Investigation of Selective Laser Melting Surface Alloyed Aluminium Metal Matrix Dispersive Reinforced Layers

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Abstract: The aim of the paper is to investigate the improvement of mechanical properties and in particular wear resistance of laser surface alloyed dispersive reinforced thin layers produced by selective laser melting (SLM) technology. The wear resistance investigation of aluminium matrix composite layers in the conditions of dry friction surface with abrasive particles and nanoindentation tests were carried out. The process parameters (as scan speed) and their impact on the wear resistant layers have been evaluated. The alloyed layers containing metalized SiC particles were studied by Optical and Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray microanalysis (EDX). The obtained experimental results of the laser alloyed thin layers show significant development of their wear resistance and nanohardness due to the incorporated reinforced phase of electroless nickel coated SiC particles.

Keywords: wear resistant layers, selective laser melting (SLM), laser surface alloying, SiC particles.

1. Introduction

Lasers provide a powerful, high-speed source with precise control of the applied amount of energy. On their basis, the selective laser melting technology (SLM) is developed, and is used for the local melting of powder mixtures for the purpose of layer construction of monolithic details, as well as for cladding of individual layers [1].

The purpose of this work is to investigate the characteristics of wear of laser surface alloyed dispersive reinforced thin layers of composite material on aluminium alloy matrix produced by selective laser melting (SLM) technology. Two types of powder mixtures with different content of metalized microparticles of silicon carbide have been used. The introduction of the reinforcing phase of metalized SiC microparticles is accomplished by pre-deposition and subsequent laser melting of a powder mixture to produce an alloyed layer of composite material on an aluminum alloy matrix.

2. Materials and equipment

The following materials were used for the realization of the study: substrate (basic alloy) of aluminium alloy EN AW-2017; electroless nickel coated silicon carbide microparticles, fraction 7-10 µm. To
improve wettability of the reinforcement, a surface electroless nickel plating (Ni-P) on SiC particles in alkaline bath using two nickel salts (NiSO$_4$ and NiCl$_2$) is conducted [2, 3]. The electroless nickel coated particles are heat treated in order to increase the hardness of the electroless nickel-phosphorus (Ni-P) coating deposited on their surface. Applying a temperature between 250°C and 400°C leads to microhardness increase due to the formation of the Ni$_3$P compound in the crystallization of the amorphous phase [4].

The alloying of layers with dispersive reinforced material on a metal matrix is performed by the SLM 125 HL system for selective laser melting in the Prototype Lab at the Faculty of Industrial Technologies of the Technical University of Sofia. The main parameters of the laser installation are: YLR-Faser-Laser emitting source; maximum power of the laser beam 100/200 W; dimensions of the workspace in the camera 125 x 125 x 75 (125) mm; (Ar / N$_2$) inert gas consumption 0.5 l/min. The mechanical properties of the basic aluminium alloy EN AW-2017A are as follows: yield strength R$_{p0.2}$ = 279 MPa; ultimate tensile strength R$_m$ = 437 MPa.

Laser surface alloying is performed on a substrate (base metal) of aluminum alloy EN AW-2017A with dimensions 125 x 125 x 10 mm (figure 1a) at several different SLM scanning speeds in the range from 400 mm/s to 600 mm/s. Two types of powder mixtures were deposited on the substrate (figure 1), namely: - substrate SLM2 – electroless nickel coated silicon carbide microparticles and aluminum powder in a 1:1 ratio - for 1L and 1R samples; - substrate SLM2 – electroless nickel coated silicon carbide microparticles only for 2L and 2R samples.

The L-specimens are scanned only with longitudinally strokes and the R-specimens are scanned both with transversely and longitudinally strokes.

Five strips of 16 mm width and 80 mm lengths are laser surface alloyed on each substrate at SLM speeds in the range 400 to 600 mm/s through 50 mm/s (figure 1b and figure 1c). For the purpose of the study, five specimens of the same size are prepared, as well as a reference specimen of the base alloy, without coating.

The experimental study of wear resistance is carried out under the guidance of Prof. Dr. M. Kandeva, applying dry friction study according to a procedure developed in the Applied Laboratory "Tribology" at the department "Material Sciences and Material Technologies" in Technical University of Sofia. Abrasive wear at dry friction sliding according to pin-on-disc kinematic scheme is investigated in laboratory conditions [5-7]. The abrasive surface is modelled by impregnated corundum (E) with 9.0 Mohs hardness, which meets the requirement of the standard for at least 60% higher hardness than that of the surface layer of the tested materials.

3. Experimental results and analysis

3.1. Experiment conducting
The reinforcing phase is introduced according to the technology of laser surface alloying through selective laser melting (SLM). A mixture of metal powder and reinforcing phase of nickel coated SiC microparticles are melted locally on the aluminum alloy surface through the laser beam into the SLM 125 HL camera.

