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Wear resistance of aluminum alloy modified with SiC by laser surface treatment

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Abstract

The work is devoted to establishing the effect of laser modification by SiC particles of the surface layers of 7075 aluminum alloy, on its wear resistance in friction conditions with a rigidly fixed and non-fixed abrasive. It has been revealed that with increasing linear energy of the laser beam, the thickness of the modified layer increases and the volume content of SiC particles in it increases. X-ray spectral and X-ray phase analysis of the layers modified with SiC particles confirmed the presence of silicon carbide particles and aluminum carbides in them. The speed of movement of the laser beam (linear energy of the beam) over the surface affects the structure and wear resistance of laser-modified layers as well as the heating of the substrate. In particular, with an increase in heat input from 740 to 1100 J/cm, the concentration of SiC particles increases by 25% in the modified layer, and the wear resistance during friction tests with a rigidly fixed abrasive by 1,7...2 times. It has been found that the wear resistance of the modified layer is almost not affected by the direction of friction (along or across the laser processing tracks), however, the ratio of adjacent tracks overlap significantly affects. Thus, the wear resistance of the modified layer under friction by a rigidly fixed abrasive increases with an increase in the size of SiC particles and their volume content, an increase in the linear energy of the laser beam and the tracks overlap ratio. When testing with a non-fixed abrasive, the trends in wear resistance remained, however, the influence of the factors analyzed above is much weaker.

Key words: aluminum alloy, laser-modified layers, carbide silicon, rigidly fixed abrasive, non-closed abrasive, wear resistance.

Introduction

About 30% of all metals are melted annually, which are spent on repairing losses caused by corrosion and wear. [1, 2]. Therefore, it is important to develop and implement modern surface hardening methods [3]. At present, aluminum alloys are widely used in industry, it has high specific strength at relatively low cost. However, their surface characteristics are not sufficient for use in structures that work on wear. Various methods of creation and application of coatings are used to increase the durability of a surface [1-3]. A promising direction for the surface hardening of aluminum alloys is the surface modification by a concentrated light beam of energy, [2, 4], which localizes and melts the upper layers of metal with a given thickness, with the possibility of additional introduction of other material into its [2, 5]. Carbides are of particular interest as a reinforcing phase in such composite materials SiC [6-15]. Such materials, with a certain composition of the matrix alloy and the particle reinforcement, have low values of friction coefficient and high rates of wear resistance.

The process of laser modification of the surface of aluminum alloy powders of silicides, oxides, carbides and other compounds causes significant technological difficulties due to the large difference in their physical properties, which complicates the uniform distribution of powder grains in the molten metal bath [16]. It is also necessary to take into account the turbulent molten metal flows, the uneven temperature distribution that causes the melt viscosity gradient and the rapidity of the melt-crystallization process of the alloy [17]. In view of the above, the aim of this work was to determine the effect of scanning speed by laser beam of the surface, the coefficient of overlap of the scan tracks and the substrate temperature on the structural changes of the surface layers, as a consequence, its durability.

Experimental setup

The alloy surface of 7075 was modified by a continuous diode laser with operating parameters: maximum power – 2200 Watt; wavelength – 1,06 μm; spot diameter– 3 mm; protective atmosphere – argon; scanning speed – 1,0…1,5 m/min,

Fig.1 shows a scheme of laser treatment, which includes the creation of coatings by blowing, in a molten laser beam and inert gas-protected tubes, dispersed powders of SiC carbides with a dispersion of 75 μm and a hardness of 26 μV. The overlap ratio of the previous track was 25 and 50%.

The float of the surface of both the unheated specimen and the preheated specimen is 100 and 250°C.

Metallographic studies were performed on a scanning electron microscope with a micronutrient prefix and ZEISS EVO 40XVP with the INCA Energy X-ray microanalysis system.

The phase composition of the surface layers was examined using a diffractometer ДРОН-3.0 у Cu-K – radiation focusing the tube according to the Bragg-Brentano scheme [18].

