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# ВЛИЯНИЕ МЕТОДА ФОРМИРОВАНИЯ ПРОМЕЖУТОЧНОГО СЛОЯ НА СТРУКТУРУ И СВОЙСТВА СЛОИСТЫХ КОМПОЗИЦИЙ СИСТЕМЫ «СТАЛЬ – АЛЮМИНИЙ»

Рассмотрены технологические особенности получения слоистых композиций системы «сталь – алюминий» с применением промежуточного слоя. Раскрыто влияние метода формирования промежуточного слоя на структуру границы раздела «сталь – алюминий», а также свойства слоистых сталеалюминиевых композиций. Для получения на подложке из низкоуглеродистой стали 20 по ГОСТ 1050 промежуточного слоя из чистого алюминия марок А5 по ГОСТ 7871 и АД1 по ГОСТ 4784 опробованы жидкофазный метод дугового алитирования по технологии Cold Metall Transfer, а также процесс сварки взрывом в твердой фазе. Показано, что в процессе дуговой наплавки рабочего покрытия на сталь с предварительно нанесенным промежуточным алюминиевым слоем алюмокремниевый расплав контактирует не с чистой сталью, а с имеющимся на границе раздела интерметаллидным слоем системы Fe–Al, что сопровождается частичным его растворением, степень которого зависит от температуры и времени существования сварочной ванны. При сплошном слое интерметаллидов системы Fe–Al, образующихся при нанесении промежуточного слоя методом дугового алитирования, скорость растворения исходных интерметаллидов меньше скорости образования новых тройных систем Fe–Al–Si, что приводит к росту с 8,2 до 18 мкм среднего значения толщины интерметаллидного слоя в процессе дуговой наплавки покрытий. Дискретный интерметаллидный слой системы Fe–Al, образовавшийся при нанесении промежуточного слоя сваркой взрывом, полностью разрушается при контакте с алюмокремниевым расплавом, вследствие чего происходит образование нового сплошного слоя из тройных интерметаллидов системы Fe–Al–Si, характеризующегося меньшей толщиной (10 мкм против 16 мкм в исходном состоянии). Определено, что композиции, имеющие промежуточный слой, сформированный жидкофазным процессом дугового алитирования, обладают средними значениями адгезионной прочности до 25 МПа. Применение твердофазного процесса сварки взрывом для нанесения промежуточного слоя позволяет получать слоистые композиции системы «сталь – алюминий», характеризующиеся адгезионной прочностью до 43 МПа. Достигнутые значения адгезионной прочности позволяют рекомендовать разработанные слоистые композиции системы «сталь – алюминий» для применения в узлах трения современной техники.

**Ключевые слова**: слоистые композиции, система «сталь – алюминий», промежуточный слой, интерметаллиды, дуговая наплавка, сварка взрывом, дуговое алитирование, структура, граница раздела, адгезионная прочность.

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# INFLUENCE OF THE INTERMEDIATE LAYER FORMING METHOD ON THE STRUCTURE AND PROPERTIES OF STEEL-ALUMINIUM SYSTEM LAYERED COMPOSITIONS

The technological features of manufacturing steel-aluminium system layered compositions with intermediate layer are considered. The influence of the intermediate layer forming method on interface structure, as well as the properties of layered steel-aluminum compositions is disclosed. For deposition of intermediate layer of pure aluminium of grades A5 GOST 7178 and AD1 GOST 4784 on low-carbon steel 20 GOST 1050 substrate the liquid-phase method of arc aluminizing using the Cold Metall Transfer technology, as well as the solid phase explosion welding process were used. It was shown that during the arc cladding process with a preliminary deposited intermediate aluminium layer Al-Si melt contacts not with pure steel. It contacts with the intermetallic layer of the Fe-Al system presented at the interface, which is accompanied by its partial dissolution. The dissolution degree depends on temperature and the existence time of the weld pool. With a continuous layer of the Fe-Al system intermetallic compounds formed during the deposition of an intermediate aluminum layer by arc aluminizing method using CMT technology the dissolution rate of the initial intermetallics is lower than the rate of new ternary Fe-Al-Si systems formation. It leads to an increasing from 8,2 to 18 μm in the average thickness of the intermetallics during the arc cladding of working coatings. The adhesion strength level of such coatings is 25 MPa. The discrete intermetallic layer of the Fe-Al system, formed during the deposition of an intermediate aluminum layer by explosion welding process, is completely destroyed upon contact with the Al-Si melt. As a result of it a new continuous layer of ternary Fe-Al-Si system intermetallic compounds is formed. The layer is characterized by a smaller thickness (10 μm versus 16 μm in the initial state). The specimens have adhesion strength level of 43 MPa. The achieved values of adhesion strength make it possible to recommend the produced steel-aluminum system layered compositions for using in friction units of modern technology.

**Keywords**: layered compositions, steel-aluminium system, intermediate layer, intermetallics, arc cladding, explosion welding, arc aluminizing, structure, interface, adhesion strength.

