DOI: 10.21062/mft.2022.076 http://www.journalmt.com

Microscopic Analysis of the Surface Morphology of Multilayer Structures of the Aluminum Alloy - Silicon Type after Water Jet Cutting

Jerzy Józwik (0000-0002-8845-0764)[1], Alessandro Ruggiero (0000-0002-5111-2331)[2], Michał Leleń (0000-0002-6398-4014)[1]

[1]Lublin University of Technology, Faculty of Mechanical Engineering, Department of Production Engineering, 20-618 Lublin, ul. Nadbystrzycka 36, Poland, Email: j.jozwik@pollub.pl, m.lelen@pollub.pl

[2]University of Salerno, Department of Industrial Engineering, (Bio) Tribology, Applied Mechanics Noise and Vibration Control, National Coordinator AIMETA Tribology Group- GAIT, Via Giovanni Paolo II, 132 - 84084 Fisciano (SA) Italy, Email: ruggiero@unisa.it

The paper presents the results of an experimental work on the assessment of microscopic morphology of the surfaces obtained as a result of cutting with a Water Jet (WJ) water abrasive beam. During the tests, the following values were taken as input values: feedrate v_f [mm·min^{-1}] and mass flow rate of the abrasive material m_a [g·s^{-1}]. As constant parameters were assumed: the angle of incidence of the water-abrasive mixture stream on the workpiece material equal to 90°, the type of abrasive (garnet 80 mesh), the pressure value p [MPa] and the distance of the nozzle from the cut material l [mm]. The values disturbing the process were vibrations generated during the cutting process and motion resistance resulting from friction processes in the guides and kinematic gears. The subject of analysis were the interfacial structures of multilayer structures connected in a vulcanization process with the surface of thin-walled parts made of AW-5754 aluminum alloy. As an effect, the results describing the nature of changes in spatial parameters of surface roughness as well as parameters of skewness and kurtosis as a function of WJ technological cutting of composites materials conditions were obtained.

Keywords: AluminumAlloy, Microscopic Analysis, Water Jet Cutting, Surface Morphology.

1 Introduction

Polymer-based composites have found wide application as functional and structural materials in the aeronautic, aerospace, automotive and petroleum industries. A well-known example of metal-polymer composites are fibrous-metal laminates (FML) [1][2]. These composites are referred to as advanced materials due to their low density and mechanical properties such as specific strength and modulus of elasticity. Aluminum plates with applied silicone coating (aluminum alloy structure - silicone) are characterized by special properties, which include high strength, good impact properties, proper rigidity, high abrasion resistance[3][4][5].

In addition, mechanical properties of an aluminum alloy - silicone structures can be freely modified and adjusted to a specific application by a selection of a proper silicon mixture and thickness of a silicone layer applied [6][7][8].

Aluminum alloy - silicone structures show high potential for applications in the aeronautics, defence and automotive industries [9][10]. They are also widely used in the machine tool industry or in food packaging applications. The application of these materials are also presented in the literature [11][12].

Previous experimental studies on the connection of polymers with metals focused on the analysis and modification of the outermost layer of the metal surface and the assessment of its impact on the mechanical adhesion of the metal/polymer structure. It is believed that the interfacial reaction, which takes place at the place of silicone - aluminum alloys joint, leads to the formation of a complex structure and determines its mechanical properties. The analysis of the properties such as strength, durability and resistance of the metal/polymer connection (as it is the case in the presented publication), the structure: aluminium alloy – silicone (synthetic silicoorganic polymer) allows to state that this combination is resistant to aging and to external factors.

The reliability of products made of these structures depends on the parameters that have been mentioned. Aluminium alloy - silicone structures combined permanently are used in the production of car tires, conveyor belts and vibration isolators. In the automotive industry, such structures are used in the production of couplers and seals [13][14].

Due to different physicochemical and thermodynamic properties of metals and polymers, direct joining requires different methods. In the case of direct joining of these materials, it is necessary to use unconventional joining methods. Defects often occur at the interface of these materials. It is very difficult to achieve a high bond strength of metals and polymers in one composite due to the different nature of these materials. According to McBain's mechanical theory of adhesion [15], it should be noted that high bond strength between materials with the same properties, for example in metal/metal structures, occurs due to the formation of metallic bonds on atoms as a result of diffusion, dislocation and recrystallization mechanisms. However, in the case of metals and polymers, the combination of materials is much weaker and possible only thanks to adhesive bonds [16][17].

The production of metal/polymer structures is obtained using various technologies. One of them is injection molding. The adhesive force thus obtained between the bonded materials is not too high due to the poor wettability of the polymer by the molten metal, a significant difference between the thermal expansion coefficients and the high stress level at the polymer-metal boundary.

Another method of joining materials from the metal/polymer group is vulcanization. In the case of vulcanization under the pressure and while subjecting the silicone to high temperature, adhesion of materials occurs. Other methods include mechanical bonding of polymers and metals with rivets or screws and the hot and cold adhesive bonding technology [18].

However, the advantage of joining metal/polymer structures in a durable manner thanks to their properties, such as lower weight, lower stress level on the surface, homogeneous surface, or greater resistance to cyclic loads, eliminates mechanically connected structures from practical applications. Thanks to their properties, materials such as rubbers and silicones are one of the most popular and available polymers with high elasticity, compressibility and very good damping properties [19][20].

Silicone has very good properties as a material that can be used to dampen noise and vibrations in machine parts that are subjected to vibration. However, under the influence of temperature and mechanical loads, its physical and mechanical properties degrade. This degradation is associated with the appearance of surface fractures, which results in the occurrence of volume fractures. Metallic materials, on the other hand, behave differently. Their characteristic feature is high plasticity in a wide temperature range under constant cyclic loads [21][22].

The disadvantage of aluminum-silicone structures is a relatively low strength of the adhesive bond on the interfacial connection. In extreme cases, it may lead to phase-to-phase debonding, i.e. peeling off the silicone layer from the aluminum substrate. Another disadvantage is the loss of usable properties, caused by wear of the layer under the influence of mechanical loads and physicochemical phenomena. In order to obtain an even distribution of stresses at the metal/polymer interface, the structure must be symmetrical, and the metal surface should be characterized by high stiffness. The composition of multi-layer structures with more than two connection surfaces provides increased impact strength and fatigue resistance, due to the extensive surface between individual layers, which is an effective barrier for the formation of cracks and delaminations.This is confirmed by the analyses of interfacial structures carried out with the use of a scanning electron microscope [23][24].