Abrasive wear by friction with non-attached abrasive particles was performed by quartz sand, which was constantly fed into the contact area of the rubber disk and the sample by the metering device. Friction mode: loading P = 44 H, disc rotation speed was 25 m/min. The diameter and thickness of the rubber disk were 50 and 15 mm, respectively. Wearing of the samples by friction with rigidly fixed abrasive was carried out by an abrasive disc of electrocorundum of medium-soft hardness SM-2 on a ceramic link 7K15 with a diameter of 150 mm and a width of 8 mm, a linear friction speed of 100 m/min, loading in the zone of linear contact 15 N. the friction under the two friction schemes was the same and it was 1800 m. The wear of the laser modified samples was estimated by the weight loss of the samples up to $2{\cdot}10^{-4}$ г on KERN ABJ 220 4M electronic analytical scales both from the surface and after grinding to a depth of 0.5 mm and 0.8 mm from it.

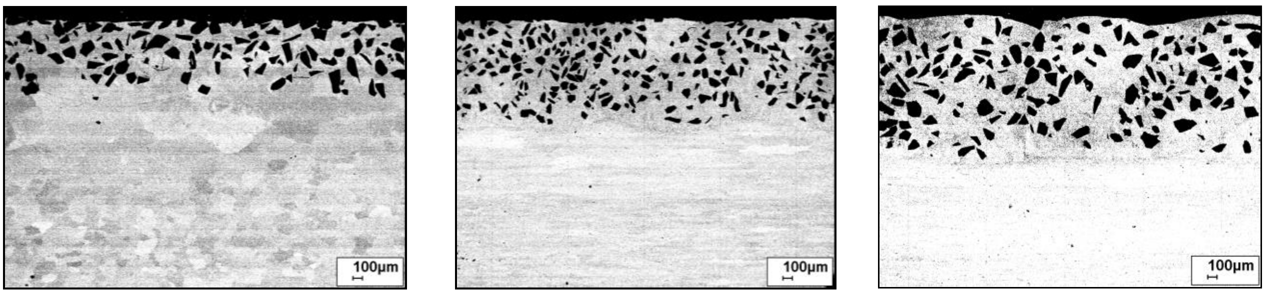
Research results

Due to the laser modification by SiC particles, the surface of the alloy 7075 is covered by hemispherical projections (fig. 1), the dimensions of which depend on the overlapping coefficient of adjacent tracks. As the laser beam passes, molten metal paths are formed on the surface of the alloy after injection of SiC particles and solidification, rollers of crystallized molten coating are formed. Modified surface has less roughness (R_z = 20 μm), and 25% (R_z = 30 μm) (fig. 1*a*) because of 50% overlap adjacent tracks (fig. 1b). This is caused by repeated laser heating of the surface. It aligns the chemical composition and causes the formation of a highly dispersed, nonporous structure.

a *b*

Fig. 1. General view the surface of the laser modified SiC carbide layer on the alloy 7075 with a coefficient of overlap of the laser tracks 25% (*a*) and 50% (*b*), ×25

Microstructural analysis of laser modified layers of alloy 7075 revealed that with increasing the heating temperature of the substrate to 250 °C, accordingly, reducing the viscosity of the melt, the SiC particles more intensively interact with it, forming secondary phases – aluminum carbides. The thickness of the modified layer increased almost twice, the volume content of SiC particles in the modified layer increased to 26 vol.%, and aluminum carbide particles from 2 to 4 vol.% compared with the unheated substrate (fig. 2, fig. 3).



a *b* *c*

Fig. 2. The effect of the substrate temperature of the 7075 alloy on the thickness of the laser modified layer:
***a* – unheated;**
***b* – 100°C;**
***c* – 250°C**

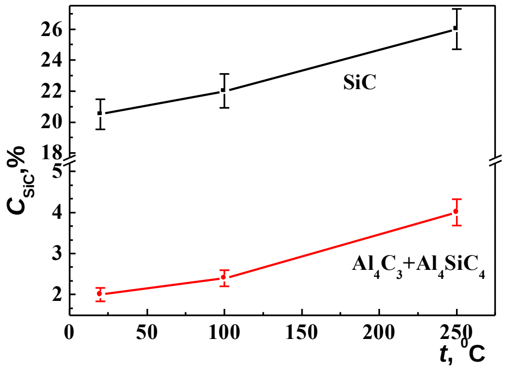


Fig. 3 The influence of the heating temperature of the substrate (*t*) alloy 7075 on volume content (*C*) of particles SiC and Al_4C_3+Al_4SiC_4 in laser modified layer.