The reinforcing phase of metalized SiC microparticles is introduced in the SLM 125 HL camera by means of preliminary deposition and mechanical flattening of powder layer with thickness of about 100 µm on the substrate. The next melting by laser beam scanning results in obtaining an alloyed laser cladding track of dispersive reinforced layer (figure 2b).

![Image](image.png)

**Figure 2.** SLM 125 HL camera view during laser surface alloying.

Laser surface alloying is considered to be successful in obtaining a solid homogeneous black laser surface alloyed layer with clearly outlined contours on the field of the aluminum substrate (figure 2c). The technological parameters of the laser beam, which produce a stable surface alloyed layer with nickel coated SiC microparticles, are: scanning speed - from 400 to 600 mm/s; laser spot diameter in the working plane - 200 µm; distance between the tracks (distance between axes) 140 - 200 µm.

Upon completion of the alloying, the substrate is partially cooled in the chamber and removed to its final cooling in atmospheric air. It is followed by mechanical cleaning of the surface layer of soot and uncharged particles, washing and drying. Before the test of nanoindentation, specimens are cut out of the aluminum substrate and metallographic sections transverse to the direction of scanning are prepared.

### 3.2. Structure and chemical composition of the alloyed laser cladding tracks

The alloyed laser cladding tracks represent alternating strokes of absorbed SiC microparticles with a width of about 160 - 220 µm. Figure 3 gives top view of the alloyed tracks on the aluminium substrate obtained by optical macrostructure analysis (figure 3a) and scanning electron microscopy (figure 3b) without further surface treatment.
Figure 3. Alloyed laser cladding surface view.

Figure 4 shows different magnifications of the surface of the alloyed layers made again by scanning electron microscopy. At higher magnifications, it is clearly shown the morphology of the individual alloy strokes, as well as the common areas with attached microparticles of silicon carbide.

Figure 4. Specimen 2L-4 – SLM3 scanning electron microscopy.
The conducted energy dispersive X-ray spectroscopy microanalysis confirms the presence of silicon carbide particles in the alloyed layers. The presence of elements C, Si, Ni, Al in the range of the scanned areas is established. The additional scanning electron mapping (with higher magnifications) confirms the conclusions drawn about the content and chemical composition of the alloyed layers (figure 5).

![Figure 5. Energy dispersive X-ray spectroscopy microanalysis of specimen 1L-4 – SLM2](image)

In the prepared transverse metallographic sections (figure 6) of the specimens, the alloyed layers stand out clearly enough, so that their geometrical dimensions can be determined.

![Figure 6. Optical microscopy with geometric dimensions of the alloyed layers.](image)
The data from the optical microscopy show the following geometric parameters of the alloyed layer: average alloy depth about 40 - 50 μm at the average track width about 200-220 μm. Overlapping of the alloy layers is observed in an area of about 10 - 40 μm (figure 6).

3.3. Results of the nanoindentation test

The modulus of elasticity and hardness are determined by indentation of the aluminum alloy substrate and the alloyed layer (obtained by selective laser melting) of the reinforcing phase (SiC microparticles). The nanoindentation tests are performed on metallographic sections in depth of the cross-sections covering the alloyed zone and the transition to the basic metal [8].

The observed increase in nanohardness (figure 7b) in the alloyed layer area (up to about 40 μm) is 1.5 to 2.0 times higher than that of the aluminium alloy due to the absorbed reinforcing phase of SiC nickel coated microparticles. The measured nanohardness confirms the results for the geometry of the alloyed layer obtained by the optical metallographic analysis. This characteristic changes, i.e. the hardness decreases to values typical for the basic metal (after about 50 μm), with no clear heat impact area. The elasticity modulus shows the same trend, namely, relatively high values in the area of the alloyed layer (up to about 40 μm), a decrease after about 70 μm, and a slight increase in depth of the values typical of the base alloy.

3.4. Results of the wear resistance tests of laser cladded layers of dispersive reinforced material

The tribological parameters of the basic aluminium alloy (EN AW-2017A) are used as reference parameters of the wear resistance tests. The wear characteristics for the base metal specimens under the given test conditions indicate a deformation strengthening and an almost linear increase in the relative intensity of wear at the increasing of cycles number. Figure 8 and figure 9 show the results of the tests for the wear resistance of the 1R (transversely and longitudinally scanned) sample coating and the 2L (longitudinally scanned) sample coating (electroless nickel coated silicon carbide microparticles and aluminum powder in a 1: 1 ratio). The characteristics of the basic metal are represented by a dashed line.
Figure 8. Relative wear resistance for specimens 1L at different scanning speeds (SLM)

Figure 9. Relative wear resistance for specimens 1R at different scanning speeds (SLM)

Figure 10 and figure 11 show the results of the tests for the wear resistance of the 2R (transversely and longitudinally scanned) sample coating and the 2L (longitudinally scanned) sample coating (only of nickel coated silicon carbide microparticles). The characteristics of the basic metal are represented by a dashed line.