2 Research methodology

The aim of the study is the microscopic evaluation of the microstructure of double-walled metal-polymer composites obtained by vulcanization under the influence of high temperature. Samples of two-layer structures for testing, consisting of an aluminum alloy and silicone (synthetic silicoorganic polymer), were prepared using the hydro-abrasive cutting process with the Eckert Combo cutter. The aim of the research is to identify geometrical defects of the surface and interfacial changes of the AW-5754 aluminum alloy - silicone during the cutting process, and to analyze the impact of variable cutting technological parameters (such as feedrates v_f [mm·min^{-1}] and the mass flow rate of the abrasive m_a [g·s^{-1}]) on the change of the surface microstructure. The research work was carried out using a scanning electron microscope (SEM).

2.1 Research object

Test included two-layer aluminium alloy-silicone structures obtained with the use of a silicone pressing technology under the influence of high temperature. The material prepared for cutting was a 500 x 500 mm plate. Fig. 1. shows the plate prepared for hydroabrasive cutting.

The development of the two-layer structure began with the preparation of the AW-5754 aluminium alloy plate. The chemical composition of the AW-5754 aluminium alloy used is shown in Table 1. The 4 mm thick AW-5754 plate was subjected to mechanical surface treatment with the use of sandpaper in accordance with the FEPA standard, gradation P240. The aluminium surface was then cleaned and degreased with a chlorine solvent at neutral pH to remove metallic residues, grease and oxides. This also reduces the occurrence of potential corrosion sites.

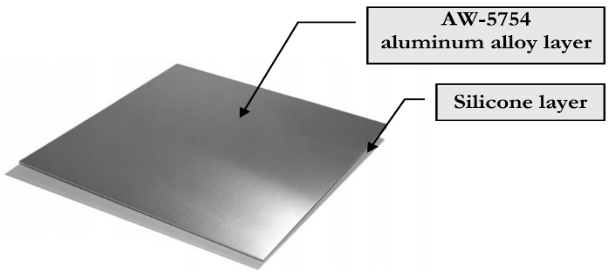

Fig. 1 *Two-layer structure of AW-5754 aluminium alloy – silicone, prepared for hydroabrasive treatment*

Tab. 1. *Chemical composition of the workpiece – AW-5754 aluminum*

AW-5754 aluminum alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr
Chemical composition (%)	0.40	0.40	0.10	0.50	2.6	0.3	0.2	0.15	-

A primer was applied to the surface of the aluminium alloy - Sika Primer 210. It is a low viscosity agent that is used to prepare the surface before it is combined with other materials. This primer is also suitable for improving the adhesion of adhesives and sealants on porous and non-porous surfaces. It also increases mechanical adhesion. Thanks to such surface preparation methods used on the aluminum plate, the roughness was increased, which in turn positively influenced the geometric development of the surface and increased adhesion, and thus allowed for the creation of a connection with high tear strength.

Colourless MVQ silicone with a density of 1.25 $g \cdot cm^{-3}$ was used for the tests. The hardness of the silicone was 60 ShA. The aluminium alloy-silicone structure was created on the Lema 301G hydraulic press with a built-in double heating plate. The heating plates in the hydraulic press are placed symmetrically in the upper and lower area. Such a distribution of the heating plates allowed to obtain a high temperature and its even distribution. The aluminium alloy-silicone bond was formed under silicone polymerization conditions at 170°C for a period of 7 min. Press pressure at that time was even and amounted to 40000 kg per 1 m^2 (40 MPa). The structure was cooled at ambient temperature until the temperature was equal to the ambient temperature (20°C).

2.2 Test station and cutting process conditions

The sample cutting process was carried out on the Eckert Combo portal cutter, designed for thermal cutting and hydroabrasive cutting. The abrasive water cutting machines are numerically controlled machines for cutting sheet metal using the mounted cutting tools, to wit: a clean water cutting head, a water-abrasive cutting head, and a plasma torch. The hydroabrasive cutting device is presented in Fig. 2. Test samples were also collected and amounted to 22 pieces with dimensions of 5x30 mm and a height of 5 mm.

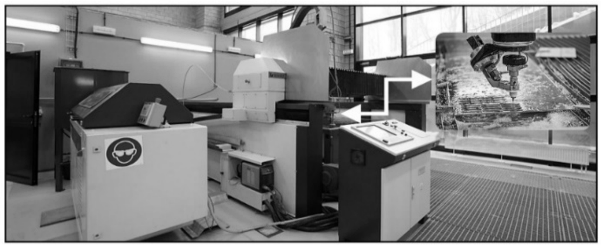

Fig. 2. *Eckert COMBO portal cutter used in the process of preparation of research samples*

For the cutting process, the following processing conditions were established: nozzle diameter 0.7 mm (constant), garnet abrasive 80 mesch (constant granulation), nozzle distance from the cut material 3 mm (constant), nozzle length 100 mm (constant), stream angle in relation to the cut material 90°(constant), pump pressure 350 MPa (constant). The following variables were adopted: the mass flow rate of the abrasive m_a [$g \cdot s^{-1}$] and the feedrate v_f [$mm \cdot min^{-1}$]. On the basis of the presented parameters, the test program was determined and a combination of 22 material cutting attempts was prepared. Table 2 presents the combination of technological parameters of the hydroabrasive treatment.

Tab. 2 *Cutting process variable parameters*

Attempt no.	Feedrate v_f [$mm \cdot min^{-1}$]	Mass flow rate m_a [$g \cdot s^{-1}$]	Attempt no.	Feedrate v_f [$mm \cdot min^{-1}$]	Mass flow rate m_a [$g \cdot s^{-1}$]
1	50	0.8	12	50	0.4
2	100		13	100	
3	200		14	200	
4	300		15	300	
5	500		16	500	
6	1000		17	1000	
7	1500		18	1500	
8	2000		19	2000	
9	2500		20	2500	
10	3000		21	3000	
11	3500		22	3500	

The samples obtained as a result of the cutting process were presented in Fig. 3a. Fig. 3b shows the measurement areas selected for analysis, including the native materials and the interfacial zone, numbered 1, 2, 3. Component materials constituting a multilayer composition were marked with A and B letters (letter A – silicone, and letter B – aluminum alloy). Area marked with number 1 was located and named as the extreme left measurement point, locatedat a distance of 10 mm from the left edge. The area marked with the number 2 was determined as the central place of measurement, located in the middle of the sample and including the interfacial zone, and the area marked with the number 3 was determined in the right extreme position, at a distance of 10 mm from the right edge of the sample, determining the place of measurement of the interfacial structure and native material structures.

