Modification of Surface Including Charged Particle Beams and Photon and Plasma Fluxes
Модифицирование поверхности, в том числе пучками заряженных частиц, потоками фотонов и плазмы

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Research article
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Formation of ceramic coating on VAL10 aluminum alloy surface via laser modification in polysilicate solution

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Abstract. This article presents the results of an experimental study on the physical and mechanical properties of the surface layer of the VAL10 aluminum alloy after pulsed laser treatment, conducted in a bath with an aqueous solution of polysilicates (PS) at various concentrations. Ceramic coatings were produced on specimens measuring 10×10×3 mm. The laser processing of aluminum alloy specimens was carried out using an Nd:YAG laser. The study demonstrates that the quality of the resulting surface and its properties can vary depending on the laser exposure parameters, the concentration of the polysilicate solution, and the overall processing technique. The scattering of radiation by the PS solution layer leads to a significant reduction in surface roughness. In specimens processed in ambient air, the crater sizes on the surface exceeded 400 μm, while for specimens processed in a PS solution, they did not exceed 100 μm. A comparative analysis of the impact of solution concentration on elemental composition was performed. The study also included an investigation of friction characteristics and the measurement of microhardness of the modified surface. The research revealed that surface hardening processes occur as a result of the treatment, associated with the filling of recesses with high-strength oxides. This enabled the creation of a mixture containing silicon carbide and aluminum oxide in the surface layer of the specimens. Furthermore, wear tests of the modified surface were conducted using a "ball–specimen" tribological coupling. Specimens subjected to laser irradiation in a PS solution demonstrated increased wear resistance (a 40 % reduction in wear) and a 30 % decrease in the friction coefficient. Additionally, an increase in microhardness was observed.

Keywords: aluminum alloy, laser modification, polysilicates (PS), ceramic coating, surface structure, microhardness

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Формирование керамического покрытия на поверхности алюминиевого сплава ВАЛ10 при лазерном модифицировании в растворе полисиликатов

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Аннотация. Представлены результаты экспериментального исследования физико-механических свойств поверхностного слоя алюминиевого сплава ВАЛ10 после лазерного импульсного воздействия на структуру материала, проводимого в ванне с водным раствором полисиликатов (ПС) различной концентрации. Покрытия формировались на образцах размером 10×10×3 мм. Лазерная обработка образцов алюминиевого сплава была произведена с использованием Nd:YAG-лазера. Показано, что качество формируемой поверхности и ее свойства могут меняться в зависимости от параметров лазерного воздействия, а также концентрации раствора полисиликатов и технологии процесса обработки в целом. Рассеяние излучения слоем раствора ПС приводит к существенному снижению шероховатости поверхности. Для образцов, обработанных на воздухе, размеры кратеров на поверхности составили более 400 мкм, а для образцов, обработанных в растворе ПС, они не превышали 100 мкм. Проведен сравнительный анализ влияния концентрации раствора на элементный состав. Исследованы фрикционные характеристики и измерена микротвердость модифицированной поверхности. Установлено, что в результате обработки протекают процессы упрочнения поверхности, связанные с заполнением углублений высокопрочными оксидами. Это позволило получить в поверхностном слое образцов смесь, содержащую карбид кремния и оксид алюминия. Проведены исследования износа модифицированной поверхности в трибосопряжении «шарик – образец». Для образцов, подвергнутых лазерному воздействию в растворе ПС, характерны повышение износостойкости (величина износа уменьшилась на 40 %) и снижение коэффициента трения на 30 %, также установлено увеличение микротвердости.

Ключевые слова: алюминиевый сплав, лазерное модифицирование, полисиликаты (ПС), керамическое покрытие, структура поверхности, микротвердость

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Introduction

In modern mechanical engineering, the pursuit of reducing the weight of final products while maintaining high performance properties, such as strength and wear resistance, and achieving a high degree of process automation, is of major importance [1–3]. In this context, the surface hardening of aluminum alloys, known for their low density and high specific strength, holds great promise [4–9]. Nevertheless, one significant drawback of these materials is their low hardness [10; 11]. Surface hardening allows for an increase in the overall wear resistance of the part.

