Shaping of Surface Layer Structure and Mechanical Properties After Laser Treatment of Aluminium Alloys

Tomasz Tański, Wojciech Pakieła, Maciej Wiśniowski and Leszek Adam Dobrzański

Abstract The influence of laser treatment on the structure, mechanical properties and wear resistant casting of aluminium alloys has been studied. The main objective of this investigation was to improve the tribological and mechanical properties of the surface layer of the aluminium alloy AlMg5Si2Mn by remelting and feeding the chromium particles into the melt pool with a rapid solidification. The applied size of the chromium particles have been in the range 50–120 µm. For the remelting of the surface a high power diode laser (HPDL) was used. The applied laser beam power is in the range from 1.8 to 2.2 kW. The linear laser scan rate of the beam was set to 0.5 m/min. The chromium powder has been introduced in the melt pool using a gravity feeder at a constant rate of 2 g/min. The application of the laser surface treatment of aluminum alloys enables us to obtain too much harder and better wear resistance compared to based materials.

Keywords Laser alloying · Aluminium alloy · Tribological test · Ball on plate · Intermetallic phases

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1 Introduction

The dynamic development of the industrial economy makes it necessary to find better and more advanced engineering materials able to meet the new demands [1–26]. Research is being conducted to improve mechanical and functional properties of all groups of engineering materials. There are very interesting possibilities given to materials such as aluminum and magnesium through light alloys [1–8]. The low density of aluminum or magnesium in comparison to steel and the rather simple possibilities to improve mechanical properties and to make it wear resistant is one of the main reasons why these materials are increasingly being used in particular applications where it is important to reduce the mass of elements or where corrosion resistant materials are necessary, such as in the automotive and aerospace industry and air transport. Very significant treatment enhancing properties of metals such as aluminium, magnesium and elements made therefrom are often subject to widely used surface treatment technologies [11–15, 20, 23–26]. A laser beam provides very precise delivery of energy and consequently can better and faster implement technological operations in layer treatments. The layer formed on the metal must be characterized through the high hardness and toughness, high fatigue strength and impact resistance as well as resistance to high and low temperature (creep and fracture toughness), thermal shock and the appropriate thermal conductivity. The properties of the obtained surface layers to a large extent depend on their structure, porous, material discontinuities, uniform chemical composition and phase composition. Laser radiation is also very often used for improvement of mechanical and tribological properties different engineering materials [9–23]. The laser surface treatment is currently often used for forming the structure and properties of the surface layer of not only light metals. Laser is used for reduce porosity and discontinuity in the material on the top surface in order to increase corrosion resistance [18, 19].

Goal of this investigation was to improve the mechanical properties and wear resistance in comparison to the substrate material by remelting the substrate with a small depth (max 1.5 mm) and feeding the chromium particles into the molten pool followed by a rapid solidification.

2 Methodology of Research, Material for Research

As the substrate an aluminum alloy with EN-AC 51500 magnesium was used. The chemical composition of the applied aluminium alloy is presented in Table 1. Chromium particles have been used to improve the mechanical properties and wear resistance of the surface layers. The size and shape of the particles used in the process of laser treatment has been presented in Fig. 1. The gradation of the applied particles of chromium powder was in the range of 50–120 μm.

Table 1 Chemical composition of aluminium alloy ENAC-AlMg5Si2Mn

Fe	Si	Mn	Ti	Cu	Mg	Zn	Others	Al
Max 0.25	1.8–2.6	0.4–0.8	Max 0.25	Max 0.05	4.7–6	Max 0.07	Each 0.05 Total 0.15	Remainder