## Introduction

Plain bearings are widely used in friction units of modern machines and mechanisms [1, 2]. In most cases, they are bimetals, structurally representing a load-bearing steel substrate with a working layer from antifriction material based on Al, Pb, Sn or Cu. However, according to the results of premature failures of machines and mechanisms analysis, the operational properties of working layer traditional materials have reached their limiting values, and the potential for their improvement has been exhausted [3–5]. Therefore, this problem solution is to replace them with new particle-reinforced composite materials (CM) based on aluminium. The aluminium-matrix CM structure provides low values of the friction coefficient, as well as high wear resistance in a wide temperature range due to the joint operation of dissimilar components [6–8]. In addition, the possibility of multiple recovery, as well as modifying processing of the CM working layer, allows to reduce the cost of products for tribotechnical purposes [9, 10].

The area of application of such functional layered compositions with structural steels substrate and a aluminium-matrix CMs working layer, is limited due to the low adhesive strength as a result of brittle intermetallic compounds with different stoichiometric composition $Fe_xAl_y$ formation at the substrate-coating interface [11–13]. Moreover, the appearance of such phases is mainly associated with the chemical interaction between the CM matrix material and the substrate, while the reinforcing particles do not change the mechanisms of formation and growth of intermetallic compounds [14].

The research results have shown that by using of an intermediate layer, it is possible to ensure the limitation of interphase interaction of in such layered compositions [14–16]. In this case, an intermediate layer can possibly be obtained by technological processes occurring in the solid or liquid phases differing in the kinetics of interphase interaction. Therefore, the purpose of this work was to study the influence of the intermediate layer forming method on the structure and properties of steel-aluminium system layered compositions.

## Materials and methods

An intermediate layer of pure aluminium of grades A5 (0.2–0.35 wt. % Fe; 0.1–0.25 wt. % Si, ≤0.015 wt. % Cu; Al – base, GOST 7178) and AD1 (≤0.3 wt. % Fe; ≤0.3 wt. % Si; ≤0.025 wt. % Mn; ≤0.15 wt. % Ti; ≤0.05 wt. % Cu; ≤0.1 wt. % Zn; Al – base, GOST 4784) was deposited on low-carbon steel 20 (0.17–0.24 wt. % C; 0.17–0.37 wt. % Si; 0.35–0.65 wt. % Mn; ≤0.25 wt. % Cr; Fe – base, GOST 1050) substrate with dimensions of 300×150×(2×15) mm. To obtain it, the liquid-phase method of arc aluminizing using the Cold Metall Transfer – CMT technology, as well as the explosion welding process in the solid phase, providing up to 2 and 3 mm layer thickness respectively were used.

Arc aluminizing method using CMT technology is characterized by minimum values of the welding heat source energy and allowing to limit the growth of intermetallic compounds. The process was carried out on specialized welding equipment TransPuls Synergic 2700, Fronius using a A5 grade welding wire with a diameter of 1.2 mm. Arc aluminizing technological parameters (pulse current – 150 A; base current – 40 A; voltage – 18 V; cladding speed – 0.5 m/min) were selected according to [17]. Previously the steel plate's surface was treated by hot dip galvanizing in order to improve its wetting with aluminium melt.

The explosion welding process is characterized by transience (the time of force action does not exceed $10^{-6}$ s), which limited the diffusion processes development. The process was carried out according to a parallel scheme, ensuring the constancy of the kinematic parameters within the entire area of the workpiece [18]. The technological parameters of the explosion welding process were selected according to [18, 19]: welding speed – (2000–2200) m/s, collision speed of the joining elements – 380 m/s, and ammonite No. 6ZHV (GOST 21984) was used as an explosive.

On the specimens in the form of a substrate with a preformed intermediate layer working coatings with a thickness of up to 5 mm were produced by the process of arc cladding. Welding rods with a diameter of 2.4 mm OK Tigrod 4047 (≤0.6 wt. % Fe; 11–13 wt. % Si; ≤0.15 wt. % Mn; ≤0.05 wt. % Cu; Al – base, AWS A5.10), close in chemical composition to matrix alloys of scarce CM were used. The selected according [20] arc cladding parameters (welding current – 150–200 A; arc voltage – 18–20 V; surfacing speed – 11–13 m/h) made it possible to completely melt the intermediate layer, i.e. to achieve physical contact of the Al–Si melt not with the surface of the steel substrate, but with the intermetallic compounds of the Fe–Al system.

The diffusion zone structure between the substrate and deposited coatings was studied using optical and electron microscopy. Leika DMILM light microscope equipped with a digital camera, as well as a Helios NanoLab 660 scanning electron microscope equipped with energy-dispersive X-ray (EDX) microanalysis were used.