Various methods are currently available for surface hardening of metals and alloys [12], including thermal and chemical processes, spraying, shot blasting, and laser-based techniques [13]. Modern laser systems offer advantages such as high processing speed, precision, and the ability to finely adjust energy parameters and exposure duration within the processing zone [14].

Laser modification technologies for aluminum alloy surfaces, particularly laser alloying, have made significant progress in enhancing the corrosion resistance, mechanical durability, and resistance to adhesive and abrasive wear of aluminum alloys [15]. Fusion of alloying powders with the substrate using laser radiation is a promising method for creating protective coatings on aluminum alloys [16]. This process may involve the incorporation of both metals (e.g., Ni, Cr) and non-metals (e.g., B, Si) as dopants, with a binding element being introduced into the powder composition [17]. The resulting mixture is uniformly applied to the substrate, and the surface is subsequently treated with a laser [18; 19]. t's crucial to note that the choice of components suitable for inclusion in the aluminum alloy's surface composition is limited, as they must have a melting point comparable to that of aluminum to ensure high-quality coating [20]. The use of other components often leads to a significant decrease in coating quality [21]. An alternative approach involves the introduction of alloying elements from the liquid phase. In this method, the part is immersed in a technological solution, and laser radiation, forming a vapor gas channel in the liquid, is directed onto the part's surface.

Recently, metal-ceramic composite materials with an aluminum-based matrix reinforced with refractory ceramic particles of silicon carbide (SiC) have been used [22]. Composite materials with an aluminum matrix are characterized by high specific strength combined with low density. Doping with silicon carbide particles allows for the creation of a material with a low coefficient of friction and high wear resistance [23].

The objective of this study is to investigate specific changes in the mechanical properties of ceramic coatings on an VAL10 aluminum alloy, produced using laser radiation in an aqueous polysilicate (PS) solution bath. Furthermore, we aim to determine the processing parameters that can enhance the microhardness of the surface layer and its abrasion resistance.

Materials and methods. Results and discussion

The most commonly used non-metallic dopant for aluminum alloys is silicon. Doping with silicon allows for the creation of a hypereutectic structure on the surface of hypoeutectic alloys while simultaneously increasing surface hardness. In this study, coatings were applied to 10×10×3 mm specimens of the VAL10 aluminum alloy. Surface laser processing was performed using a solid-state Nd:YAG laser with a radiation wavelength of 1.06 μm, integrated into the LIS-25 laser welding system (EIKTL Lagen LLC, Russia). Each laser pulse had a maximum energy of 25 J, a pulse duration of 5 ms, and a repetition rate of 3 Hz. During the processing, the specimen was immersed in a bath containing an aqueous solution of $(Na_2O)_n{\cdot}(SiO_2)_m$ polysilicate. The concentration of the polysilicate solution was experimentally determined to be in the range of 10–15 %. A higher concentration of polysilicate led to the release of gas bubbles from the medium, which significantly reduced the efficiency of laser radiation delivery to the specimen's surface and caused pronounced splashing of the polysilicate solution. On the other hand, a lower concentration resulted in a noticeable decrease in the silicon content within the coating (Fig. 1).

The layer of the liquid medium above the processed specimen's surface was consistently maintained at a 1 mm thickness. Reference specimens were also prepared and treated in both air and distilled water. Due to the scattering of radiation by the layer of PS solution positioned above the specimen's surface, the surface irregularities were significantly reduced.

As a result, for specimens treated in ambient air, crater sizes on the surface exceeded 400 μm, whereas when a PS solution was used, the exposure marks did not exceed a 100 μm diameter (Fig. 2).

The layer created by laser processing on the metal surface enhances the part's durability and performance. Laser processing of the aluminum alloy results in the redistribution of chemical elements throughout the depth of the material. The craters formed on the surface become filled with silicon and aluminum compounds. The chemical composition of the specimens was analyzed using a JAMP-10 S Auger analyzer (JEOL, Japan). The shape of the Auger lines indicated that aluminum exists in an oxidized state, while carbon and silicon are in the carbide state (Fig. 3).

The size and relative positioning of the surface recesses are determined by the processing mode and the concentration of the PS solution. The absence of crater overlap prevents complete coverage of the surface, leading to discontinuities in the ceramic layer. In untreated areas, the base metal remains exposed, resulting in a heterogeneous ceramic coating layer.