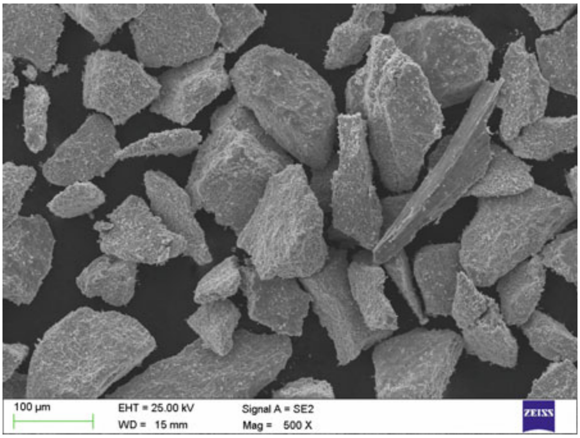


Fig. 1 Morphology of the chromium powder in the initial state

The heat source was a high power diode laser (HPDL). The high power diode laser was characterized by the very high power density of the laser beam under normal conditions of up to 10^7 W/cm^2. This makes the thermal impact on the detail limited and thus causes only minor thermal stress and strain. The high power diode laser (HPDL) was used to introduce the chromium powder into the aluminum alloy matrix. Because of the limited diffusion of hydrogen, oxygen and nitrogen gas from the atmosphere the process of melting the surface, has been carried out in argon atmosphere. The chromium powder was introduced into the molten pool by a rotary powder feeder with a fixed and predetermined amount of 2 g/m. The parameters of the laser treatment process is shown in Table 2. The shape and distribution of the undissolved Cr particles and precipitates in the aluminum alloy matrix was examined by scanning electron microscopy. The reinforcing phase constituted of undissolved particles of chromium powder and intermetallic phases formed on the

Table 2 Parameters of the laser alloying process

Laser power range	1.8; 2.0; 2.2 kW
Velocity of the laser beam	0.5 m/min
Laser spot size	1.8 × 6.8
Wavelength of the laser radiation	808–940 nm
Reinforcing particles	Cr
Quantity of the powder per min	2 g/min
Gradation of chromium powder	50–120 µm

Table 3 The parameters of the wear test "ball on plate"

Parameter	Value
Load	5 N
Distance	200 m
The length of the test	4 mm
Speed linear motion	2 cm/s

basis of chromium. To verify mechanical and tribological properties of the obtained layers such tests were made:

- hardness of the surface layers,
- microhardness along the cross-section of the solidification molten pool,
- wear resistant test "ball on plate".

The hardness of the surface has been measured steel ball with a steel ball with a diameter of 1/16 in. and a load 60 kgf (HRF scale). The microhardness of the cross-section remelted layers were measured by using Vickers Microhardness testers with an applied load of 100 gf. The wear resistance of the layers was obtained by the laser surface modification was examined using the tribological "ball on plate" test. The surface before the tribological test was grinded using an abrasive paper of grain size 68 μm. The aluminum oxide ball (Al_2O_3) was used as a counter sample in the tribological test. Parameters of wear resistant test is presented in the Table 3. Wear tack and product of wear obtained as a result of the tribological test was observed in the scanning electron microscope and analyzed using the EDS detector. Scanning electron microscopy to determine the shape and placement of the undissolved chromium particles and precipitation in the aluminium matrix also has been used.

3 Results and Discussion

In order to obtain a quasi-composite structure of the surface layer of the aluminum alloy ENAC-AlMg5Si2Mn chromium powder was used. A high power diode laser (HPDL) was used for the melting of the surface. During the laser alloying most of the powder was dissolved in the aluminum alloy matrix. There were also single undissolved chromium particles observed in the remelted zone (Fig. 2c, d).

The greatest amount of metal powder introduced to the molten pool was observed for the smallest applied laser power 1.8 kW (Fig. 3). This phenomenon is due to the moderate the impact of the laser beam (heat and lower pressure produced in melting area) on the dosed chromium powder and a liquid pool, when compared to the higher powered laser at 2.2 kW. The structure of the layers in the AlMg5Si2Mn aluminium alloy obtained by the laser alloying is presented in the Fig. 2a, b.