In order to characterize the properties level of the manufactured compositions adhesive strength of the cladding coatings was studied by peel and shear tests. These tests schemes are recommended for composite bimetallic materials using in industry. The selected test schemes were carried out on a 2054 R-5 tensile testing machine with a stepwise application of a load until the destruction of the samples and a movement speed of the grippers of 2 mm/min.

### Results and discussion

Despite the minimum heat input in the process of liquid-phase arc aluminizing method using CMT technology, a continuous layer of intermetallic compounds with an average thickness of 8.2 μm is formed at the substrate-intermediate layer interface (Fig. 1, *a*). Moreover, according to the results of EDX, compounds based on aluminium ($FeAl_3$ and $Fe_2Al_5$) are located on the intermediate layer side, and on the basis of iron $Fe_2Al_3$, FeAl, $Fe_3Al$ – on the side of the substrate (Fig. 1, *b*) Iron-based intermetallics are characterized by the shape of tongue-like outgrowths in the direction of steel. Different values of the average thickness of the intermetallic layer regions formed by compounds based on aluminium and iron (3.6 and 4.6 μm) are probably associated with a longer duration of the diffusion process of aluminium into iron compared with the opposite direction of diffusion of iron into aluminium. It should be noted that the reason for the appearance of longitudinal cracks in the intermetallic layer is believed to be a significant increase in internal stresses due to an increase in the volume of the final phase [21].

At the same time, the transience of the force action during explosion welding prevents the development of diffusion processes and leads to the appearance at the interface not only of discrete intermetallic compounds based on aluminium ($Fe_2Al_5$, $FeAl_5$ and $FeAl_6$) with an average thickness of 16 μm, but and areas free from them (Fig. 1, *c*, *d*). In addition, numerous spalls of the intermetallics are observed at a distance of up to 50 μm from the interface. These phases are formed at high crystallization rates typical of the explosion welding process [19].

The arc cladding process of working coatings results in significant changes in the initial structure of the interface. In diffusion zone can be distinguished characteristic regions (Fig. 2):

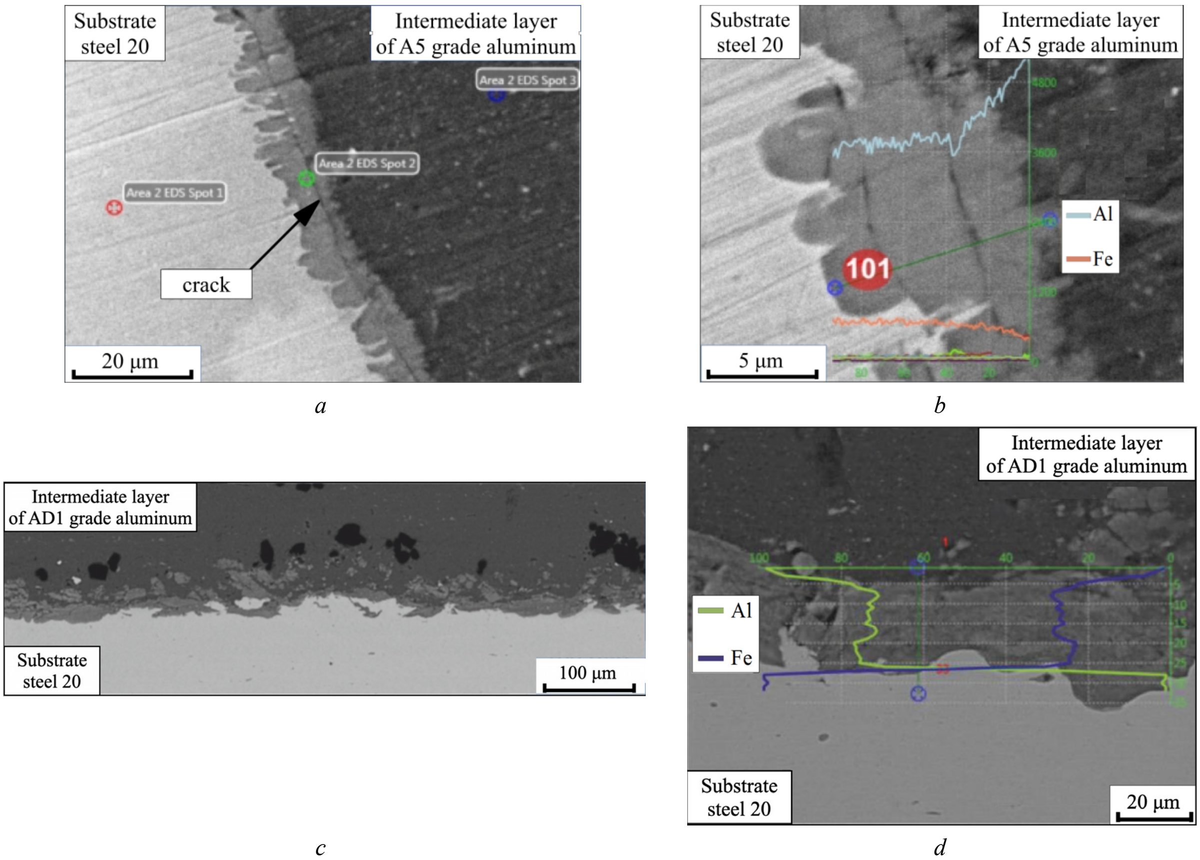
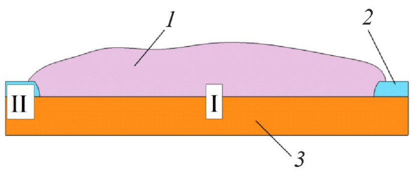