With a beam of energy 740 J/cm (surface scanning speed – 1.5 m/s), the uniform distribution of SiC particles in the modified layer was maintained to a depth of 0.85 mm. (fig. 4*a*), while behind 1100 J/cm (surface scanning speed – 1 m/s) – to 1,1 mm (fig. 4*b*).

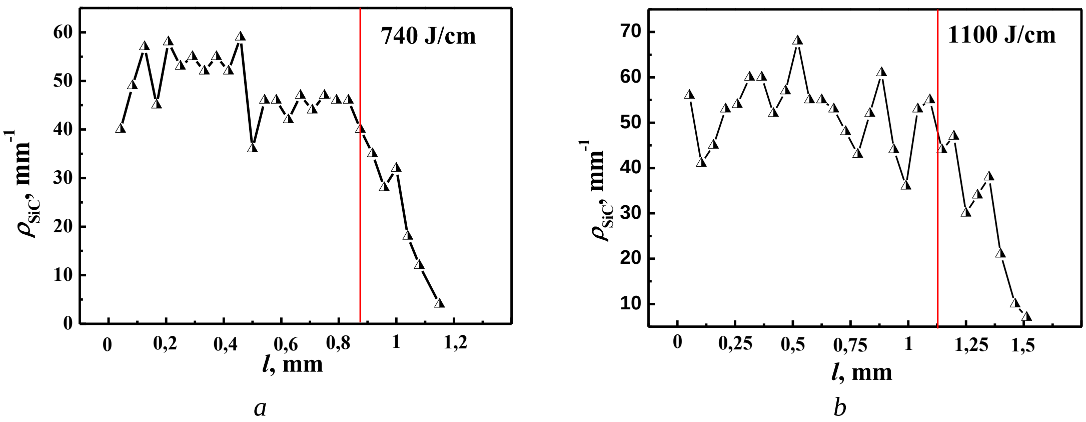


Fig. 4. The density of the distribution of particles SiC (ρ_{SiC}) by thickness (*l*) laser modified layers on the alloy 7075, obtained by using a linear energy of the laser beam 740 J/cm (*a*) and 1100 J/cm (*b*)

X-ray diffraction analysis of the modified layers revealed (fig. 5), that Al_4C_3 carbides (fig. 5a) are formed mainly in the laser modified layer at lower heating temperatures of the substrate (100 °C) and lower linear energy of the laser beam (740 J/cm). Aluminum carbides Al_4SiC_4 (fig. 5*b*) are formed mainly in the modified layers without the heating of the substrate and with the driving energy of the laser beam of 1100 J/cm.

