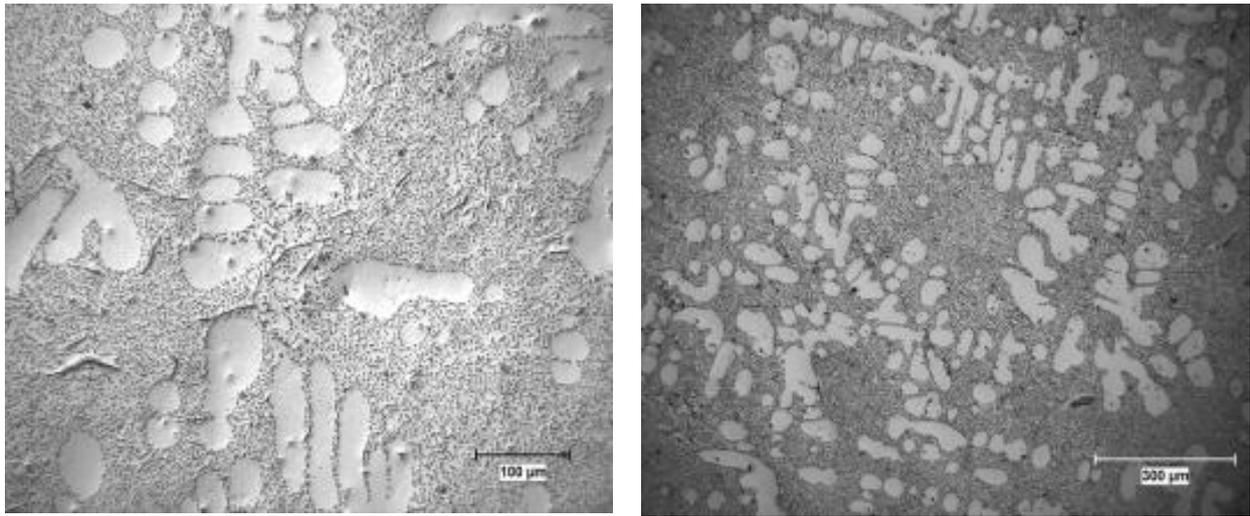


Fig. 2. Microstructure of 44200 alloy

Two types of composite material were used:

- Al 44200 alloy, reinforced with Al_2O_3 particles with a 30% volume fraction:

Volumetric composite, the matrix of which is 44200 alloy, the reinforcement is a ceramic block with a porosity of 70%. Microscopic examinations showed that the aluminum oxide particles are evenly distributed in the alloy matrix (Fig. 3a).

The hardness of the composite was measured by the Vickers method and was 140 HV0.3. The composite is characterized by high hardness, almost three times higher than that of the 44200 aluminum alloy.

- Al 44200 alloy, reinforced with Al_2O_3 particles with a 20% volume fraction.

A ceramic block with a porosity of 80% was used. The structure tests showed a good distribution of the Al_2O_3 ceramic phase in the composite (Fig. 3b).

The hardness of the composite measured by the Vickers method was: 110 HV0.3.

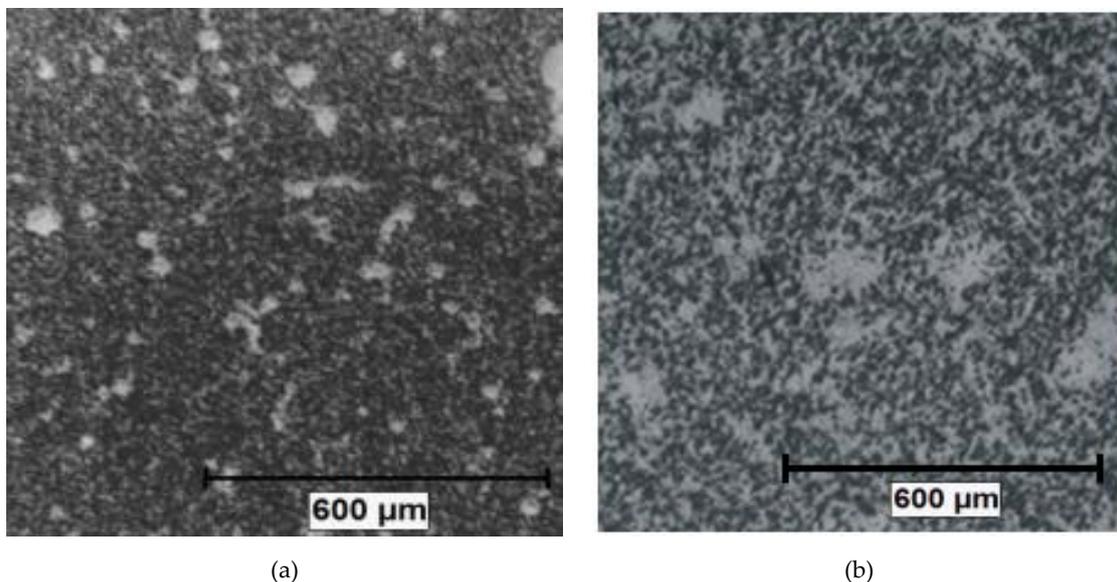


Fig. 3. Composite microstructure: a) Al44200+30% Al_2O_3 , b) Al44200+20% Al_2O_3

Friction welding trials

Attempts to join the 44200 aluminum alloy with Al/ Al_2O_3 composites were carried out on a HARMS WENDE HWH model RSM200 friction welding machine, which enables the welding of axially symmetrical materials. The welding machine allows to perform trial joining of materials in the following range of parameters:

- head rotational speed: 6000÷24000 rpm,
- friction force: 11 kN,
- upsetting force: 11 kN,
- time of friction/upsetting: 100÷7000 ms.

The materials to be welded were in the form of rods with a diameter of $\varnothing 8$ mm with flat frontal areas. The length of the welded materials was 25 mm.