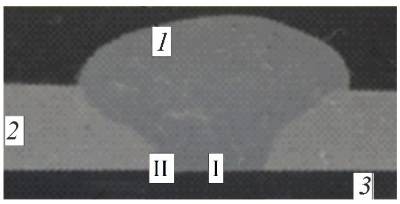

Fig. 1. Typical microstructure (*a*, *c*) and distribution of chemical elements (*b*, *d*) at the interface of specimens produced by arc aluminizing (*a*, *b*) and explosion welding (*c*, *d*)

– region I, formed as a result of complete penetration of the intermediate layer and limited by the weld pool size;

– region II, up to 400 µm in length from the deposited metal, which was heated above the temperatures of the beginning of Fe–Al system intermetallics intensive growth.




*a*

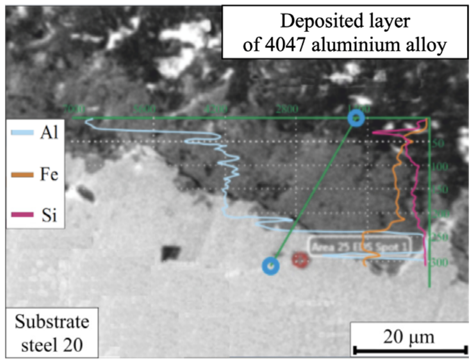



*b*

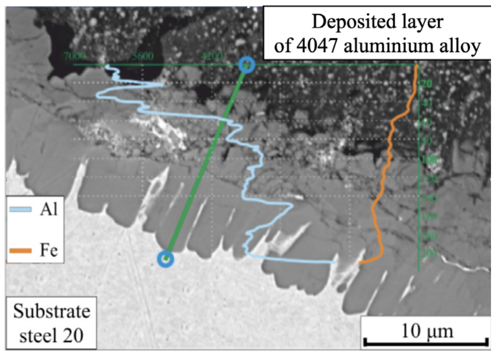
Fig. 2. Scheme (*a*) and macrostructure (*b*) of specimens: *1* – deposited layer of 4047 aluminium alloy; *2* – intermediate layer of A5 or AD1 grade aluminium; *3* – substrate of steel 20

Specimens manufactured by arc cladding process with intermediate layer obtained by arc aluminizing method using CMT technology are characterized by a continuous intermetallic layer with average thickness 18 µm in region I (Fig. 3, *a*). The result of the interaction of the Al-Si melt with the initial continuous layer of intermetallic compounds during surfacing is not only partial dissolution of the latter, but also the activation of Si diffusion into it, which is confirmed by the detection of ternary intermetallic compounds $Al_{7.4}Fe_{1.8}Si$ by means of EDX. Due to the occupation of structural vacancies by Si in the initial $Fe_xAl_y$ intermetallics, the phases of the Fe–Al–Si system have a lower diffusion permeability for aluminium and iron [22, 23]. The intermetallic layer located in region II retains the original phase composition. However, due to heating to temperatures exceeding the onset of intermetallics intensive growth during arc cladding process, its average thickness increases to 50 % (from 8 to 12 µm) compared to the initial state (Fig. 3, *b*). Moreover, the intermetallic interlayer adjacent to the intermediate layer is characterized by a multitude of cracks. Its appearance is associated with the high hardness and brittleness of the aluminum-based phases forming it ($FeAl_3$ and $Fe_2Al_5$), which is confirmed by the EDX.

In specimens with discrete intermetallic compounds based on aluminium and regions free from them in the initial state at the interface, as a result of the arc cladding process, destruction of such a diffusion zone in region I is observed and the formation of a new continuous layer of intermetallics with an average thickness of 5 µm (Fig. 4, *a*, *b*).