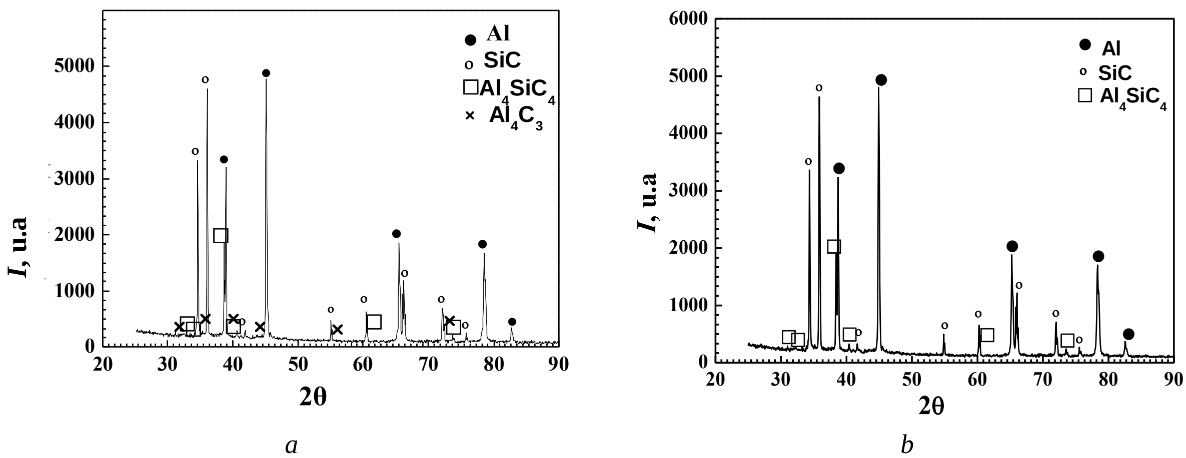
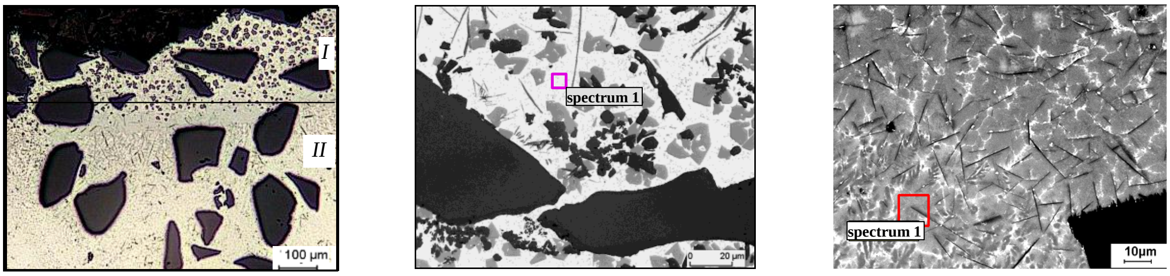


Fig. 5. The radiograph of the obtained laser modified layer: for heating the alloy substrate 7075 100°C and by the laser beam energy 740 J/cm (*a*), and without heating the substrate with laser beam energy 1100 J/cm (*b*)

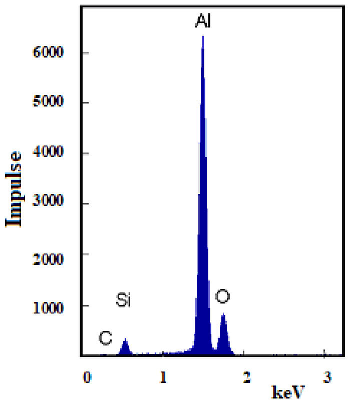
Metallographic and X-ray spectral analyzes identified aluminum carbides Al_4C_3 and Al_4SiC_4 in different zones of the modified layer in depth from the surface, which differed in morphology and location in it (Fig. 6). The possibility of forming both types of particles is consistent with the state diagram Al –SiC [19].



a *b* *c*

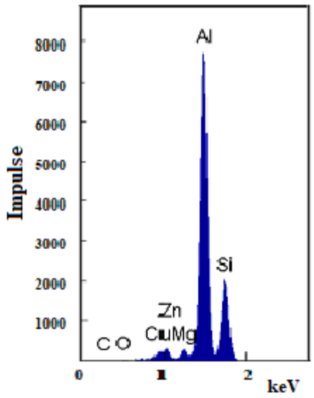
Fig. 6. The zones of the laser modified layer (*a*), which correspond to the higher (zone *I*) (*b*) and lower melt temperature (zone *II*) (*c*).

The melt temperature is maximum, carbides Al_4SiC_4 were formed with globular morphology and a small number of Al_4C_3 carbides with needle-like morphology in zone (*I*) (fig. 6*a*, *b*). As a result, the content of free Si decreased in the structure of the modified layer of this zone. A small amount of Si (2,44 weight %) (fig. 7*a*) was detected by spectral analysis in zone *I* (fig. 6*b*, spectrum 1) of laser modified layer, however it wasn't observed in structure. The needle-shaped carbides of Al_4C_3 were formed, the maximum length of which reached 30 µm and their thickness didn't exceed 1 µm in the deeper zone (*II*) (6a, c), where the melt temperature is lower. The distribution of the Al_4C_3 was not uniform, and spatial orientation – random. A significant amount of Si was detected by spectral analysis (spectrum 1) (fig. 7*b*). It can be assumed that a small amount of Si in zone *I* is due to the fact that a large number of Si is in the Al_4SiC_4 compound, while in zone *II* it is in a free state.