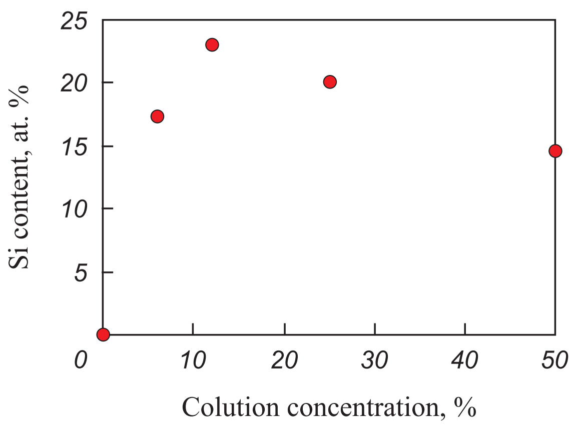

Fig. 1. Relationship between the silicon content in the coating at a depth of 3 nm and the concentration of the polysilicate solution

Рис. 1. Содержание кремния в покрытии на глубине 3 нм в зависимости от концентрации раствора полисиликата

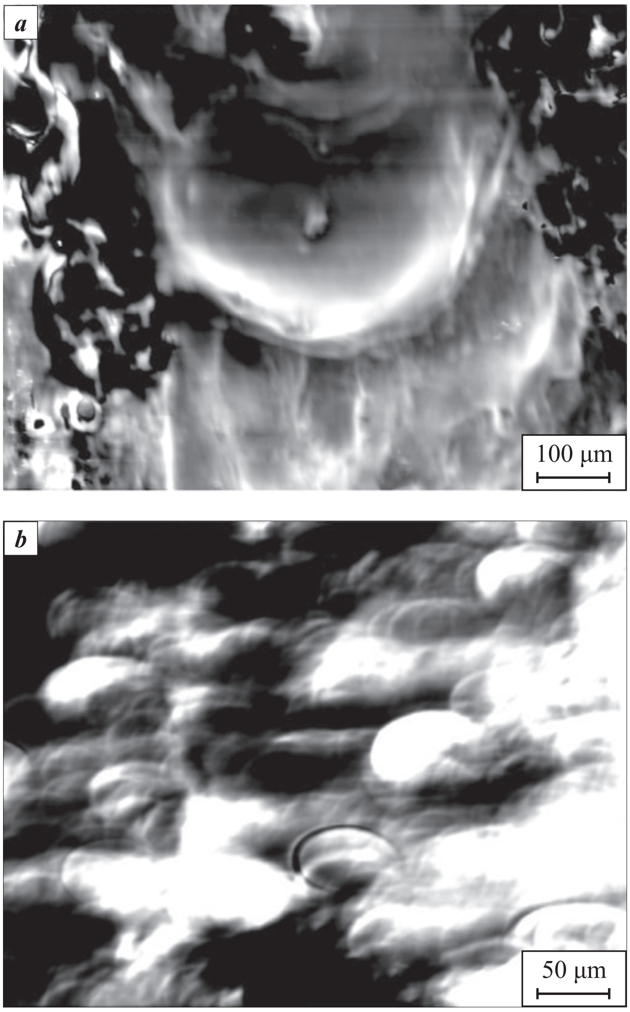

Fig. 2. Surface images of specimens treated in air (***a***) and in a polysilicate solution (***b***)

Рис. 2. Изображения поверхности образцов, обработанных на воздухе (***a***) и в растворе ПС (***b***)