The samples were subjected to geometric microstructure analysis using a scanning electron microscope (SEM) Nova Nano SEM 450 (Fig. 4a).For microscopic analysis, a low vacuum mode of 90 Pa, and 18keV and 4.0 spot voltage were used. The samples were mounted on specially prepared miniature tables with circular cross-section (Fig. 4.b). For accurate and precise analysis, the a 5nm thick layer of gold was deposited on the samples.

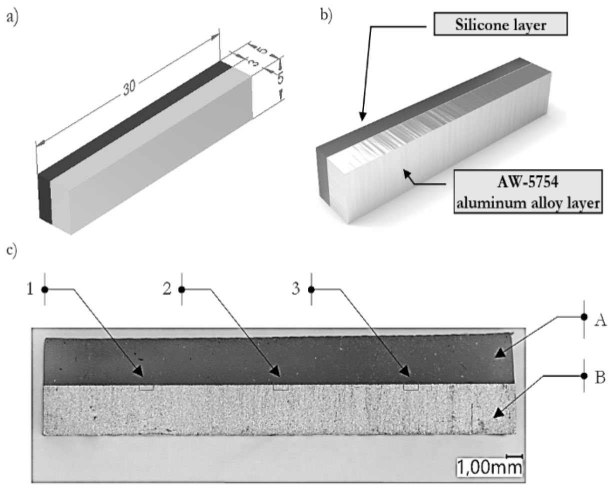

Fig. 3 *Test samples: a) general view, dimensioned b) model view, c) measurement areas: 1 - extreme right measurement area, 2 – central measurement area, 3 – extreme right measurement area, A – silicone layer, B – AW-5754aluminum alloy layer*

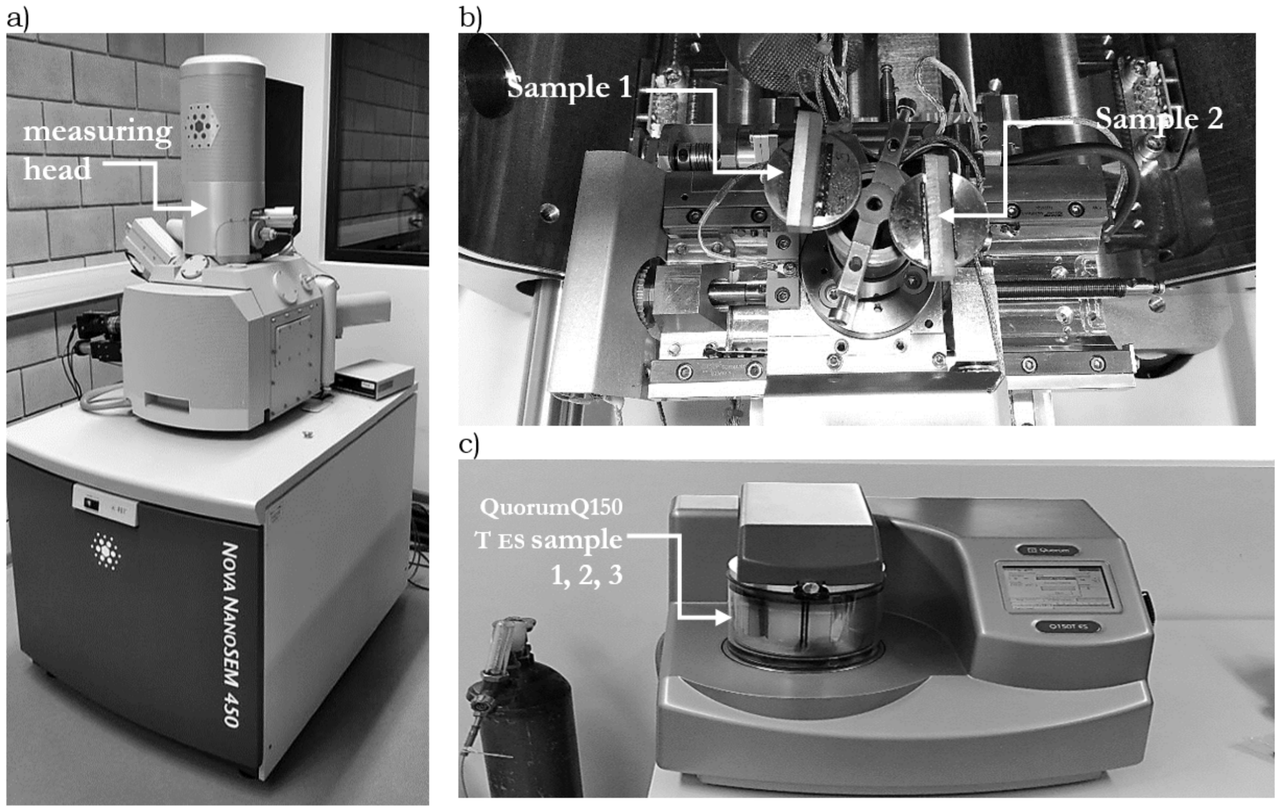

Fig. 4 *Measuring station for microscopic analysis of NovaNanoSEM 450: a) NovaNanoSEM 450 electron microscope, b) NovaNanoSEM450 microscope workspace with samples attached, c) Quorum Q150 T ES sputtering and sample preparation system*

Gold layer was deposited with the sputter coating function of the Quorum Q150T ES system (Fig. 4c). Each time, 3 test samples were placed concurrently in the vacuum chamber (Fig. 4c). The microscopic analysis of samples was performed at three magnifications: x 500, x 650 and x 2000. For each magnification, three repetitions of the recorded photos were taken.

3 Research results and analysis

Based on the conducted microscopic imaging for all samples and measurement areas included in the experiment, their graphic representations were determined along with the description and analysis of the phenomena occurring during the cutting process. Machining mechanisms affecting the surface geometry were determined, taking into account the application of the material, the migration of abrasive grains of the hydroabrasive stream and the composition phase delamination depending on the technological cutting conditions. Fig. 6÷8 show examples of microstructure views at the phase boundary: AW-5754 aluminum alloy and silicone, for three magnification used: x500, x650 and x2000. The presented results are representative of the first set of cutting technological parameters (feedratev_f $=50$ mm·min^{-1}; mass flow rate $m_a = 0.8$ g·s^{-1}) and the central measurement location of the of the selected test area indicated in Fig. 3 with number 2. As a result of the analysis of the selected area, key representative geometric elements in the analyzed sample were marked. Details presented in Fig. 5 mean, respectively:

- A – silicone,
- B – AW-5754 aluminum alloy,
- a – interfacial area,
- b – the area of the combined materials cohesion loss,
- c – abrasive grains located in the interfacial space,
- d – abrasive grains embedded in a homogeneous silicone structure,
- e – abrasive grains embedded in a homogeneous structure of the aluminium alloy.