The view of the welding machine spindle and the specimen mounting system for the welding of Al alloy with composites is shown in Figure 4. The aluminum sample was placed in a rotating spindle U. The composite material was placed in a fixed holder S with a pneumatic clamp.

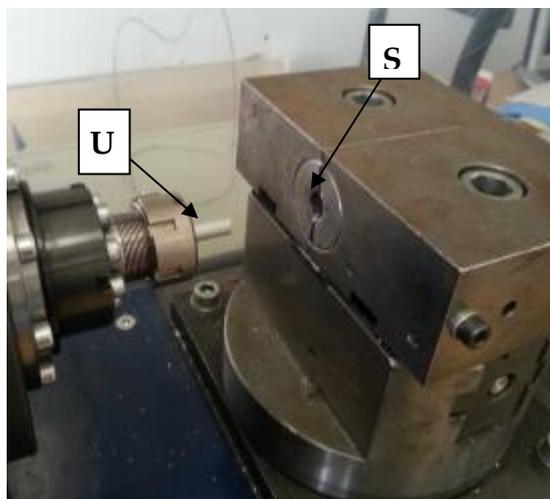


Fig. 4. View of the tooling of the friction welding process: U – aluminum alloy sample placed in a rotating spindle, S – composite material placed in a fixed holder

A series of trials and preliminary tests of the obtained joints were carried out. The parameters of the friction welding process from some of the tests performed are summarized in Table III.

Figure 5 shows the computer screen image with the welding conditions as a function of time for the joint: 44200/44200+30%Al₂O₃ (sample No. 4, Figure 6).

Table III. Friction welding process conditions of Al44200 with Al4420- Al₂O₃ composites

Sample No.	Composite material	Rotational Friction Upsetting			Pressure force in the friction phase [bar]	Pressure force in the upsetting phase [bar]	Pressure in the friction phase [MPa]	Pressure in the upsetting phase [MPa]
		speed [rpm]	time [ms]	time [ms]				
1	44200+30%-vol. Al ₂ O ₃	23000	40	3000	3	4	1.5	2.0
2	44200+30%- vol. Al ₂ O ₃	13000	40	3000	3	4	1.5	2.0
3	44200+30%- vol. Al ₂ O ₃	13000	40	3000	2	2	1.0	1.0
4	44200+30%- vol. Al ₂ O ₃	13000	40	3000	1.6	2	0.8	1.0
5	44200+20%- vol. Al ₂ O ₃	13000	40	3000	1	2	0.5	1.0
6	44200+20%- vol. Al ₂ O ₃	15000	40	3000	1	2	0.5	1.0

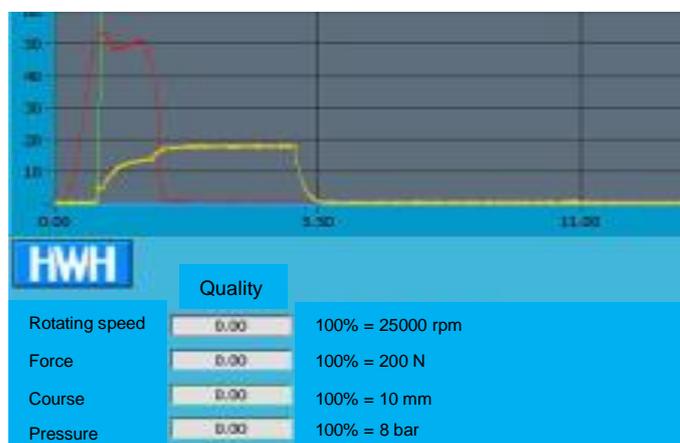


Fig. 5. Welding cycle as a function of time for the joint: 44200/44200+30%Al₂O₃. Lines: red – rotational speed expressed in % (100% = 25000 rpm), yellow – pressure expressed in % (100 = 8 bar)

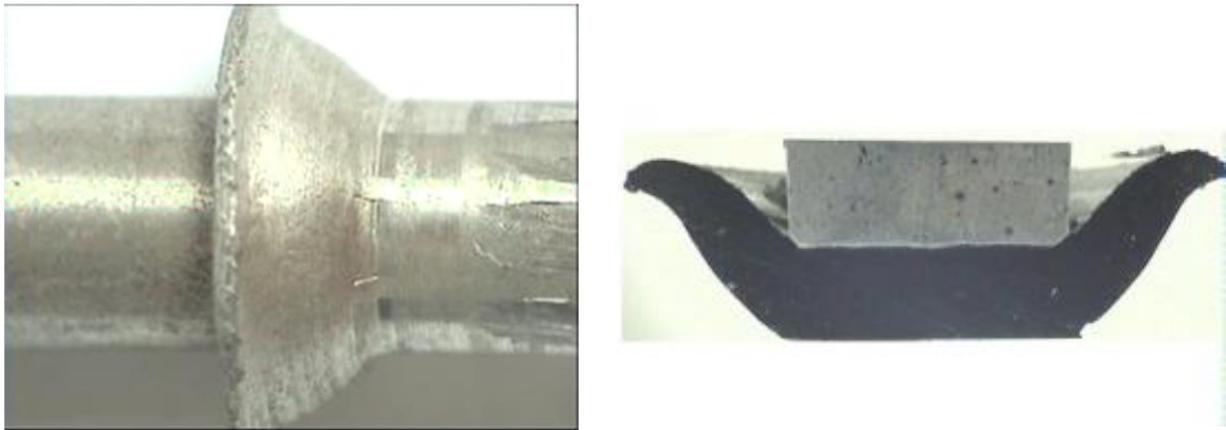


Fig. 6. View of welded joints obtained by friction welding in conditions presented in table III for sample 4

On the other hand, Figure 7 shows the joint 44200/44200+20%Al₂O₃ obtained for the welding conditions for sample no. 5 from Table III.