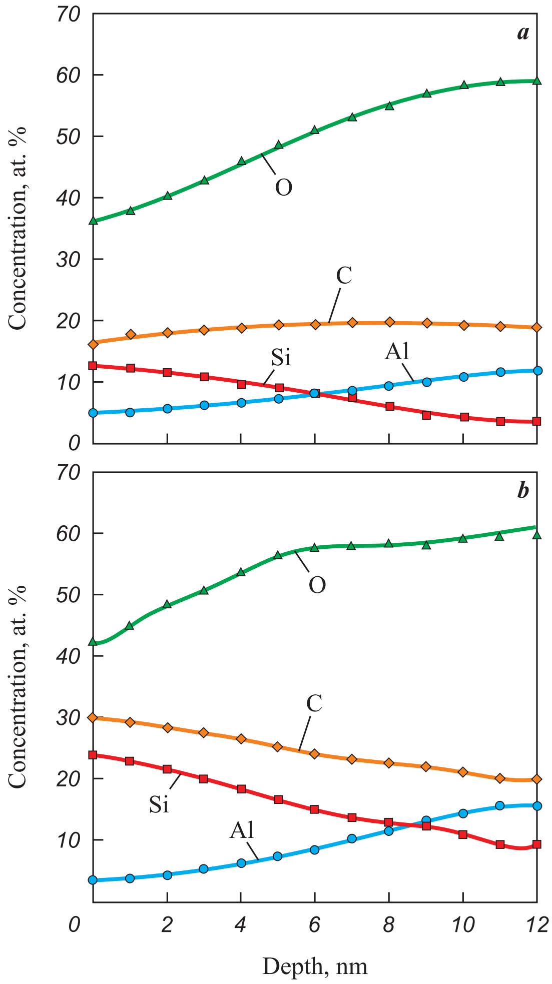

Fig. 3. Element distribution across the surface layer at polysilicate solution concentrations of 6 % (***a***) and 12 % (***b***)

Рис. 3. Распределение элементов по глубине поверхностного слоя при концентрациях раствора ПС 6 % (***a***) и 12 % (***b***)

One of the critical operational parameters influencing the quality of the surface-hardened layer is wear resistance. Fretting wear tests were conducted using an SRV Testsystem multifunctional testing device (Optimol Instruments, GmbH, Germany) at room temperature, following the disk-on-ball configuration without lubrication. The counterbody material was ShKh15 tool steel after hardening heat treatment. The tests were carried out with a vibration amplitude of 3 mm, a frequency of 2 Hz, a load of 10 N on the specimen, and a test duration of 10 min. Based on the results, it can be concluded that the amount of wear on the surface of the VAL10 alloy specimen after laser processing in a PS solution was less than 40 μm, while the untreated specimen exhibited 60 μm of wear. During testing, the friction coefficient for the treated specimen slightly exceeded 0.8, while the original specimen had a noticeably higher friction coefficient of over 1 (Fig. 4).

The presence of oxide and carbide components in the surface layer after laser processing is expected to influence microhardness. Microhardness of the surface of a VAL10 aluminum alloy specimen with an applied oxide coating was evaluated using a LOMO PMT-3M microhardness tester (LOMO, Russia). A 4-sided Vickers diamond pyramid served as the indenter. The results indicated that the average diagonal size of the indentation was 50 μm under a load of 0.196 N and a dwell time of 15 s, corresponding to a hardness of 14.8 kg/mm^2. In comparison, the microhardness of the original specimen was determined using the same method and measured 9.1 kg/mm^2, representing a 62.6 % decrease compared to the modified coated specimen. The formation of compounds with higher hardness on the surface of the aluminum alloy, in contrast to the base material, can also account for the reduction in the friction coefficient.