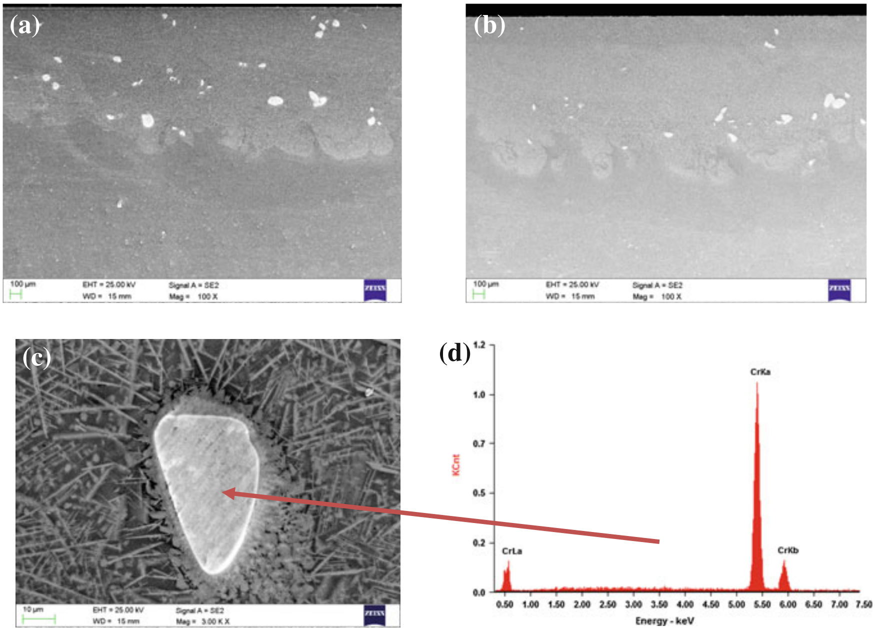


Fig. 2 Structure of the layers obtained during the laser treatment with the power **a** 1.8 kW, **b** 2.2 kW and **c**, **d** chemical analysis of the undissolved particles

Structure observation of the composite layers has shown uniform distribution of chromium powder in the liquid molten pool on a depth of about 0.7–1.7 mm (Fig. 2a, b). Analysis of the structure of the layers showed that the chromium particles are closely associated with the aluminium alloy matrix. No cracks, voids and pores were observed around the embedded particles which may indicate a good wettability of the particles by the matrix material.

Analysis of the cross section of the obtained layer and the surface topography showed that both on the top surface and inside surface layer, there is no demonstrable porosity or discontinuity. In the surface layer obtained during the alloying by the lower power of the laser beam there were observed many more undissolved particles of chromium (Figs. 2a, b and 4). Also the obtained depth was lower at about 0.4 mm compared to the maximum power of the laser. The topography of the layers obtained by the laser treatment are presented in Fig. 4.

The "ball-on-plate" test of the layers and based material AlMg5Si2Mn confirmed the increase of the wear resistance of the surface after laser treatment. It was also observed that the higher power of the laser beam did not affect wear resistance (Fig. 5). This phenomenon is caused by the distribution of the introduced metal particles in a larger volume of the deeper layer obtained during the laser treatment with the maximum power of the laser beam. The smaller power of the laser beam created a shallower layer. In result the same amount of the powder was introduced in the shallower remelting as with the maximum power laser beam. The lower heat