Element	Masse %
C	0.22
Al	91.98
Si	2.44
O	5.36
Total	100.00

a



Element	Masse %
Mg	1.17
Al	62.70
Cu	1.29
Zn	4.39
Si	28.98
O	1.47
Total	100.00

b

Fig. 7. Spectral analysis of thee laser modified layer in the zone *I* (рис. 6*b*) (*a*) and zone *II* (fig. 6*c*) (*b*)

The speed of movement of the laser beam (the linear energy of the beam) across the surface affects the structure and durability of the laser-modified layers as well as the heating of the substrate. It has been found that with increasing the running energy from 740 to 1100 J/cm, the concentration of SiC particles in the modified layer increases by 25%, and the wear resistance in the tests with rigidly fixed abrasive 1.7 ... 2 times (depending on the mutual orientation of the laser paths, the direction of friction and track overlap factor) (fig. 8).

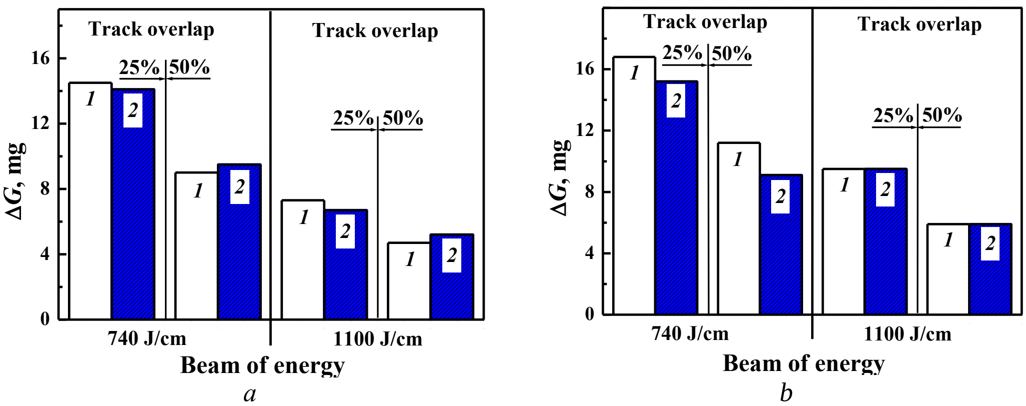
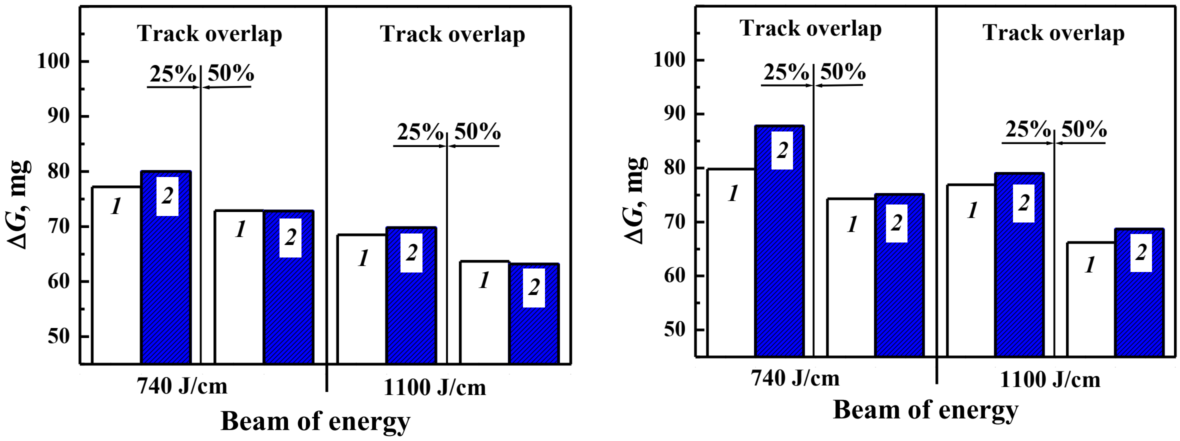