The interfacial area is maket with the letter *a*. In the interfacial area, clear phase boundaries of two materials, aluminium alloy and silicone, are visible. In the case of the applied test method, mixing of materials at the selected cutting parameters does not occur. The clear boundary between the materials allows for easy metrological analysis of the thickness of the materials and identification of the connection continuity.

An unfavorable phenomenon when cutting multilayer structures is the occurrence of *b*-delamination. This phenomenon can be observed in all analyzed magnifications and almost all tested samples. This phenomenon occurs when a water jet passes through a soft material and encounters a hard one. Part of the jet energy, due to the increase in cutting resistance of the subsequent layer of material, changes the impact in
a direction perpendicular to the action of the stream. As a result, water and abrasive particles cause intense interfacial interactions, resulting in delamination.

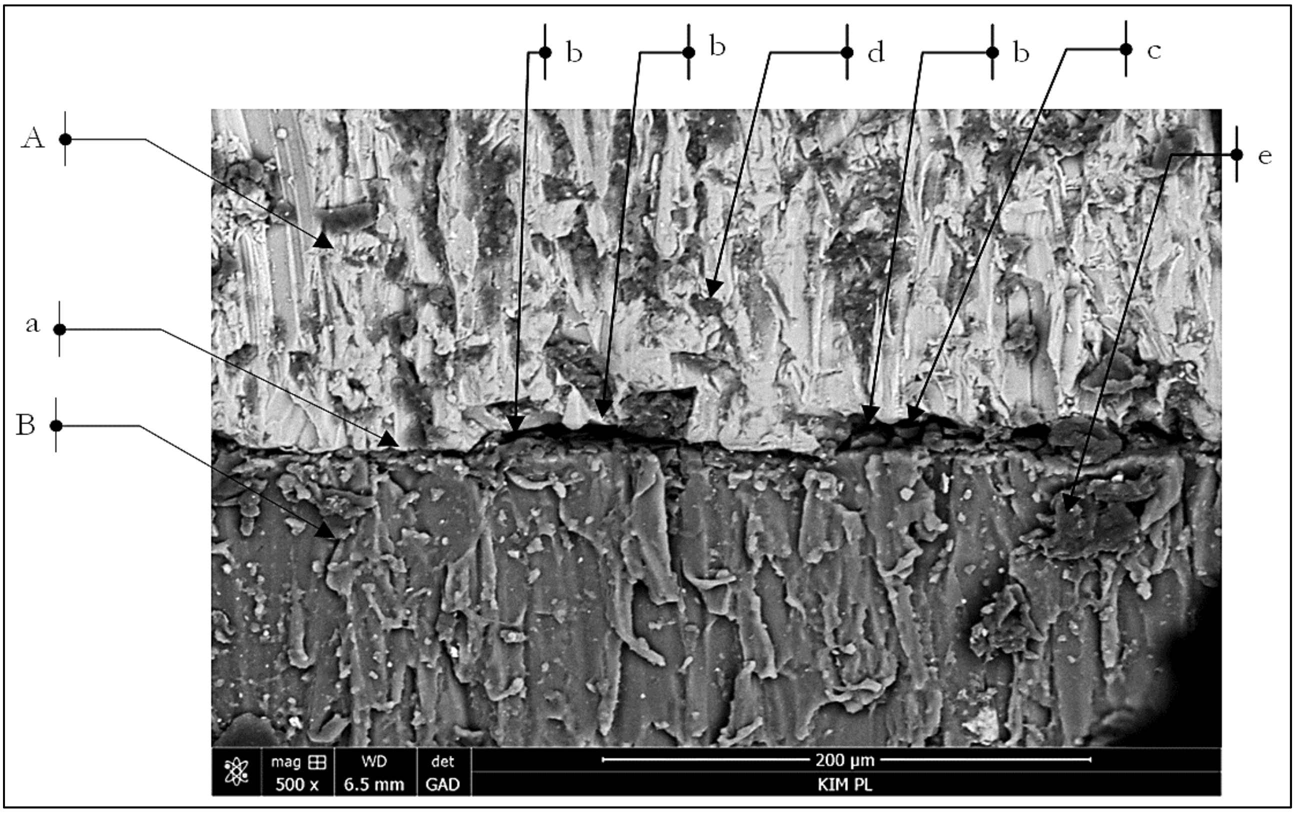

***Fig. 5** SEM surface morphology of hydroabrasively cut multilayer structure, composed of the AW-5754 aluminium alloy and silicone, together with a view of the interfacial space of both materials in x500 magnification*

Fig. 5 presents a multilayer structure after hydroabrasive cutting (composed of AW-5754 aluminium alloy (A) and silicone (B)) together with a view of the interfacial space (a) of both materials (in x500 magnification) and proves the formation of delamination in the interfacial zone and the damage to the consistency of silicone with the AW-5754 aluminum alloy surface in the contact micro-areas marked with the letter (b). Letter (c) indicates abrasive grains located (embedded) in the interfacial space, present in the areas of delamination, letter (d) marks abrasive grains embedded in a homogeneous silicone structure, and letter (e) marks abrasive grains embedded in a homogeneous AW-5754 aluminum alloy structure. Particularly visible are changes in the inconsistency (b) of the vulcanized silicone material (A) with the AW-5754 aluminum alloy surface (B) after hydroabrasive cutting, that can be observed at higher SEM image magnifications, shown in Fig. 6 (x650) and Fig. 7 (x2000). The identified discontinuities of the two-phase structure consistency extend to the length of sections of 30 μm and more. Nonetheless, structural discontinuities of approximately 30 μm have a dominant share. It was found that with the increase in the mass flow rate m_a [$g \cdot s^{-1}$], the number and length of discontinuities of the structure slightly increases. This is associated with an increase in the number of abrasive grains and the total energy of the hydroabrasive stream beam, as a consequence of increased silicone interactions on the vulcanized connection. The embedding of abrasive grains into the silicone structure is easier, and the resistance provided by the aluminum alloy material - especially in the interfacial area - leads to a sudden increase in force causing significant elastic and plastic deformations leading to the formation and propagation of a gap in the interfacial area. Subsequent high kinetic energy abrasive grains support this process leading to further propagation of structural delamination.