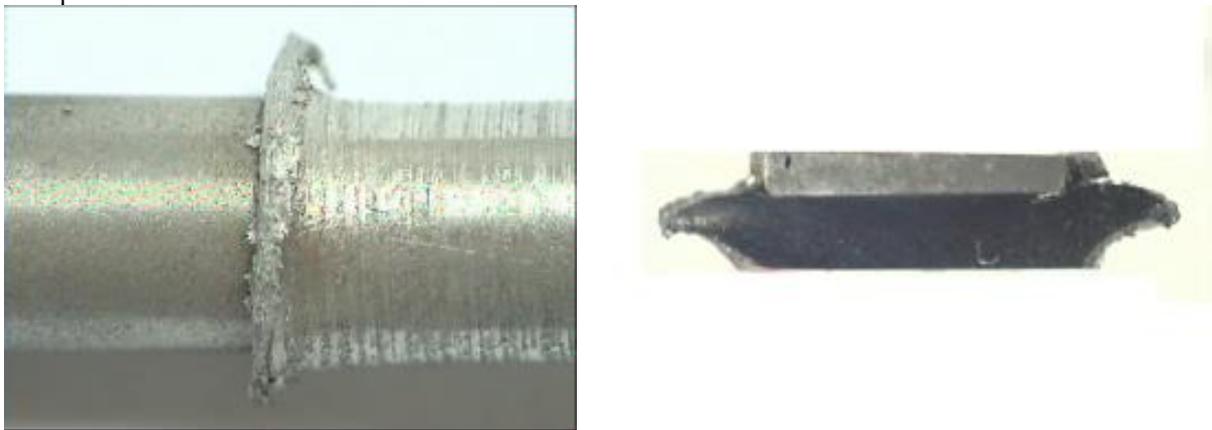


Fig. 7. Friction welded joints of 44200/44200+20%Al₂O₃ obtained for process parameters compiled in table III, sample 5

Research results

Hardness, microstructure and tensile strength tests were carried out on the obtained joints of the 44200 aluminum alloy with the Al/Al₂O₃ composite materials.

The hardness test was carried out using the Vickers HV0.3 method on the Struers Durascan 10 device. The hardness distribution test was performed according to the diagram in Figure 8 along three measurement lines: I, II and III. The obtained measurement results are presented in Tables IV and V.

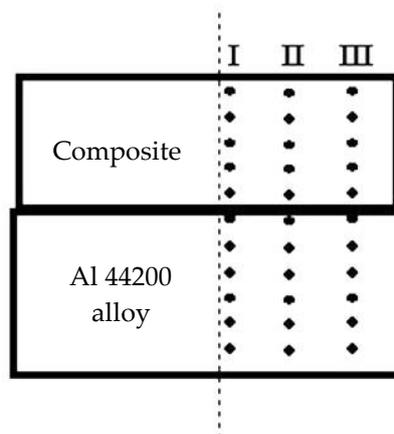


Fig. 8. Scheme of hardness measurement in welded joints aluminum 44200-composite

Graphical hardness distributions for the alloy/44200+30%Al₂O₃ and alloy/44200+20%Al₂O₃ welded joints are presented in Figures 9 and 10.

Table IV. Results of hardness measurements in 44200 alloy – 44200+30% Al₂O₃

Material	Hardness HV [0,3]			Distance from connection [mm]
	I	II	III	
Composite	148	151	136	-1.75
	134	148	139	-1.5
	143	133	151	-1.25
	148	151	141	-1
	146	141	156	-0.75
	120	116	130	-0.5
	124	104	132	-0.25
44200 Alloy	60.7	59.3	61.5	0.25
	57.7	53.5	56.9	0.5
	48.1	42.9	47.6	0.75
	41.8	45	46.3	1
	43.3	42.8	45.3	1.25
	40.3	41.8	43.8	1.5

Table V. Results of hardness measurements in 44200 alloy – 44200+20%Al₂O₃

Material	Hardness HV [0,3]			Distance from connection [mm]
	I	II	III	
Composite	103.5	101.4	98.5	-1.5
	101	98.1	94.2	-1.25
	105	95.5	101	-1
	96.9	110	95.8	-0.75
	102	112	113.6	-0.5
	90.5	95.5	112	-0.25
	65.7	70.3	66.2	0.25
44200 Alloy	58.1	61.5	48.9	0.5
	50.3	51.3	45.7	0.75
	46.3	43.5	47.6	1
	44.9	44	43	1.25
	39.6	38.9	43.8	1.5
	43.3	41.9	43.8	1.75