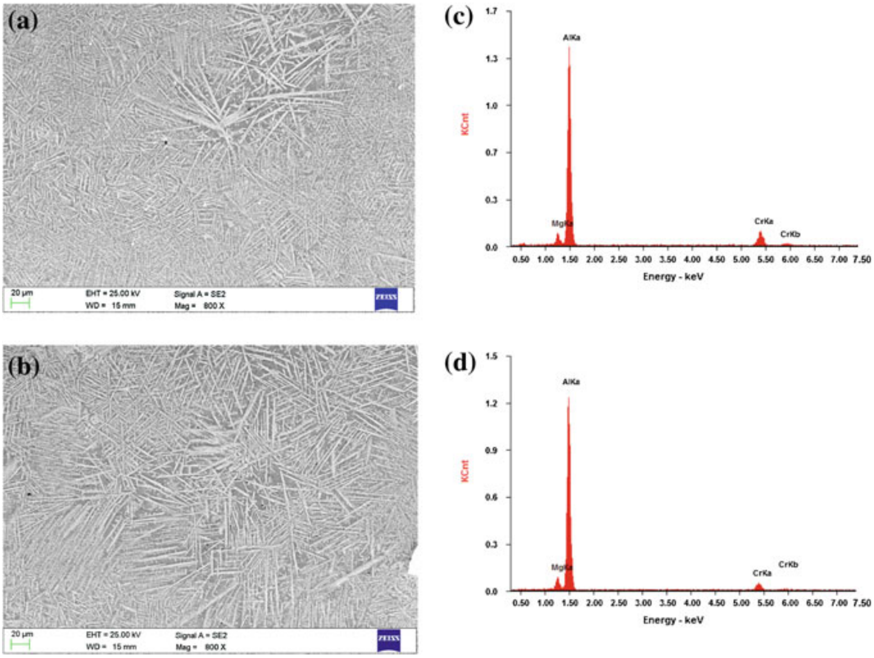


Fig. 3 Structure of the layers obtained during the laser alloying with the power **a** 1.8 kW, **b** 2.2 kW and **c**, **d** chemical analysis of the layers

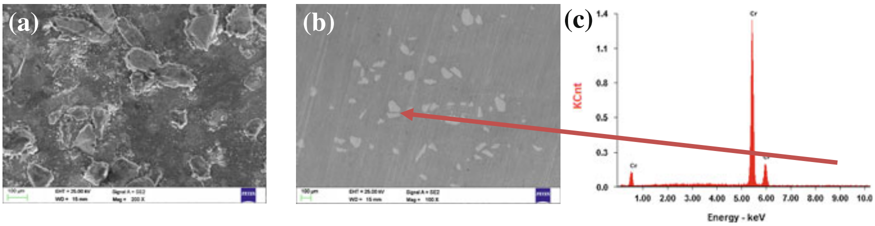


Fig. 4 Topography of the surface **a** after alloying with the 2.0 kW powered laser, **b** alloying and grinding and **c** chemical analysis at the point

input caused faster heat transfer from the volume of the aluminium and faster crystallization of the remelted area after the laser treatment. In all cases the layers enriched with chromium have not been interrupted. The topography of the wear track with the chemical analysis is presented in the Fig. 6.

The analysis of the product (the powder obtained during the scratched and abrasion) of the wear test did not reveal the presence of large particles of the metal powder removed from the surface or hard phases created by the laser alloying. The wear product after the tribological test of the aluminium alloy without the layers

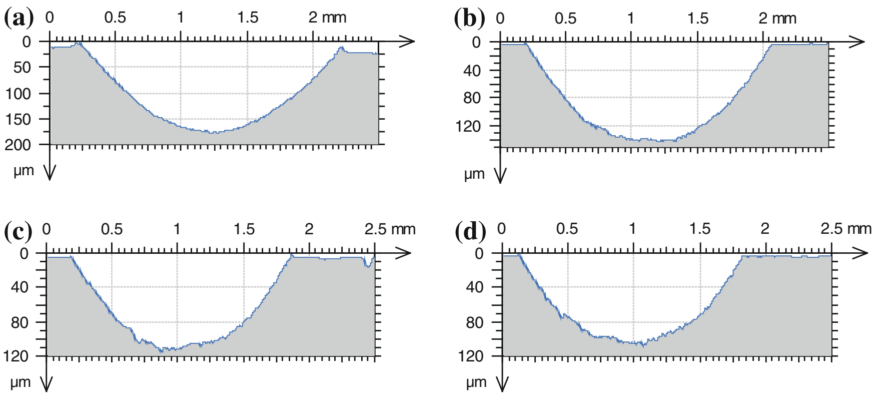


Fig. 5 Wear track after "ball-on-plate test" **a** based aluminium alloy AlMg5Si2Mn, and layers obtained the laser alloying with the power of the beam, **b** 2.2 kW, **c** 2.0 kW and **d** 1.8 kW