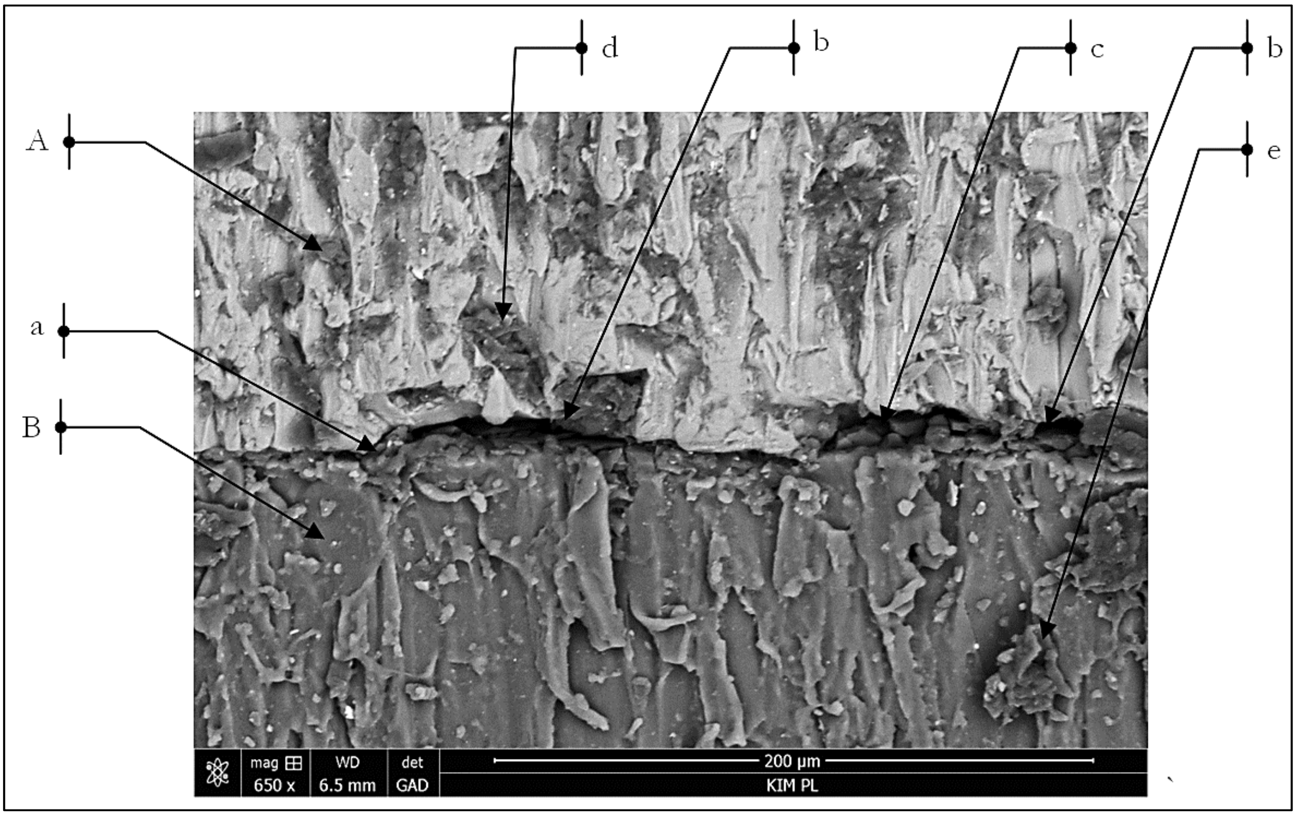

Fig. 6 *Morphology of the surface of a hydroabrasively cut multilayer structure composed of an AW-5754 aluminium alloyand silicone, together with a view of the interfacial space of both materials in x650 magnification*

Visible at high magnification (x2000) in Fig. 7 is tight packing of abrasive grains (c) concentrated in the gap (b). Supported by a high pressure hydroabrasive stream, it creates an additional hydraulic wedge increasing the expanding effect as a result of the Rebinder effect, which creates a permanent disruption of the cohesion of the materials connected by vulcanization (A – silicone and B – AW-5754 aluminum alloy).

The Rebinder effect can manifest in various forms: adsorption plasticization (facilitating plastic deformation), adsorption strength loss or spontaneous dispersion of a solid body. Abrasive grains are visible both in the created gap but also in the material of both silicone and aluminum alloy, which is marked in Fig. 5-7 with letters *d* and *e*. The grains embedded in the material are garnet particles in the form of irregular grains. At the stage of preparation for the material cutting process, an 80 mesch garnet is usually selected.

However, as a result of cutting and energy changes, grains wear out and change their size and shape. Abrasive particles are mainly embedded in the silicone fraction, as shown in Fig. 5 and Fig. 6. This is related to the properties of silicone. To a much lesser extent, particles of abrasive grains embed in and settle on harder materials. Fig. 5-6 abrasive grains are almost completely absent (with a few exceptions) from the cutting surface of AW-5754 aluminum alloy.

Fig. 8 ÷ 9 shows SEM microscopic images at x500 magnification as a function of feed speed and mass flow rate ma. Three comparative configurations of samples cut under different technological conditions, for different values of feedrate vf and mass flow rate (m_a = 0.8 g·s^{-1} and 0.4 g·s^{-1}) were selected for analysis. Fig. 8 shows SEM morphology of the structure surface: AW-5754 aluminum alloy - silicone for variable feedrates in the range of v_f = 50÷3000 mm·min^{-1}. From the SEM images presented in Fig. 8 we can deduce that increase in the speed of the feed movementvf results in a reduction of the amount of abrasive grains deposited in the silicone material and aluminum alloy. Abrasive grains with high kinetic energy perform cutting work and are carried by a water stream and discharged outside the cutting zone.