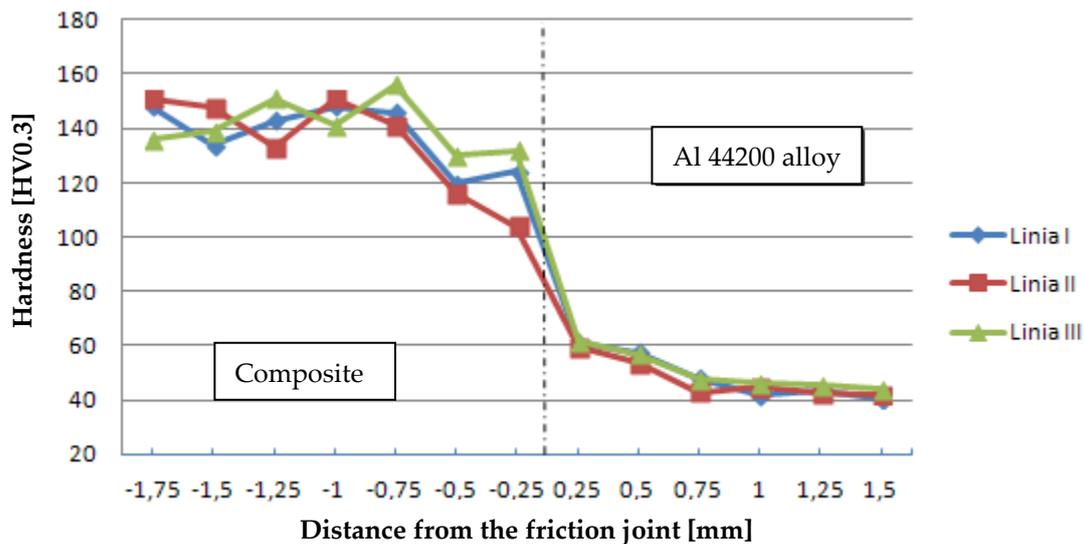


Fig. 9. Hardness distribution in 44200+30%Al₂O₃/44200 friction welded joints

The measurement results show that the hardness distribution coincides for all three measurement lines. At a distance of 0.5 mm from the joint, a decrease in the hardness of the composite was observed from the value of 140 HV0.3 (the hardness of the native material) to the value of approx. 110 HV0.3.

In the case of 44200 alloy, it is slightly different. In the area adjacent to the joint itself (up to 0.5 mm), the hardness of the aluminum alloy increases to 60 HV0.3. In the area of 0.7 mm, the 44200 alloy already has a native material hardness of ~ 50 HV0.3.

For a joint of an aluminum alloy with a composite reinforced with Al₂O₃ particles with a 20% share, the hardness of the composite material in the area adjacent to the joint itself (0.25 mm) is reduced. For the 44200 alloy, an increase in hardness within the joint itself (~ 60 HV) can be seen, and from a distance of 0.75 mm from the joint, the alloy already has the hardness of the native material.

The hardness value distribution is almost identical for all of the three measuring lines.

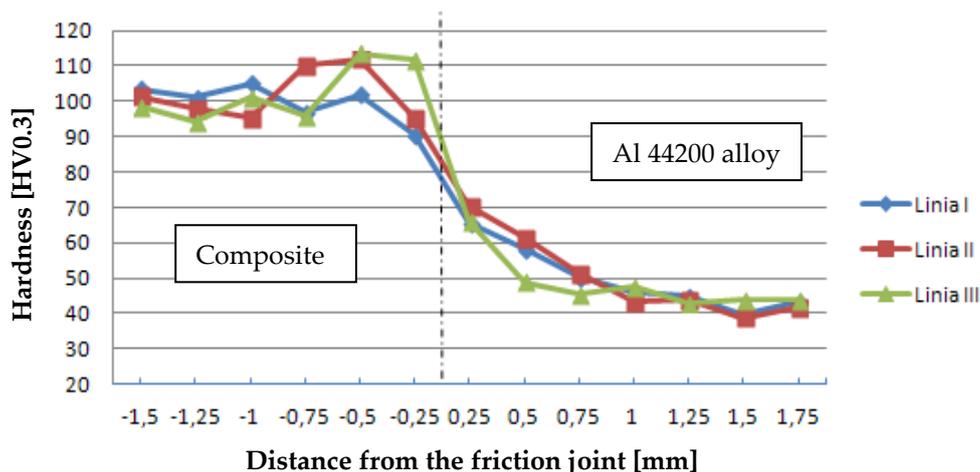


Fig. 10. Harness distribution in 44200+20%Al₂O₃/44200 friction welded joints

Selected results of the structural tests of the obtained alloy-composites joints are presented below. Photographs of the microstructures were taken using an Axiovert 40 MAT optical microscope.

Figure 11 shows the joint of the 44200 alloy with the 44200+30%Al₂O₃ composite at x50 magnification, obtained with the conditions from Table III. In the upper part of the photo you can see the structure of the composite, while in the lower part you can see the structure of the 44200 alloy.

The structural photos confirm the good quality of the alloy-composite joint. Continuity of the connection along the entire joint is observed. There are no discontinuities to be seen. The structure of the composite material has not changed. No cracks or deformations were observed in the composite material reinforced with alumina particles. Low plasticity of the composite resulting from the high content of Al₂O₃ particles (30%) makes the composite non-deformable. However, strong plasticization and mixing of the Al alloy in the area of the joint can be observed and, as a result of the pressure force, it is displaced to the flash.

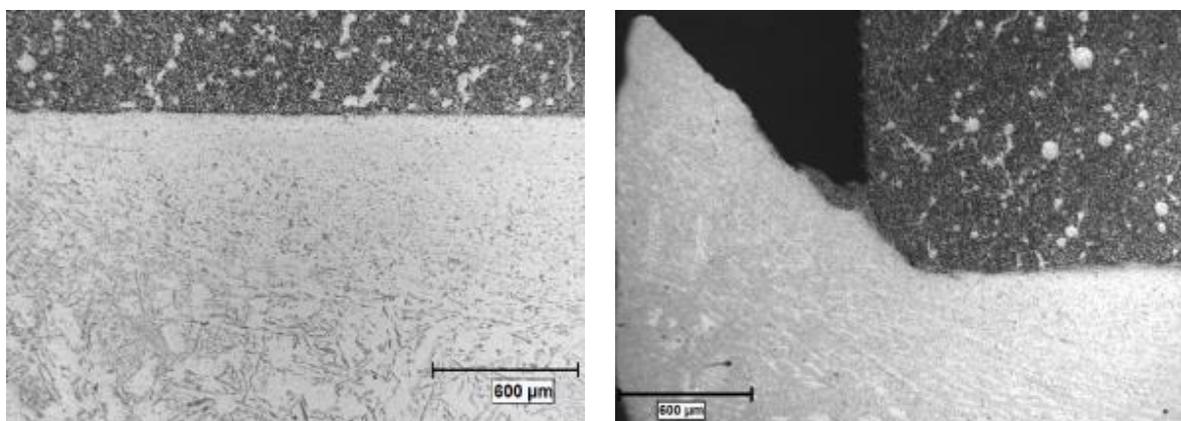


Fig. 11. Microstructure of 44200 alloy/44200+30% Al₂O₃

In the area of the joint itself, a change in the structure of the 44200 alloy is observed. Structure refining takes place, thus this area shows greater hardness. In further areas from the joint, band-like precipitations of Si crystals can be seen.