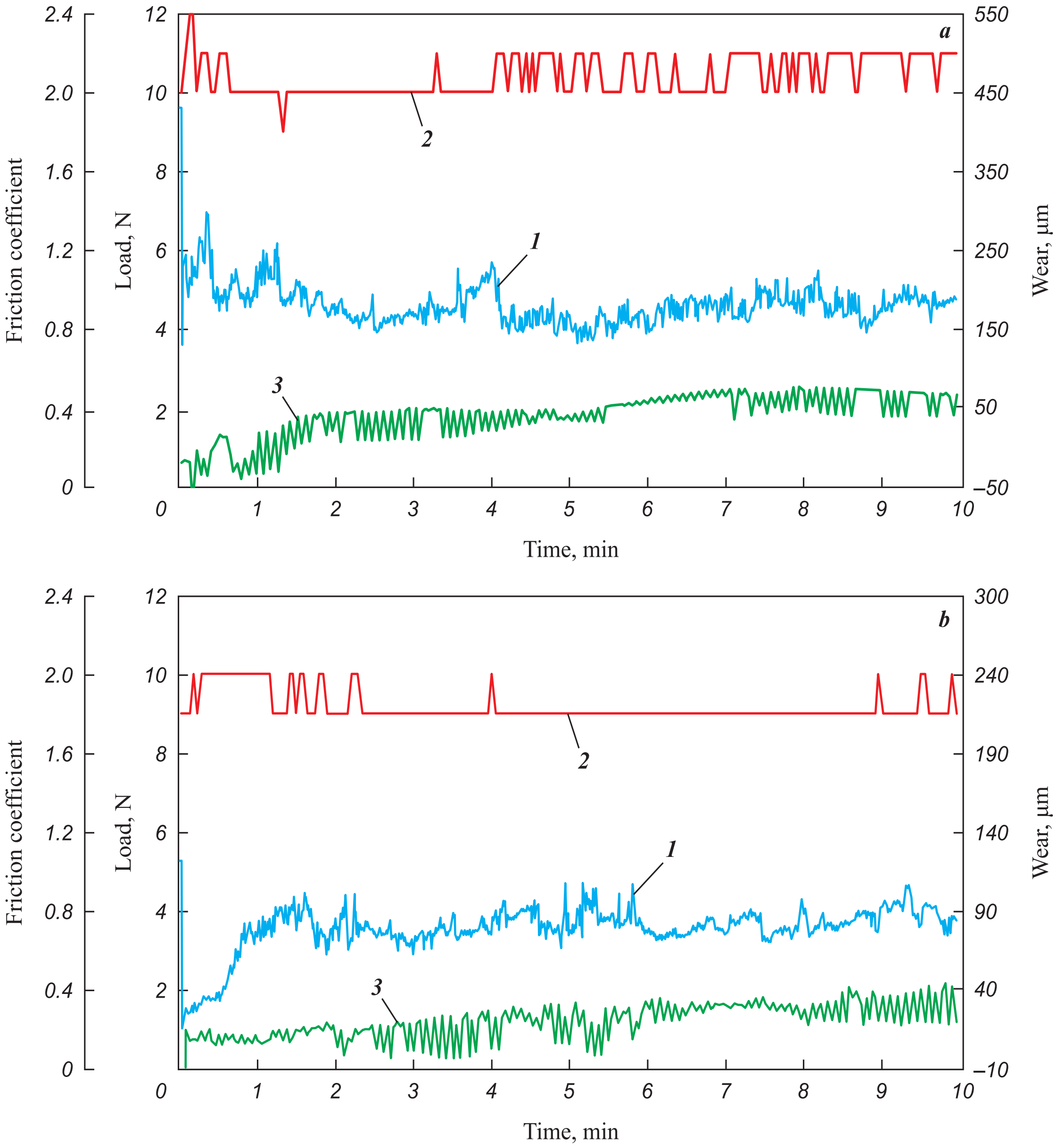

Fig. 4. Results of fretting wear tests of the original VAL10 alloy specimen (***a***)
and specimen treated with laser radiation in a 12 % polysilicate solution (***b***):
1 – friction coefficient; ***2*** – load; ***3*** – wear

Рис. 4. Результаты испытаний на фреттинг-изнашивание исходного образца сплава ВАЛ10 (***a***)
и обработанного лазерным излучением в растворе полисиликата концентрацией 12 % (***b***):
1 – коэффициент трения; ***2*** – нагрузка; ***3*** – износ

Conclusions

Analysis of the modified surface of VAL10 aluminum alloy specimens revealed the dependency of surface layer properties on the modification parameters. By adjusting laser processing parameters, such as pulse repetition rate, surface fill factor, concentration, and the thickness of the solution layer above the specimen's surface, it becomes possible to control the extent of the impact and, consequently, the chemical composition of the resulting coating.

The study conclusively demonstrated that laser processing of VAL10 alloy specimens in a polysilicate solution has a significant impact on their performance. In particular, it enhances surface abrasion resistance and promotes surface hardening.

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I. N. Burnyshev – prepared initial specimens and coating mixtures, conducted experiments.
V. F. Lys – investigated fretting wear of the coatings, determined their microhardness.
V. I. Ladyanov – formulated the research objectives and methodology for its implementation.

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