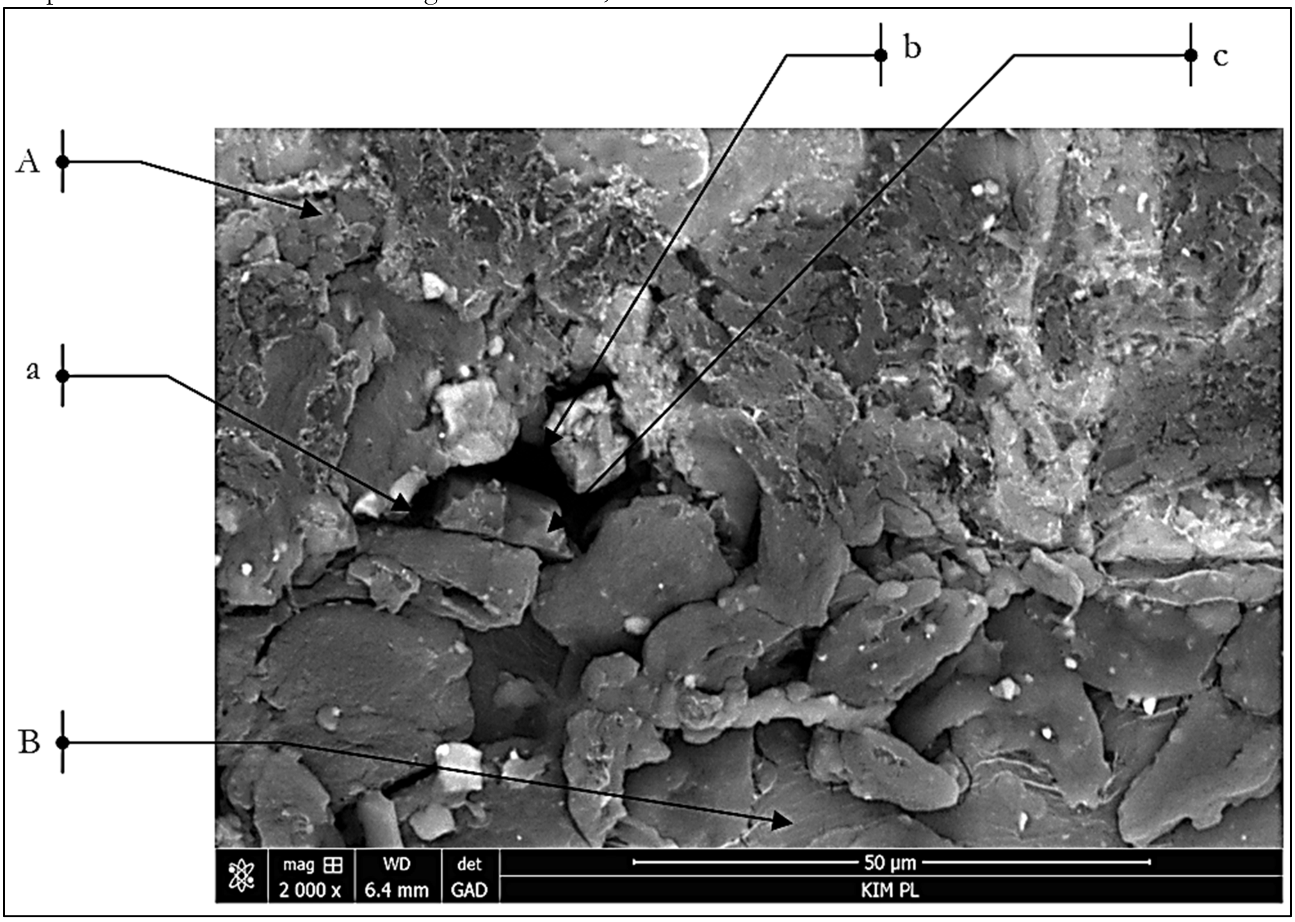

Fig. 7 *SEM surface morphology of hydroabrasively cut multilayer structure, composed of the AW-5754 aluminium alloy and silicone, together with a view of the interfacial space of both materials in x2000 magnification*

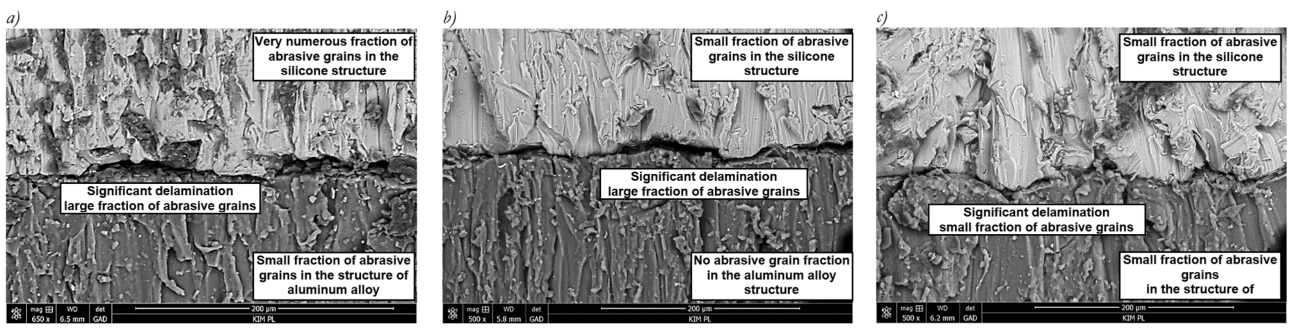

Fig. 8 *SEM surface morphology of AW-5754 aluminum alloy – silicone structure: a) for m_a=0.8 g·s^{-1}, v_f=50 mm·min^{-1}, b) for m_a=0.8 g·s^{-1}, v_f=500 mm·min^{-1}, c) for m_a=0.8 g·s^{-1}, v_f=3000 mm·min^{-1}*

The surface of silicone is clean and relatively homogeneous. Also, the fraction of abrasive grains accumulated in the interfacial zone is reduced. This is the result of high kinetic energy and a decrease in delamination. There are also unambiguous traces of cutting caused by individual grains as well as agglomerates of abrasive grains.