*a*




*b*

Fig. 3. Diffusion zone microstructure and composition in regions I (*a*) and II (*b*) of manufactured specimens with intermediate layer obtained by arc aluminizing method using CMT technology

Alloying the surfacing coatings material with silicon and the development of diffusion processes during contact of the melt with a solid substrate, lead to the formation of Fe–Al–Si ternary systems, which have lower growth rates compared to the Fe–Al binary system [22, 23]. Moreover, as in the previously considered case, due to the presence of Si in the composition of the filler material, intermetallic compounds of the Fe–Al–Si ternary system are formed, which are characterized by lower growth rates in comparison with the $Fe_xAl_y$ compounds [24, 25]. During the arc cladding prosess the growth of imtermetallics occurs in region II (Fig. 4, *c*). The activation of diffusion processes due to the thermal effect of the cladding process is accompanied by the saturation of intermetallic compounds with iron and a change in their stoichiometric composition from $FeAl_5$ and $FeAl_6$ to $Fe_2Al_7$, $FeAl_2$, $Fe_2Al_5$ (Fig. 4, *d*). The intermetallic inclusions are characterized by an increased average size from 16 to 30 µm in comparison with the initial state. Also, it should be noted that they have a variable stoichiometric composition: from $FeAl_2$ in the central part to $FeAl_5$ / $FeAl_6$ in the periphery (see Fig. 4, *d*).

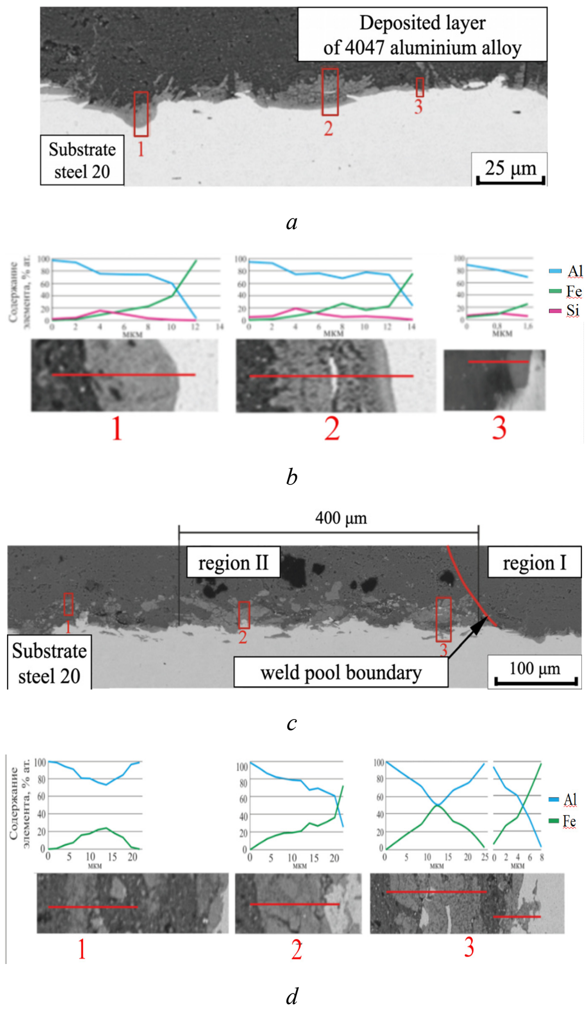



Fig. 4. Diffusion zone microstructure and composition in regions I (*a*, *b*) and II (*c*, *d*) of manufactured specimens with intermediate layer obtained by explosion welding process

The adhesion strength test results showed that the compositions with an intermediate layer formed by the liquid-phase arc aluminizing process using CMT technology have average shear and tear strength values of 15 and 25 MPa, respectively. The adhesion strength of the compositions with the intermediate layer made by the solid-phase explosion welding process is 37.8 and 43 MPa in shear and peel tests.

Thus, an increase in the diffusion rate as a result of thermal action during the application of an aluminium coating on steel with intermediate layer of pure A5 aluminum, obtained previously by arc aluminizing process using CMT technology, in combination with an uneven distribution of intermetallic compounds of various stoichiometric compositions, lead to an increase in the thickness of the intermetallic layer by up to 50 % in comparison with the original samples, as well as significant cracking mainly from the side of the deposited layer, as a result of which the adhesion strength values correspond to 25 MPa. When an aluminium coating is deposited on steel with intermediate layer of AD1 grade aluminium, obtained previously by the explosion welding process, a discrete layer of Fe–Al double intermetallic compounds dissolves. It leads to a decrease of intermetallic layer thickness by up to 60 % compared to the initial samples, as a result of which the adhesion strength values reach 43 MPa. The achieved values of adhesion strength make it possible to recommend the produced steel-aluminum system layered compositions for using in friction units of modern technology.

## Conclusions

1. It is shown that during the arc cladding process with a preliminary deposited intermediate aluminium layer Al–Si melt contacts not with pure steel. It contacts with the intermetallic layer of the Fe–Al system presented at the interface, which is accompanied by its partial dissolution. The dissolution degree depends on temperature and the existence time of the weld pool.

2. With a continuous layer of the Fe–Al system intermetallic compounds formed during the deposition of an intermediate aluminum layer by arc aluminizing method using CMT technology the dissolution rate of the initial intermetallics is lower than the rate of new ternary Fe–Al–Si systems formation. It leads to an increasing from 8.2 to 18 µm in the average thickness of the intermetallics during the arc cladding of working coatings. The adhesion strength level of such coatings is 25 MPa.