Fig. 8. The wear resistance of the modified layer on the alloy 7075 from the surface (*a*), at depth ~0,4 mm (E_{beam} = 740 J/cm) and ~ 0,8 mm (E_{beam} = 1100 J/cm) from the outer surface (*b*) in conditions of rigidly fixed abrasive, depending on the laser beam energy, track orientation and its overlap track:
1 **– along the track;**
2 **– across.**

With the increase of the laser track overlap coefficient from 25% to 50%, the wear of the SiC layer-enhanced surface layer at a distance of 0.5 mm from the surface generated by the running energy of 740 J/cm decreased by 38% by friction along the tracks and by 32%. transverse direction (fig. 8a). With the linear energy of the beam 1100 J/cm, the effect of overlap tracks on the sample wear decreased to 33% by friction along the tracks and to 21% - across. Moreover, irrespective of the driving energy of the laser beam, the wear resistance of the laser-modified layers at the coefficient overlap of the tracks of 25% of the friction across their orientation is slightly higher (by 3…6%) than along. The wear of such surfaces increases to 10% with a 50% overlap of laser tracks.

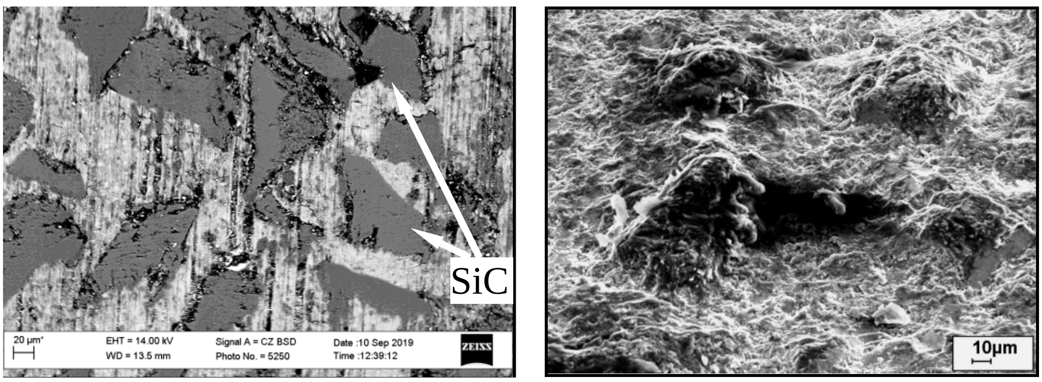
With non-bonded abrasive wear, the test conditions are more rigid and contribute to much more wear than the conditions when the abrasive is rigidly fixed. However, even with non-bonded abrasive tests, the tendency to change wear resistance obtained during hard-bonded abrasive tests remains, but the impact of the analyzed factors was much weaker (Fig. 9). Depending on the treatment mode, the wear resistance of the laser modified layers compared to the unmodified surface (ΔG_{sur} = 98 mg), grew only by 10...35 %. Also insignificant was the influence on the wear resistance of the modified linear energy of the laser beam and the overlap coefficient of the tracks. It has been determined that the wear resistance of the deeper layers of the modified layer (at a depth of ~ 1 mm) was also lower (Fig. 9b) compared to the layers closer to the surface (Fig. 3.9a).



a *b*

Рис. 9. The wear resistance of the modified layer on the alloy 7075 from the surface (*a*) at depth ~0,4 mm (E_{beam} = 740 J/cm) and ~ 0,8 mm (E_{beam} = 1100 J/cm) from the outer surface (*b*) in the conditions of unattached abrasive, depending on the energy of the laser beam, the orientation of the tracks and the coefficient of their overlap:
***1* – along the track;**
***2* – across.**