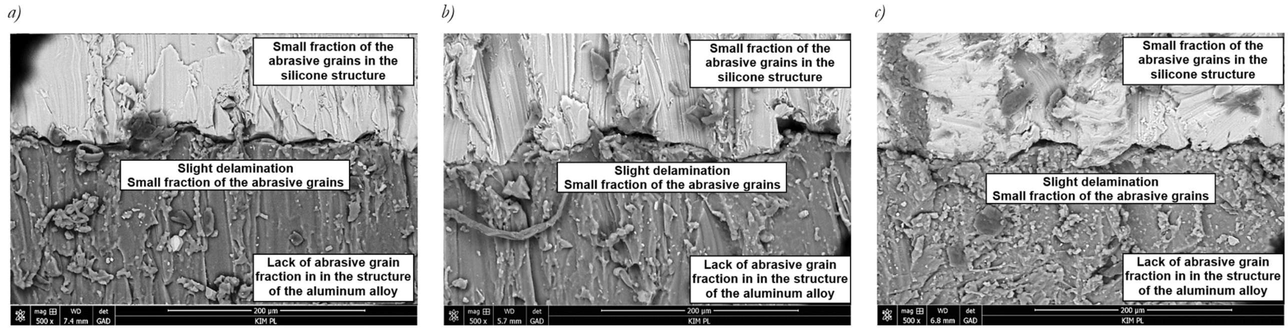

Fig. 9 *SEM surface morphology of the AW-5754 aluminum alloy – silicone structure: a) for m_a=0.4 g·s^{-1}, v_f=300 mm·min^{-1}, b) for m_a=0.4 g·s^{-1}, v_f=2500 mm·min^{-1}, c) for m_a=0.4 g·s^{-1}, v_f=3500 mm·min^{-1}*

Analyzing the influence of parameters such as feed speed and mass abrasive flow, it can be observed that they directly affect the surface quality after processing. For the technological parameters of cutting used during the experiment, especially for higher feed rates, SEM images show characteristic traces of the cutting process, which are the result of intense interactions of abrasive grains suspended in a hydroabrasive stream (Fig. 9).

It can be concluded that in the case of lower feedrates and with higher mass abrasive flow, the phenomenon of delamination is much greater than in the case of high feedrates and low mass abrasive flows. This is due to the fact that at a lower feedrate there is an unfavorable distribution of kinetic energy of the water jet, and a significant presence of the Rebinder effect in the delamination process – delamination of the AW-5754 aluminum alloy – silicone bond.

4 Summary and conclusions

This paper analyzed images of the microstructure of silicone-aluminum tiles cut in the process of hydroabrasive processing. As a result of the analysis of the mechanisms of interaction in the interfacial zone, it was revealed that the abrasive grains are an important factor in the process of separation of materials combined in the vulcanization process. An increase in the mass abrasive flow and a large amount of grains in the hydroabrasive stream adversely affects the interfacial connections, weakening the combined multilayer structure. Based on the obtained research material, one may conclude that:

- production of resistant and durable multilayer structure bonds in the process of 'AW-5754 aluminum alloy - silicone' in a vulcanization process is a complicated operation, with complex and not yet fully explained mechanisms of connection formation and its mechanical properties,
- during the process of hydroabrasive cutting of multilayer structures, local interfacial damage occur in the combination of AW-5754 aluminum alloy - silicone, manifested by delamination of the structure components,
- for lower feedratesvf (50-1000 mm·min-1) and with higher mass abrasive flow ma(0.8 g·s-1), the phenomenon of separation at the interface of the phases of the combined materials of the multilayer structure is much greater than in the case of high feedratesvf (2000-3500 mm·min-1) and low mass flow of abrasive (0.4 g·s-1),
- the increase in feedratevf does not cause significant changes in the delamination process when cutting the materials combined through vulcanization. The identified discontinuities of the two-phase structure consistency extend to the length of sections of 30 μm and more. Nevertheless, the dominant structures incosistencies are those roughly 30 μm in size,
- increase in the feed speed vfresults in a reduction in the amount of abrasive grains deposited in the silicone material and aluminum alloy,
- it was found that as the mass flow rate ma [g·s-1] increases, the number and length of discontinuities of the structure increases slightly. This is related to the increase in the number of abrasive grains and the total energy of the hydroabrasive stream and, consequently, increased force interactions on the vulcanized connection,

- the durability and strength of the connection of multilayer structures depend on a number of factors, including but not limited to: the type of joined materials, the method of surface preparation of the joined materials, and presence of intermediate layers between the joined materials (e.g. substances that activate the surface, increasing its adhesive properties),
- an important factor that determines the quality and strength of the combined multi-layer structure and the aging process of the combined structure is the chemical composition of silicone and the technology of vulcanization,
- an important factor of multilayer structures is their resistance to corrosion in the interfacial area, mainly conditioned by the tightness of the connection,
- low interfacial strength promotes the layered separation of materials. The increase in interfacial strength can be increased by applying appropriate surface preparation, which in turn translates into improved final strength.

As confirmed by the authors of other publications, it is possible to cut multilayer structures made of different materials. The microscopic images presented in the work [12] confirm the detailed analysis of the authors of the work consists chemical adhesion of silicone elastomers on primed metal surfaces. In this work the main objective is to compile information regarding the chemical adhesion of silicone elastomers on primed metal surfaces. The obtained microscopic results show confirmation of the lack of adhesion described in the work [12]. It additionally aims at giving some hints to formulate primer formulations, according to the mechanical and environmental properties targeted in the manufacture of composite parts. The results of similar work on, among others effect of waterjet machining parameters on cut quality of polymeric composite materials based on biological reinforcement in form of cotton post-harvest line residues are presented by the authors in publications [2, 6, 7]. Their results are consistent with the results obtained in this article, but they concern composites with a slightly different structure. This is also confirmed by other authors of publication [22, 24, 25], in which aluminum - rubber materials are cut. With reference to the research results presented in this publication, the authors of other publications note similar phenomena occurring in the interfacial zone. The results of the tests included in this publication, which concerned the study of aluminum alloy - silicone structures, confirm the correctness of the experiment and are similar to the results published by other authors. As presented by the authors of other studies, the phenomenon of adhesion and delamination occurs at the junction of two materials. The results of the research, which have been published in publications, indicate a wide range of issues. The current state of the writer describes many phenomena that occur in the interfacial zone and characterizes them. Referring the results of this work to other works carried out on SEM microscopes [24, 25] appearing in the literature, such an analysis allows for the correct synthesis of the phenomena of joined materials.

Acknowledgments

The project/research was financed in the framework of the project Lublin University of Technology - Regional Excellence Initiative, funded by the Polish Ministry of Science and Higher Education (contract no. 030/RID/2018/19).