Figure 12a shows the structure of the Al44200/44200+20%Al₂O₃ joint at a magnification of x100 (welding process conditions from Table III, sample No. 5). No discontinuities are observed along the entire joint. The connection structure is homogeneous, with no visible cracks or pores.

In Figure 12b, at x50 magnification, the direction of material flow can be observed: Al alloy moves from the sample axis (center) to the outside, forming a flash.

The structure of the composite remains intact. No cracks or deformations are observed. However, the structure refining of the 44200 alloy can be observed.

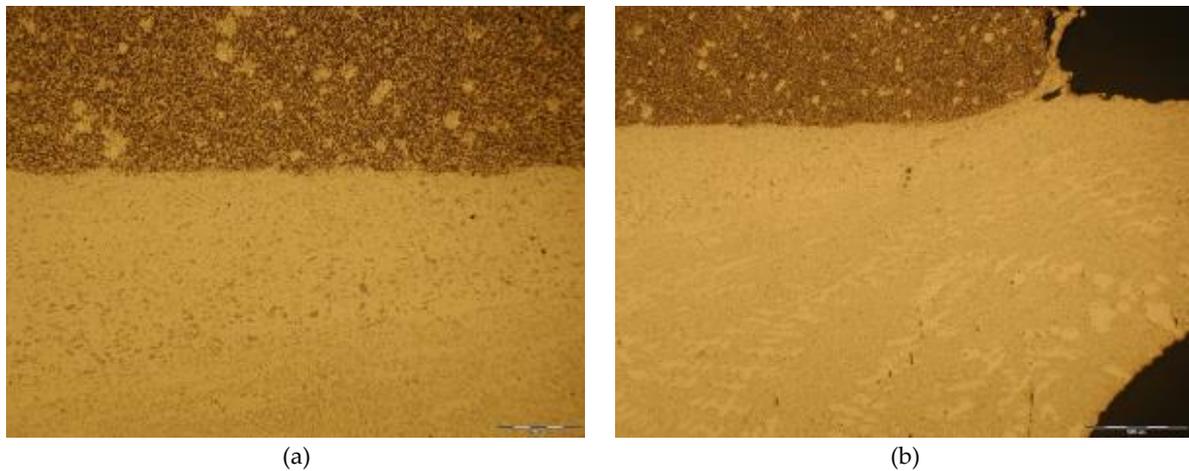


Fig. 12. Microstructure of 44200/44200+20%Al₂O₃ welded joint

The study also performed the surface distribution of elements and EDS spectra on the cross-section of alloy-composite joints (Fig. 13 and Fig. 14).

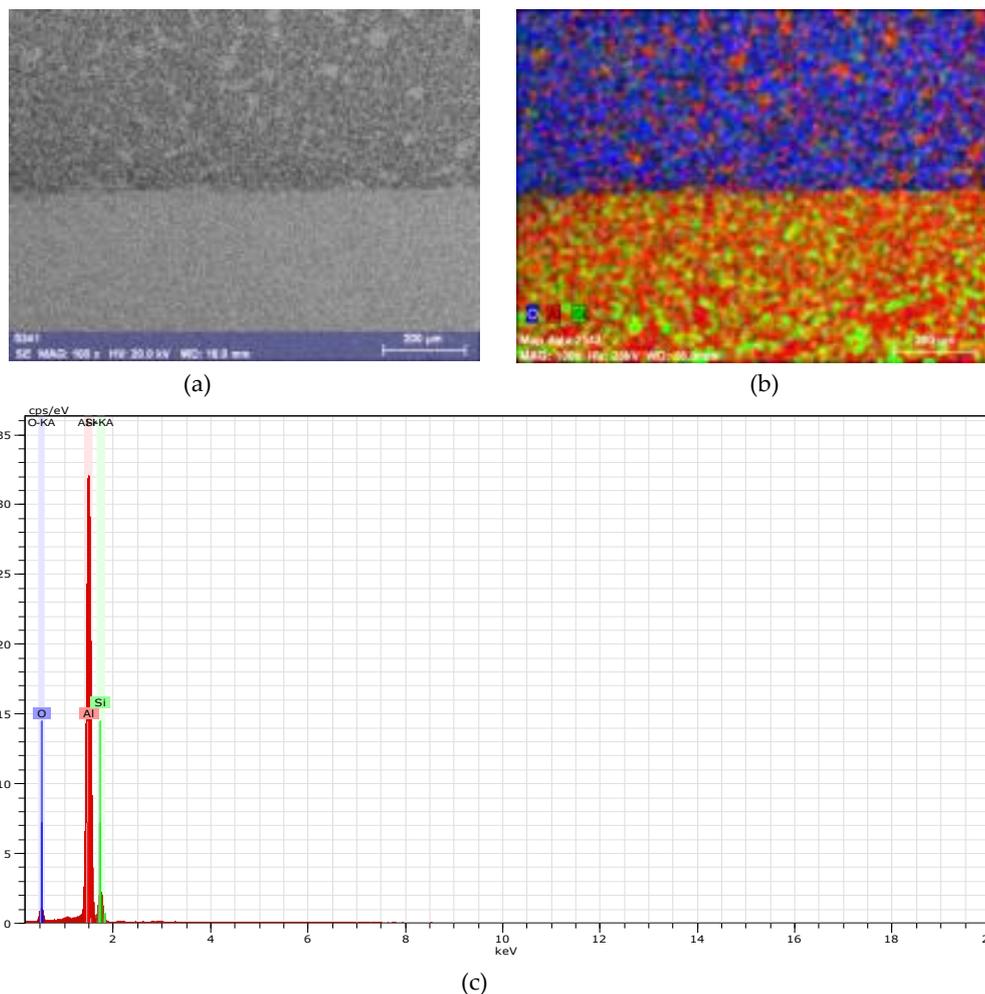


Fig. 13. Cross-section of welded joint: a) Microstructure, b) surface distribution of elements; c) EDS spectrum on 44200/44200+20%Al₂O₃