3. The discrete intermetallic layer of the Fe–Al system, formed during the deposition of an intermediate aluminum layer by explosion welding process, is completely destroyed upon contact with the Al–Si melt. As a result of it a new continuous layer of ternary Fe–Al–Si system intermetallic compounds is formed. The layer is characterized by a smaller thickness (10 µm versus 16 µm in the initial state). The specimens have adhesion strength level of 43 MPa.

## Список литературы

1. Дроконов А.М., Осипов А.В., Бирюков А.В. Подшипники турбинных установок: учеб. пособие / БГТУ. – Брянск, 2009. – 103 с.

2. Совершенствование материалов для подшипников скольжения двигателей внутреннего сгорания (обзор) / Н.П. Бурковская, Н.В. Севостьянов, Т.А. Болсуновская, И.Ю. Ефимочкин // Труды ВИАМ. – 2020. – № 1 (85). – С. 78–91.

3. Паровай Е.Ф., Ибатуллин И.Д. Актуальные проблемы надежности узлов трения газотурбинных двигателей // Вестник Самарского государственного аэрокосмического университета. – 2015. – Т. 14, № 3-2. – С. 375–383.

4. Языков А.Е., Казанский В.Н., Бускунов Р.Ш. Подшипники и маслосистемы: учеб. пособие. – Челябинск: Цицеро, 2010. – 202 с.

5. Пилюшина Г.А., Памфилов Е.А. Причины потери работоспособности насосов и гидромоторов мобильных машин // Актуальные направления научных исследований XXI века: теория и практика. – 2017. – Т. 5, № 6 (32). – С. 219–224.

6. Development and testing of Al–SiC and Al–TiC composite materials for application in friction units of oil-production equipment / T.A. Chernyshova, R.S. Mikheev, I.E. Kalashnikov, I.V. Akimov, E.I. Kharlamov // Inorganic materials: Applied research. – 2011. – No. 3. – P. 322–329.

7. Sijo M.T., Jayadevan K.R. Analysis of stir cast aluminium silicon carbide metal matrix composite: A comprehensive review // Procedia Technology. – 2016. – Vol. 24. – P. 379–385.

8. A review on aluminium matrix composite with various reinforcement particles and their behaviour / S. Arunkumar, M. Subramani Sundaram, K.M. Suketh kanna, S. Vigneshwara // Materials Today: Proceedings. – 2020. – Vol. 33. – P. 484–490.

9. Panwar N., Chauhan A. Fabrication methods of particulate reinforced Aluminium metal matrix composite. A review // Materials Today: Proceedings. – 2018. – Vol. 5. – P. 5933–5939.

10. Chaka V., Chattopadhyayb H., Doraa T.L. A review on fabrication methods, reinforcements and mechanical properties of aluminum matrix composites // Journal of Manufacturing Processes. – 2020. – Vol. 56. – P. 1059–1074.

11. Intermetallic $Fe_xAl_y$-phases in a steel/Al-alloy fusion weld / L. Agudo, D. Eyidi, C.H. Schmaranzer, E. Arenholz, N. Jank, J. Bruckner, A.R. Pyzalla // Journal of Materials Science. – 2007. – Vol. 42. – P. 4205–4214.

12. Effects of Fe-Al intermetallic compounds on interfacial bonding of clad materials / Q. Wang, X. Leng, T. Yang, J. Yan // Transactions of Nonferrous Metals Society of China. – 2014. – Vol. 24, no. 1. – P. 279–284.

13. Formation of $Fe_5Si_3$ precipitate in the $Fe_2Al_5$ intermetallic layer of the Al/steel dissimilar arc welding joint: A transmission electron microscopy (TEM) study / P. Xu, X. Hua, C. Shen, G. Mou, F. Li // Materials Characterization. – 2021. – Vol. 178. – P. 111236.

14. Ковалев В.В., Михеев Р.С., Коберник Н.В. Особенности получения сталеалюминиевых соединений методами сварки плавлением // Вестник МГТУ им. Н.Э. Баумана. Сер. Машиностроение. – 2016. – № 4. – С. 93–112.

15. Experimental and numerical analysis of the formation behavior of intermediate layers at explosive welded Al/Fe joint interfaces / Y. Aizawa, J. Nishiwaki, Y. Harada, S. Muraishi, S. Kumai // Journal of Manufacturing Processes. – 2016. – Vol. 24, no. 1. – P. 100–106.

16. Cold metal transfer welding of aluminium alloy AA 2219 to austenitic stainless steel AISI 321 / S. Babua, S.K. Panigrahia, G.D. Janaki Ramb, P.V. Venkitakrishnan, R. Suresh Kumar // Journal of Materials Processing Technology. – 2019. – Vol. 266. – P. 155–164.

17. The arc characteristics and metal transfer behaviour of cold metal transfer and its use in joining aluminium to zinc-coated steel / H.T. Zhang, J.C. Feng, P. He, B.B. Zhang, J.M. Chen, L. Wang // Materials Science and Engineering: A. – 2009. – Vol. 499, no. 1–2. – P. 111–113.