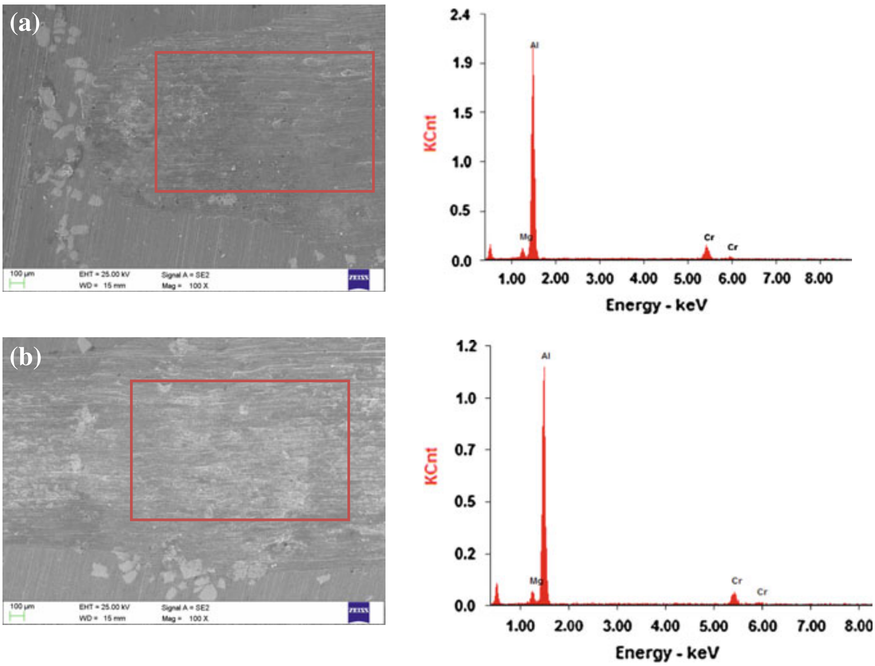


Fig. 6 Chemical analysis of the wear track after tribological test the surface layers obtained during laser the alloying with the beam power **a** 2.2 kW and **b** 1.8 kW

include large particles of aluminum uprooted from the surface particles. This kind of wear product confirms that the dominant mechanism was destructive chipping. The wear product of the layers enriched by the the chromium powder particles for

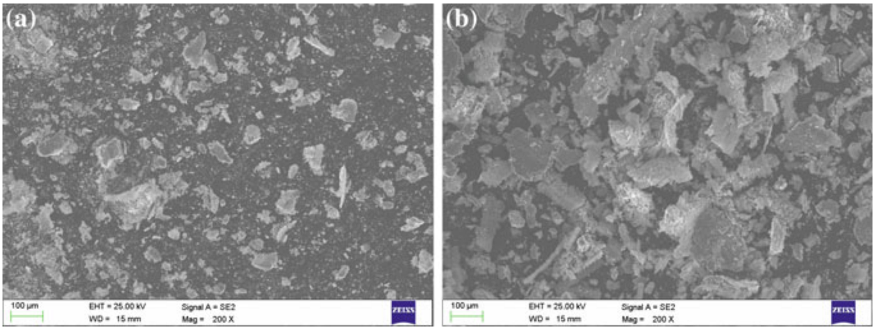


Fig. 7 Wear product after the "ball on plate" test. The samples **a** with layer formed by laser treatment with the power of 2.2 kW and **b** AlMg5Si2Mn without the laser surface treatment

all cases consisted of the fine powder. The product of the wear test is presented in the Fig. 7.