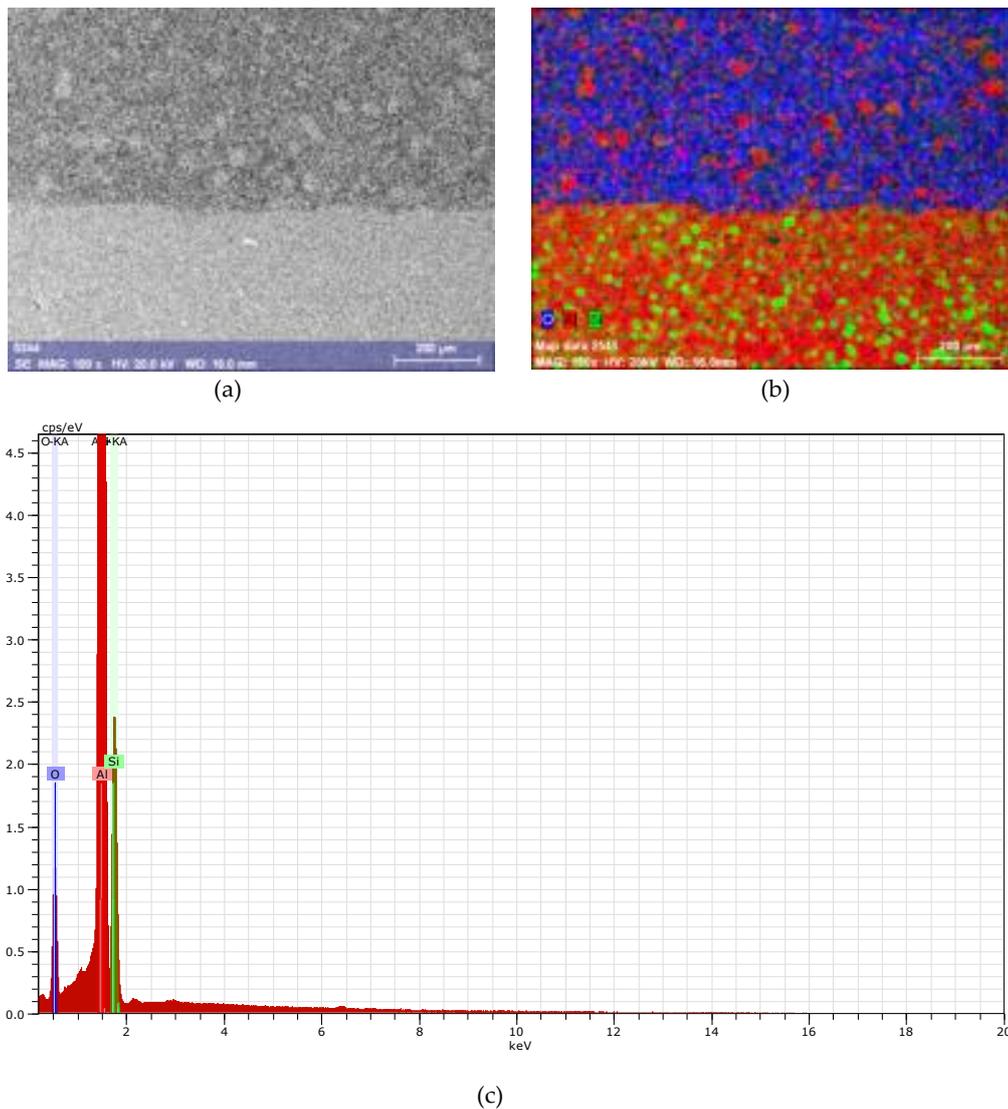


Fig. 14. Cross-section of welded joint: a) Microstructure, b) surface distribution of elements; c) EDS spectrum on 44200/44200+20%Al₂O₃

EDS maps show the homogeneous distribution of the individual phases within the joint. Characteristic silicon precipitates are observed for the Al44200 alloy, visible as light green fields. The distributions shown in Figures 13 and 14 show the same character of joints. There is a clear border of the alloy-composite connection.

Strength tests of the obtained joints were also performed. The reference sample was the 44200/44200 joint, for which the rupture took place at the force $F = 4.73$ kN (Fig. 15), which corresponds to the stress $UTS = 94$ MPa.