18. Особенности сварки взрывом толстолистовых сталеалюминиевых композитов / В.В. Литвинов, В.И. Кузьмин, В.И. Лысак, О.В. Строков, А.С. Кузьмин // Известия ВолгГТУ. – 2010. – Т. 5, № 4. – С. 44–49.

19. Совершенствование технологии изготовления сталеалюминиевых вкладышей подшипников скольжения / Б.С. Злобин, В.В. Сильвестров, А.А. Штерцер, А.В. Пластинин // Известия ВолгГТУ. – 2012. – Т. 5, № 14. – С. 57–63.

20. Tribotechnical properties of antifriction coatings based on composite materials / R.S. Mikheev, N.V. Kobernik, I.E. Kalashnikov, L.K. Bolotova, L.I. Kobeleva // Inorganic materials: Applied research. – 2015. – № 5. – P. 493–497.

21. Crystallography of $Fe_2Al_5$ phase at the interface between solid Fe and liquid Al / N. Takata, M. Nishimoto, S. Kobayashi, M. Takeyama // Intermetallics. – 2015. – Vol. 67. – P. 1–11.

22. Effects of Si additions on intermetallic compound layer of aluminum-steel TIG welding-brazing joint / J.L. Song, S.B. Lin, C.L.Yang, C.L. Fan // Journal of alloys and compounds. – 2009. – Vol. 488, no. 1. – P. 217–222.

23. Effect of Si on growth kinetics of intermetallic compounds during reaction between solid iron and molten aluminum / F. Yin, M. Zhao, Y. Liu, W. Han, Z. Li // Transactions of Nonferrous Metals Society of China. – 2013. – Vol. 23, no. 2. – P. 556–561.

24. Effect of silicon and manganese on the kinetics and morphology of the intermetallic layer growth during hot-dip aluminizing / H. Azimaee, M. Sarfaraz, M. Mirjalili, K. Aminian // Surface and Coatings Technology. – 2019. – Vol. 357. – P. 483–496.

25. Influence of silicon on growth kinetics of $Fe_2Al_5$ during reactive diffusion between solid iron and aluminum / W. Han, F. Yin, M. Zhao, Y. Liu, Z. Li // Transactions Materials and Heat Treatment. – 2010. – Vol. 31, no. 6. – P. 28–32.

## References

1. Drokonov A.M., Osipov A.V., Biriukov A.V. Podshipniki turbinnykh ustanovok: uchebnoe posobie [Turbine unit bearings]. BGTU. Briansk, 2009, 103 p.

2. Burkovskaia N.P., Sevost'ianov N.V., Bolsunovskaia T.A., Efimochkin I.Iu. Sovershenstvovanie materialov dlia podshipnikov skol'zheniia dvigatelei vnutrennego sgoraniia (obzor) [Improvement of materials for internal combustion engine plain bearings (review)]. *Trudy VIAM*, 2020, no. 1 (85), pp. 78–91.

3. Parovai E.F., Ibatullin I.D. Aktual'nye problemy nadezhnosti uzlov treniia gazoturbinnykh dvigatelei [Actual Problems of Friction Nodes Reliability in Gas Turbine Engines]. *Vestnik Samarskogo gosudarstvennogo aerokosmicheskogo universiteta*, 2015, vol. 14, no. 3-2, pp. 375–383.

4. Iazykov A.E., Kazanskii V.N., Buskunov R.Sh. Podshipniki i maslosistemy: uchebnoe posobie [Bearings and oil systems]. Cheliabinsk: Tsitsero, 2010, 202 p.

5. Piliushina G.A., Pamfilov E.A. Prichiny poteri rabotosposobnosti nasosov i gidromotorov mobil'nykh mashin [Causes of loss of serviceability of pumps and hydraulic motors of mobile machines]. *Aktual'nye napravleniia nauchnykh issledovanii XXI veka: teoriia i praktika*, 2017, vol. 5, no. 6 (32), pp. 219–224.

6. Chernyshova T.A., Mikheev R.S., Kalashnikov I.E., Akimov I.V., Kharlamov E.I. Development and testing of Al–SiC and Al–TiC composite materials for application in friction units of oil-production equipment. *Inorganic materials: Applied research*, 2011, no. 3, pp. 322–329.

7. Sijo M.T., Jayadevan K.R. Analysis of stir cast aluminium silicon carbide metal matrix composite: A comprehensive review. *Procedia Technology*, 2016, vol. 24, pp. 379–385.

8. Arunkumar S., Subramani Sundaram M., Suketh kanna K.M., Vigneshwara S. A review on aluminium matrix composite with various reinforcement particles and their behavior. *Materials Today: Proceedings*, 2020, vol. 33, pp. 484–490.