The smallest roughness of the track was measured for the layer after laser alloying by the chromium powder with power of the laser beam 1.8 kW. The highest measured roughness was identified for untreated sample and their surface. It is closely related with the increasing hardness of the tested materials after the laser treatment.

During the wear resistance test the friction coefficient was also measured (Fig. 8). The analysis of the data showed a lower friction coefficient for the samples

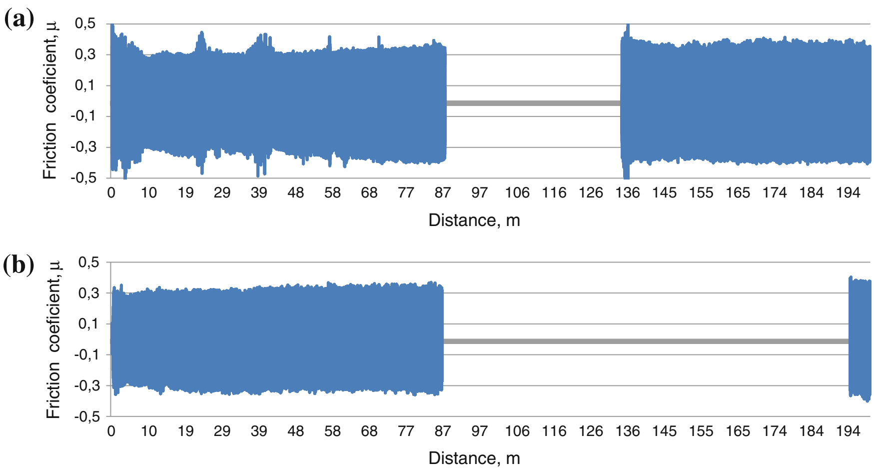


Fig. 8 The friction coefficient as a function of the distance registered during the "ball on plate" test for samples with composite layers obtained by laser treatment at the powers: **a** 1.8 and **b** 2.2 kW

after laser treatment by about 0.2. Futhermore, the friction coefficient curve for samples after laser alloying was smoother when compared to the based material.

The irregular nature of the friction coefficient curve from the AlMg5SiMn2 sample is caused by the removal of particles from the aluminum surface and the adhesive which connects the aluminum with the ceramic counter-specimen. The reason for this phenomenon is the lower tendency of the adhesive connect the counter-specimen (Al_2O_3) with the remelted layer enriched in chromium particles and created during the laser alloying phases with chromium. The presence in the volume of solidification molten pool the phase was created as a result of the laser alloying providing an increase of the wear resistance and as a result the wear track is more smooth. The results of the measurements of size and roughness of the wear track surface i shown in Fig. 5 and Table 4.

Observations of the wear track using scanning electron microscopy and analysis of the chemical composition using X-ray spectrometry confirmed the nature of the wear of the based material and the samples after laser treatment. Analysis of the wear track using scanning electron microscopy and analysis of the chemical composition using X-ray spectrometry confirmed that the layer on the aluminium alloy surface had not been interrupted. On the bottom part of the crater the chromium particles in aluminium matrix was confirmed. The topography of the wear track layers obtained during the laser treatment was much smoother and did not contain particles torn from the surface (Fig. 9b). The topography of the wear track and its the chemical analysis is presented in the Fig. 6a−b. The wear track of the samples without laser treatment have visible traces of losses caused by fissures, wear and ridging of material particles from the substrate (Fig. 9a).

Comparing the hardness of the based aluminum alloy AlMg5Si2Mn and the layers obtained during the surface alloying has shown the significant impact of the laser treatment on the obtained results. The greatest increase of hardness was observed for the sample after laser alloying with a 1.8 kW powered laser beam, which was due to the great amount of powder applied to the top part of the obtained layers. The results of the hardness test are presented in Table 4.