Analyzing the morphological features of the wear surfaces (Fig. 10), we have found that during the friction of the rigidly fixed abrasive, all the phases of the modified layer are erased in almost one plane in a single layer (Fig. 10a). However, the deep traces of abrasion and tearing caused by the grasping of the abrasive wheel with the surface of the sample have not been recorded. This is due to the fact that the matrix around SiC grains, micro-reinforced with Al_4C_3, Al_4SiC_4 dispersed carbides, has a higher hardness and, therefore, less susceptible to plastic flow as a prerequisite for setting.



a *b*

Fig. 10. The topography of the surface the alloy 7075, laser-modified SiC particles after tests of friction rigidly fixed (*a*) and non-fixed (*b*) abrasive

The low wear resistance of laser-modified SiC alloy particles during friction with an unattached abrasive is due to the fact that the free abrasive, falling into the intervals between the solid SiC particles, easily destroys the soft matrix, releasing the solid SiC grains, it is then easily pulled through unattached abrasive (Fig. 10b). It is obvious that the wear resistance under non-bonded abrasive conditions depends on the distance between SiC particles, because first of all, the modified surface of the aluminum alloy is destroyed around these particles. [21, 22].

Conclusions

1. It has been found that only the Al_4C_3 aluminum carbides are formed in the modified layer at the laser beam energy up to 740 J/cm when the melt temperature doesn't exceed 1200°C. With an increase in the melt temperature above 1200°C (using the higher laser beam energy mode or due to the preheating of the substrate), two types of aluminum carbides are formed in the modified layer structure - Al_4C_3 and Al_4SiC_4. Al_4C_3 carbides are located in a deeper zone, closer to the aluminum substrate, while Al_4SiC_4 carbides are concentrated in the upper zone of the modified layer, where the temperature exceeds 1200 °C.

2. It has been established that laser modification of aluminum alloys with SiC particles increases its abrasion resistance by 40...95 times during the tests of rigidly fixed abrasive. Moreover, the wear resistance increases in proportion to the volume content of SiC particles in the modified layer. The wear of this layer is due to the abrasion of SiC particles by abrasive particles. The friction of the non-bonded abrasive will increase the wear resistance of the modified layer by 10...35% compared to the unmodified surface.

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М. Студент, Х. Задорожна, В. Гвоздецький, Г. Веселівська, Г. Похмурська, Ю. Дзьоба.
Зносостійкість алюмінієвого сплаву модифікованого SiC шляхом лазерної обробки поверхні

Анотація

Робота присвячена встановленню впливу лазерної модифікації частинками SiC поверхневих шарів алюмінієвого сплаву 7075 на його зносостійкість в умовах тертя з жорстко закріпленим і нефіксованим абразивом. Було виявлено, що зі збільшенням лінійної енергії лазерного променя збільшується товщина модифікованого шару та збільшується об'ємний вміст частинок SiC у ньому. Рентгенівський спектральний та рентгенофазовий аналіз шарів, модифікованих частинками SiC, підтвердили наявність у них частинок карбіду кремнію та карбідів алюмінію. Швидкість руху лазерного променя (лінійна енергія променя) по поверхні впливає на структуру і зносостійкість лазерно-модифікованих шарів, а також на нагрівання підкладки. Зокрема, зі збільшенням тепловіддачі від 740 до 1100 Дж / см концентрація частинок SiC у модифікованому шарі збільшується на 25%, а зносостійкість під час випробувань на тертя з жорстко фіксованим абразивом на 1,7 ... 2 рази. Було встановлено, що на зносостійкість модифікованого шару майже не впливає напрям тертя (вздовж або поперек доріжок лазерної обробки), однак на відношення сусідніх доріжок перекриття суттєво впливає. Таким чином, зносостійкість модифікованого шару при терті жорстко закріпленим абразивом збільшується зі збільшенням розміру частинок SiC та їх об'ємного вмісту, збільшенням лінійної енергії лазерного променя та коефіцієнта перекриття доріжок. Під час випробувань нефіксованим абразивом тенденції до зносостійкості залишалися, однак вплив вищезгаданих факторів значно слабкіше.

Ключові слова: алюмінієвий сплав, лазерно-модифіковані шари, твердосплавний кремній, жорстко закріплений абразив, незакріплений абразив, зносостійкість.