9. Panwar N., Chauhan A. Fabrication methods of particulate reinforced Aluminium metal matrix composite. A review. *Materials Today: Proceedings*, 2018, vol. 5, pp. 5933–5939.

10. Chaka V., Chattopadhyayb H., Doraa T.L. A review on fabrication methods, reinforcements and mechanical properties of aluminum matrix composites. *Journal of Manufacturing Processes*, 2020, vol. 56, pp. 1059–1074.

11. Agudo L., Eyidi D., Schmaranzer C.H., Arenholz E., Jank N., Bruckner J., Pyzalla A.R. Intermetallic FexAly-phases in a steel. Alalloy fusion weld. *Journal of Materials Science*, 2007, vol. 42, pp. 4205–4214.

12. Wang Q., Leng X., Yang T., Yan J. Effects of Fe-Al intermetallic compounds on in-terfacial bonding of clad materials. *Transactions of Nonferrous Metals Society of China*, 2014, vol. 24, no. 1, pp. 279–284.

13. Xu P., Hua X., Shen C., Mou G., Li F. Formation of Fe5Si3 precipitate in the Fe2Al5 intermetallic layer of the Al/steel dissimilar arc welding joint: A transmission electron microscopy (TEM) study. *Materials Characterization*, 2021, vol. 178, p. 111236.

14. Kovalev V.V., Mikheev R.S., Kobernik N.V. Osobennosti polucheniia stalealiuminievykh soedineniĭ metodami svarki plavleniem [Peculiarities of obtaining steel-aluminum connections by fusion welding methods]. Vestnik MGTU imeni N.E. Baumana. Seriay Mashinostroenie, 2016, no. 4, pp. 93–112.

15. Aizawa Y., Nishiwaki J., Harada Y., Muraishi S., Kumai S. Experimental and numerical analysis of the formation behavior of intermediate layers at explosive welded Al/Fe joint interfaces. *Journal of Manufacturing Processes*, 2016, vol. 24, no. 1, pp. 100–106.

16. Babua S., Panigrahia S.K., Janaki Ramb G.D., Venkitakrishnan P.V., Suresh R. Kumar Cold metal transfer welding of aluminium alloy AA 2219 to austenitic stainless steel AISI 321. *Journal of Materials Processing Technology*, 2019, vol. 266, pp. 155–164.

17. Zhang H.T., Feng J.C., He P., Zhang B.B., Chen J.M., Wang L. The arc characteristics and metal transfer behaviour of cold metal transfer and its use in joining aluminium to zinc-coated steel. *Materials Science and Engineering: A.*, 2009, vol. 499, no. 1–2, pp. 111–113.

18. Litvinov V.V., Kuz'min V.I., Lysak V.I., Strokov O.V., Kuz'min A.S. Osobennosti svarki vzryvom tolstolistovykh stalealiuminievykh kompozitov [Peculiarities of explosion welding of thick sheet steel-aluminum composites]. *Izvestiia VolgGTU*, 2010, vol. 5, no. 4, pp. 44–49.

19. Zlobin B.S., Sil'vestrov V.V., Shtertser A.A., Plastinin A.V. Sovershenstvovanie tekhnologii izgotovleniia stalealiuminievykh vkladyshei podshipnikov skol'zheniia [Improvement of manufacturing technology for steel-aluminum sliding bearing liners]. *Izvestiia VolgGTU*, 2012, vol. 5, no. 14, pp. 57–63.

20. Mikheev R.S., Kobernik N.V., Kalashnikov I.E., Bolotova L.K., Kobeleva L.I. Tribotechnical properties of antifriction coatings based on composite materials. *Inorganic materials: Applied research*, 2015, no. 5, pp. 493–497.

21. Takata N., Nishimoto M., Kobayashi S., Takeyama M. Crystallography of Fe2Al5 phase at the interface between solid Fe and liquid Al. *Intermetallics*, 2015, vol. 67, pp. 1–11.

22. Song J.L., Lin S.B., Yang C.L., Fan C.L. Effects of Si additions on intermetallic compound layer of aluminum-steel TIG welding-brazing joint. *Journal of alloys and compounds*, 2009, vol. 488, no. 1, pp. 217–222.

23. Yin F., Zhao M., Liu Y., Han W., Li Z. Effect of Si on growth kinetics of intermetallic compounds during reaction between solid iron and molten aluminum. *Transactions of Nonferrous Metals Society of China*, 2013, vol. 23, no. 2, pp. 556–561.

24. Azimaee H., Sarfaraz M., Mirjalili M., Aminian K. Effect of silicon and manganese on the kinetics and morphology of the intermetallic layer growth during hot-dip aluminizing. *Surface and Coatings Technology*, 2019, vol. 357, pp. 483–496.

25. Han W., Yin F., Zhao M., Liu Y., Li Z. Influence of silicon on growth kinetics of Fe2Al5 during reactive diffusion between solid iron and aluminum. *Transactions Materials and Heat Treatment*, 2010., vol. 31, no. 6, pp. 28–32.

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