Table 4 Roughness and hardness of the surface before the wear test, friction coefficient registered during the process and dimension of the wear track after "ball-on-plate" test

Power of the laser beam, kW	Roughness of the surface Ra μm	Hardness of the surface HRF	Friction coefficient	Dimension of the wear profile	
				Depth, μm	Width, mm
Aluminium alloy ENAC 51–100 before the laser treatment					
–	0.59	67	0.38	169	2.12
Aluminium alloy ENAC 51–100 after the laser treatment					
1.8	0.57	115	0.33	137	1.88
2.0	0.44	113	0.34	104	1.75
2.2	0.36	109	0.334	109	1.68

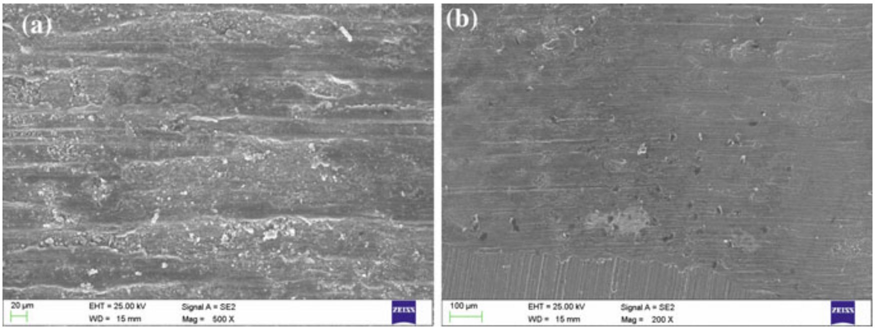
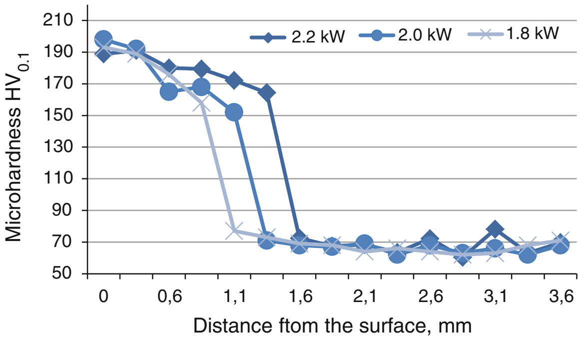


Fig. 9 Wear track after tribological "ball-on-plate" test of the sample: **a** auminium alloy AlMg5Si2Mn without laser treatment and **b** layers obtained during the laser treatment with the power 2.0 kW

Fig. 10 Microhardness along the cross section of composite layers obtained at different laser powers



For testing the change of hardness on the obtained layers as a correlate of their depth along the cross-section, the Vickers microhardness test has been used. The test shows an increase of the hardness in solidification molten pool in all cases. The greater hardness increase was measured from the layers obtained during the alloying with the smaller power of the laser beam, then layers depth was the smallest. The greater depth of the remelted area was observed from the layers obtained with the highest power of the laser, but the maximum hardness was smaller when compared to those obtained by the lower powered laser (at 1.8 kW). The results of the microhardness test is presented on the Fig. 10.

4 Conclusions

Based on the findings our analysis it can be unambiguously stated that the resulting layer has a greater hardness and better wear resistance compared to the base material. The wear resistance test demonstrated that the best properties of wear resistance belonged to samples which were obtained by using the lowest power laser, at 1.8 kW. An increase in the laser beam power during the alloying of Al Mg5Si2Mn aluminium alloy by the high power diode laser (HPDL) did not cause a growth of the wear resistance composite layers. The analysis of the results of the friction coefficient at a function of distance confirmed that the introduction of chromium particles into the aluminum alloy matrix reduces the friction coefficient by 0.2 compared to the based aluminium alloy. Introducing the chromium particles to the aluminium matrix greatly increases the mechanical properties and and the wear resistance of the top surface layer of aluminum alloy. Increasing the laser beam causes a greater remelting zone but the maximum hardness of this layers is lower compared to the layers obtained with the power of the laser beam of 1.8 kW.

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