Figure 10. Relative wear resistance for specimens 2L at different scanning speeds (SLM)

Figure 11. Relative wear resistance for specimens 2R at different scanning speeds (SLM)

The 2L and 2R samples coatings (only of nickel coated silicon carbide microparticles) show the lowest wear rate and respectively the highest relative wear resistance at a higher scanning speed (in the range of 600 - 550 mm/s). The results for the change of relative wear resistance tests at different scanning speeds for the coating on 2L samples are given in figure 12.

The average relative change in the wear resistance of coatings on 2L specimens (only of nickel coated silicon carbide microparticles) in figure 10 is high - from 37% to 96%, with a maximum values of 172% at scanning speed of 600 mm/s. The average relative change in the wear resistance of coatings on 2R specimens (only of nickel coated silicon carbide microparticles) in figure 11 is also high - from 25% to 54%, with a maximum values of 128% at scanning speed (SLM) of 600 mm/s. The maximum values of the relative wear resistance for SLM layers with metalized SiC microparticles on the aluminium alloy matrix are obtained at a scanning speed of 600 mm/s. This shows a significant increase in wear resistance compared to the base alloy and indicates the obtaining a high percent alloyed and absorbed phase of nickel coated silicon carbide microparticles at higher scanning speeds.
Figure 12. Relative wear resistance change for specimens 2L under different scanning speeds (SLM)

Figure 12 shows the results of the tests for the relative wear resistance of the 2L (longitudinally scanned) sample coating (only of nickel coated silicon carbide microparticles). Figure 13 shows the results of the tests for the relative wear resistance of the 2R (transversely and longitudinally scanned) sample coating (only of nickel coated silicon carbide microparticles).

The average relative change in the wear resistance of coatings on 1L samples (of nickel coated silicon carbide microparticles and aluminium powder) is relatively low – from 14% to 33%, with a maximum values of 34% at scanning speed (SLM) of 450 mm/s. The average relative change in the wear resistance of coatings on 1R samples (of nickel coated silicon carbide microparticles and aluminium powder) is also low – from 23% to 34%, with a maximum values of 61% at scanning speed (SLM) of 400 mm/s. This shows a relatively low increase in the wear resistance compared to the basic metal, due to the obtaining of coatings of low percent alloyed and absorbed phase of nickel coated silicon carbide microparticles.
3.5. Analysis and comparison of the obtained results

Comparison of the different coatings (figure 14 and figure 15) is performed with respect to the relative wear resistance intensity of the coating at different scanning speeds (SLM) ranging from 400 - 600 mm/s obtained from the nearly stable test data for 75 and 100 cycles. The summarized data from the test are given in Figure 14 and Figure 15.

The characteristics of the basic metal are represented by a two-point dotted line. The characteristics of the coating of metalized microparticles of silicon carbide and aluminum powder (1L and 1R) are given with a dotted line and of the coating only with metalized particles (2L and 2R) - with a solid line.

![Figure 14. Relative wear resistance intensity at 75 cycles for the different coatings ranged in 400 – 600 mm/s scanning speed (SLM)](image)

![Figure 15. Relative wear resistance intensity at 100 cycles for the different coatings ranged in 400 – 600 mm/s scanning speed (SLM)](image)

Laser surface alloyed dispersive reinforced thin layers with only metalized silicon carbide microparticles (2L and 2R samples) showed an 1.9 to 3.0-fold higher average relative wear resistance intensity within the whole range of speeds, with the maximum wear resistance at scanning speed (SLM) of 450 mm/s. Increasing of the wear resistance intensity of the coating to 3.0 times compared to the basic metal is due to the realization of a laser cladded layer with a high content of alloyed and absorbed reinforcing phase.

Laser surface alloyed dispersive reinforced thin layers with metalized silicon carbide microparticles and aluminium powder in 1:1 ratio (1L and 1R samples) show relatively weak coating wear resistance intensity increase (from 1.2 to 1.5 times), which decreases to the values of the basic aluminium alloy at the higher scanning speeds (SLM).
4. Conclusions

1. A surface layer of a dispersive reinforced composite material with an aluminum alloy matrix containing metalized SiC microparticles is obtained by selective laser melting (SLM) technology at scanning speeds ranging from 400 mm/s to 600 mm/s.

2. Nanohardness in the alloyed zone of dispersive reinforced composite material containing nickel coated SiC microparticles increases from 1.5 to 2.0 times, compared to that of the basic aluminum alloy.

3. The maximum values of the relative wear resistance for SLM layers with metalized SiC microparticles on the aluminum alloy matrix are obtained at a scanning speed of 600 mm/s, however their mixing with aluminum powder reduces and removes its maximum values toward a lower scanning speed.

4. Alloying of the reinforcing phase of metalized SiC microparticles provides up to 3 times higher relative wear resistance intensity of the SLM layers than the basic alloy, however their mixing with aluminium powder significantly reduces its tribological parameters.

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