References

[1] HAJJARI E., DIVANDARI M., MIRHABIBI A.R. (2010). The effect of applied pressure on fracture surface and tensile properties of nickel coated continuous carbon fiber reinforced aluminum composites fabricated by squeeze casting. *Materials and Design,* Vol. 31, pp. 2381-2386. ISSN 0261-3069

[2] MÜLLER, M., KOLÁŘ V., AND VALÁŠEK P. (2019) Effect of Waterjet Machining Parameters on Cut Quality of Polymeric Composite Materials Based on Biological Reinforcement in Form of Cotton Post-harvest Line Residues. *Manufacturing Technology* Vol. 19, no. 4 pp. 647-54

[3] LALET G., MIYAZAKI T., KAWASAKI A., SILVAIN J.F. (2014). Thermomechanical stability of a carbon fiber-reinforced aluminum matrix composite fabricated by spark plasma sintering in various pulse conditions. *Materials Letters*, Vol. 130, pp. 32-35. ISSN 0167-577X

[4] VAŠINA M, HRUŽÍK L, BUREČEK A. Study of Factors Affecting Vibration Damping Properties of Multilayer Composite Structures. *Manufacturing Technology*. 2020 pp.104-109

[5] SHIRVANIMOGHADDAM K., HAMIM S. U., KARBALAEI AKBARI M., MOUSA S. (2017). Carbon fiber reinforced metal matrix composites: fabrication processes and properties. *Composites Part A: Applied Science and Manufacturing,* Vol. 92, pp. 70-96. ISSN 1359-835X

[6] MULLER, M., D´ARMATO, R., RUDAWSKA A. (2017). Machining of polymeric composite by means of abrasive water-jet technology. In: *16th International Scientific Conference Engineering for Rural Development.* pp. 121 - 127. Jelgava, Latvia University of Agriculture

[7] MÜLLER, M., VALÁŠEK, P., KOLÁŘ, V. (2018). Research on application of technology using water jet on machining of polymeric composite biological-reinforced materials. In: *Manufacturing Technology*. pp. 647-654, vol. 18, no. 4

[8] GONG N.N, WANG B.W., WANG Y.H., LI X.P., W.C. LIN, FU S.H. (2020). Effect of metal surface state on injection joining strength of aluminum-rubber composite. *Journal of Manufacturing Processes*, pp. 365-372, Vol. 49. ISSN 1526-6125

[9] NOVAK, M. Surface quality of hardened steels after grinding. *Manufacturing Technology*, 2011, Vol. XI, no. 11. pp. 55 - 59. ISSN 1213-2489

[10] SU Y.Y., SHEMENSKI R.M. (2001). A method for continuous monitoring of bond formation between rubber and reinforced wire. *International Journal of Adhesion and Adhesives*. Vol. 21, pp. 481-485. ISSN 0143-7496

[11] YAN H., ZHANG W.-J., JIANG H.Y., CHEN L., (2014) Energy dissipation of a ring-like metal rubber isolator. *Chinese Physics. B*. Vol. 23

[12] PICARD L., PHALIP P., FLEURY E., (2015). Ganachaud Chemical adhesion of silicone elastomers on primed metal surfaces: a comprehensive survey of open and patent literatures. *Progress in Organic Coatings*, pp. 120-141, Vol. 80. ISSN 0300-9440

[13] HASHISH, MOHAMED. (2008). Optimalization Factors in Abrasive Waterjet Machining, *Journal of Engineering for Industry*, Vol 113, pp. 29. ASME 1992

[14] ZENKIEWICZ M. (2000). *Adhezja i modyfikowanie warstwy wierzchniej tworzyw wielkocząsteczkowych*. WNT, Warsawa. ISBN:83-204-2547-6

[15] CHAO, J. AND ZHOU, G. AND LEU, M. C. AND GESKIN, E. (1955) Characteristic of Abrasive Waterjet Generated Surfaces and Effects of Cutting Parameters and Structure Vibration. *Journal of Engineering for Industry*. Vol 117, pp. 516-525. ISSN = 0022-0817

[16] BIEJOVÁ. (2013). Abrasive kind and granularity changes affects to water jet technology head vibration during cutting HARDOX material thickness alternation process. In: *Applied Mechanics and Materials*. vol. 308, pp. 75-79. - ISSN 1660-9336

[17] SÝKOROVÁ, L., Malachová, M. (2012). Laser Machining and Temperature Field Simulation Using COSMOS /M Software. *Manufacturing Technology*. No. 12. pp. 113-117 ISSN 12132489

[18] ČIERNA, H., ŤAVODOVÁ, M. (2013). Using the design of experiment method to evaluate quality of cuts after cutting aluminum alloy by AWJ. In: *Manufacturing technology: journal for science, research and production*. vol. 13, pp. 303-307 no. 3

[19] PEREC, A., ŤAVODOVÁ, M. (2016). Abrasive Water Jet Cutting Depth Optimization by Taguchi Approach. *Manufacturing Technology,* vol. 16, p. 585-590. iss. 3

[20] SHARMA, V., CHATTOPADHYAYA, S. A., HLOCH, S. (2011). Multi response optimization of process parameters based on Taguchi—Fuzzy model for coal cutting by water jet technology. *In: The International Journal of Advanced Manufacturing Technology*, vol. 56, no. 9-12, pp. 1019-1025

[21] PEREC, A., KAUFELD, M, PUDE, F., WEGENER, K. (2014). Taguchi Approach Optimization of Steel Surface Roughness in Abrasive Water Jet Cutting. *International Conference on Mechanical Engineering and Mechatronics*. Slovakia

[22] NAPRSTKOVA, N., KALINCOVA, D. (2015). Influence of additional chemical components on machining properties of selected alumunium-silicon alloy. In: *14th International Scientific conference: Engineering for Rural Development*. Vol. 14, pp. 766-771. Jelgava, Latvia University of Agriculture

[23] RAJ, P., HLOCH, S., TRIPATHI, R.,SRIVASTAVA, M., NAG, A., KLICHOVÁ, D.,KLICH, J., HROMASOVÁ, M., MÜLLER, M.,LINDA, M., CHATTOPADHYAYA, S., ADAMCIK, P. (2019). Investigation of sandstone erosion by continuous and pulsed water jets. In: *Journal of Manufacturing Processes*, vol. 42, pp. 121-130. ISSN 1526-6125

[24] OSTAPIUK M. (2020). Corrosion resistance of PEO and primer coatings on magnesium alloy. *Journal of Asian Ceramic Societies*, Vol. 9 pp 40-52, Issue 1 Article 1249

[25] KUTENEVA S.V., GLADKOVSKY S.V., VICHUZHANIN D.I., NEDZVETSKY P.D. (2022) Microstructure and properties of layered metal/rubber composites subjected to cyclic and impact loading. *Composite Structures*. Vol. 285. pp. 115078. ISSN 0263-8223