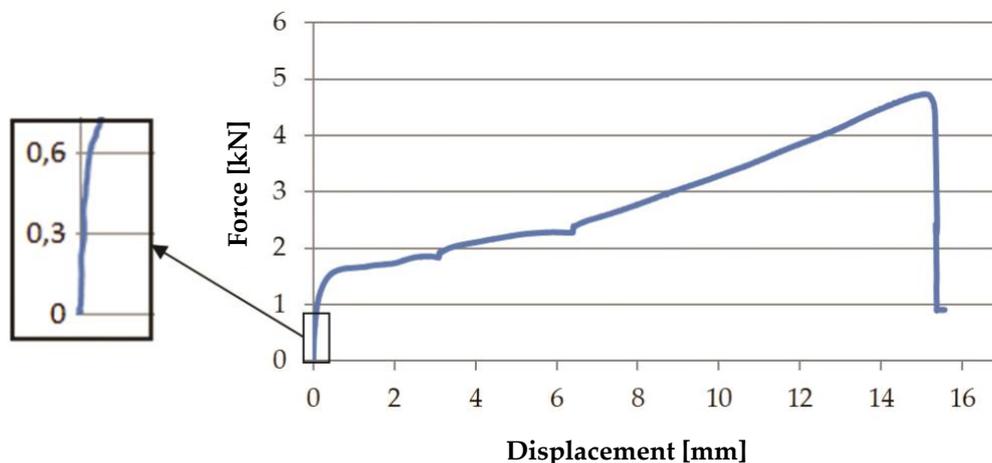


Fig. 15. Graph of a static tensile test for a 44200-44200 joint

For joints with composite materials reinforced with Al_2O_3 particles in a share of 30% and 20%, the breaking strength was 5 kN and 4.6 kN, respectively (Fig. 16a, 16b). The obtained tensile strength results of the joints of 44200 alloy with composites reinforced with alumina particles correspond to the strength of the 44200-44200 connection.

In all the curves obtained in the static tensile test, a very short straight line segment (enlarged areas) is observed at the very beginning of the graph. This is a part of the chart where the tested samples deform elastically. The smallest elastic deformation was recorded for the 44200/44200+30% Al_2O_3 joint (Fig. 16a).

Behind the rectilinear part of the tension curves, there is a stage that corresponds to the plastic deformation of the tested samples. Then, further permanent plastic deformations are recorded up to the moment of breaking the tested materials with the force contained in Table VI.

In addition, for the 44200-44200 joint, the largest displacement recorded was over 15 mm. This is due to the high ductility of the alloy. In the case of joints with composite materials, the displacement is much smaller, less than 10 mm. This is due to the higher Young's modulus of the composite materials used, reinforced with Al_2O_3 particles.

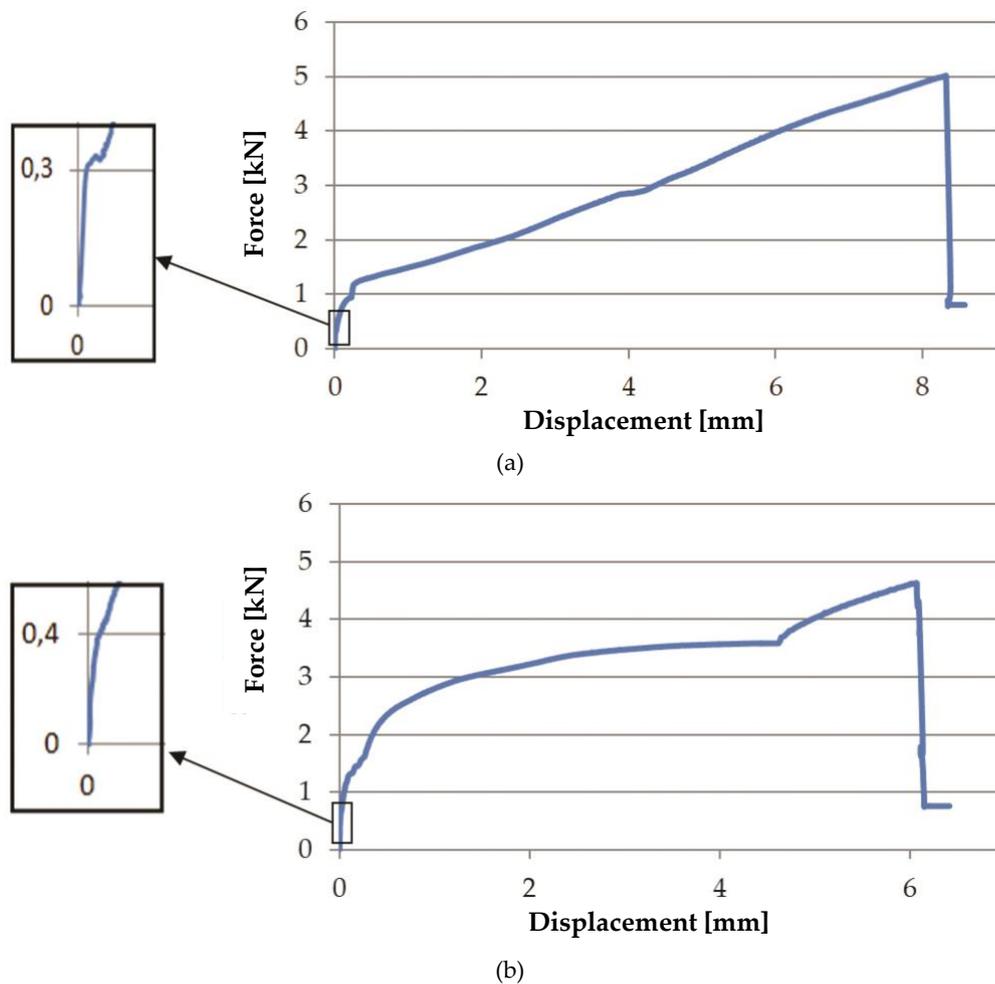


Fig. 16. Graph of a static tensile test for welded joints: a) 44200/44200+30% Al_2O_3 , b) 44200/44200+20% Al_2O_3

Table VI. Statement of static tensile test results

Description of the joint	Force [kN]	Stress [MPa]
44200-44200	4.73	94.1
44200/44200+30% Al_2O_3	5.01	99.7
44200/44200+20% Al_2O_3	4.63	92.2

Summary

The paper presents the possibility of using the friction welding technique to join two dissimilar materials: Al alloy - Al/Al₂O₃ composite. The study contains the parameters of the friction welding process for joints of aluminum alloy with composite materials reinforced with Al₂O₃ particles with a different percentage of volume fraction. The conducted structural tests of the obtained joints confirm the high quality of the joint, both for composites with 30% and 20% of volume fraction. The joints are characterized by a stable structure along the entire cross-section, the connection zone is free from defects in the form of discontinuities. Additionally, the results of tensile strength tests show the high strength of the obtained alloy-composite joints at the level of the 44200-44200 reference joint.

The applied method gives very good results in the case of bonding composites from the Al/Al₂O₃ group with the Al alloy. The friction welding technique is most often used in the automotive industry. The advantage of this bonding method is that the process is very fast. Additionally, no additional materials are introduced into the connection area. Short welding time and no need to prepare the joined surfaces before the process, makes this method simple and economical.

Attention should also be paid to the difficulties that arise when joining aluminum: high thermal conductivity, relatively low melting point and high oxygen affinity. Metallically pure aluminum surfaces rapidly become covered with an oxide layer, which has a much higher melting point than pure aluminum. Due to the high chemical affinity of oxygen with aluminum and the possibility of occurrence of pores, shielding gases are used in the process of welding this metal. Friction welding gains a significant advantage here, due to the fact that all kinds of contamination, including Oxides are removed from the joint area and moved to the flash as a result of the strong plasticization of the material and the action of the pressure force.

In order to reduce the differences in properties between the brittle composite material and the plastic aluminum alloy, additional procedures are often used during joining, such as applying coatings to the joined materials or using materials with intermediate properties as a spacer (interlayer) through which bonding occurs. Thanks to the use of the friction welding method, a permanent alloy-composite connection was obtained, without the need of modification or special surface preparation of the materials before the process.

Author Contributions: conceptualization, C.S. and R.S.; methodology, R.S.; software, C.S.; validation, C.S. and R.S.; formal analysis, R.S.; investigation, C.S.; resources, R.S.; data curation, R.S.; writing—original draft preparation, R.S.; writing—review and editing, C.S.; visualization, C.S.; supervision, C.S.; project administration, R.S.; funding acquisition, C.S.

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Conflicts of Interest: The authors declare no conflict of interest.

Resources

- [1] Szala M., Hejwowski T., Cavitation Erosion Resistance and Wear Mechanism Model of Flame-Sprayed Al₂O₃-40%TiO₂/NiMoAl Cermet Coatings. *Coatings*, 2018, Vol. 8(7), 254. <https://doi.org/10.3390/coatings8070254>
- [2] Basheer U.M., Mohd Noor A.-F., Microstructural Development in Friction Welded Aluminum Alloy with Different Alumina Specimen Geometries. *Friction and Wear Research*, 2013, Vol. 1(2).
- [3] Ambroziak A., Korzeniowski M., Using resistance spot welding for joining aluminium elements in automotive industry. *Archives of Civil and Mechanical Engineering*, 2010, Vol. 10(1), 5–13. [https://doi.org/10.1016/s1644-9665\(12\)60126-5](https://doi.org/10.1016/s1644-9665(12)60126-5)
- [4] Skowrońska B., Chmielewski T., Pachla W., Kulczyk M., Skiba J., Presz W., Friction weldability of UFG 316L stainless steel. *Archives of Metallurgy and Materials*, 2019, Vol. 64(3), 1051–8. <https://doi.org/10.24425/amm.2019.129494>
- [5] Park I.D., Lee C.T., Kim H.S., Choi W.J., Kang M.C., Structural considerations in friction welding of hybrid Al₂O₃-reinforced aluminum composites. *Transactions of Nonferrous Metals Society of China (English Edition)*, 2011, Vol. 21(1), 42–6. [https://doi.org/10.1016/S1003-6326\(11\)61058-3](https://doi.org/10.1016/S1003-6326(11)61058-3)
- [6] Ahmad Fauzi M.N., Uday M.B., Zuhailawati H., Ismail A.B., Microstructure and mechanical properties of alumina-6061 aluminum alloy joined by friction welding. *Materials and Design*, 2010, Vol. 31(2), 670–6. <https://doi.org/10.1016/j.matdes.2009.08.019>
- [7] Hascalik A., Orhan N., Effect of particle size on the friction welding of Al₂O₃ reinforced 6160 Al alloy composite and SAE 1020 steel. *Materials and Design*, 2007, Vol. 28(1), 313–7. <https://doi.org/10.1016/j.matdes.2005.06.001>
- [8] Naplocha K., Kaczmar J.W., Morgiel J., Local strengthening of en AC-44200 al alloy with ceramic fibers. In: *Key Engineering Materials*, 2015. p. 237–40. <https://doi.org/10.4028/www.scientific.net/KEM.662.237>
- [9] Kurzawa A., Kaczmar J.W., Bending Strength of en AC-44200-Al₂O₃ Composites at Elevated Temperatures.

- Archives of Foundry Engineering*, 2017, Vol. 17(1), 103–8. <https://doi.org/10.1515/afe-2017-0019>
- [10] Krzyńska A., Włosiński W., Kaczorowski M., About the structure Cu-Al₂O₃ joints obtained by diffusion bonding. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 2006, Vol. 220(3), 439–45. <https://doi.org/10.1243/09544054JEM237>
- [11] Zhou Y., Zhang J., North T.H., Wang Z., The mechanical properties of friction welded aluminium-based metal-matrix composite materials. *Journal of Materials Science*, 1997, Vol. 32(14), 3883–9. <https://doi.org/10.1023/A:1018652429477>
- [12] Chmielewski T., Hudycz M., Krajewski A., Salaciński T., Skowrońska B., Świercz R., Structure investigation of titanium metallization coating deposited onto AlN ceramics substrate by means of friction surfacing process. *Coatings*, 2019, Vol. 9(12), 845. <https://doi.org/10.3390/coatings9120845>
- [13] Li W., Vairis A., Preuss M., Ma T., Linear and rotary friction welding review. *International Materials Reviews*, 2016, Vol. 61(2), 71–100. <https://doi.org/10.1080/09506608.2015.1109214>



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