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HPDL laser alloying of Al-Si-Cu alloy with Al_2O_3 powder

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ABSTRACT

Purpose: This article presents results of investigation of laser alloyed cast aluminium alloys after standard heat treatment. In general into the aluminium matrix there are fed different types of ceramic particles including aluminium oxide. The purpose of this work was also to determine the laser treatment conditions for surface hardening of the investigation alloys, like laser power, as well the laser scan rate.

Design/methodology/approach: The investigations were performed using light and electron microscopy (SEM) for structure determination, using EDS microanalysis it was also possible to determine the chemical composition changes. The morphology and size of the ceramic powder particles was also possible to determine.

Findings: Concerning the laser treatment conditions for surface hardening the scan rate as well as the laser power influence was studied. The structure of the surface laser tray changes in a way, that there are very high roughness of the surface zone and the flatness or geometry changes.

Research limitations/implications: The aluminium samples were examined metallographically using optical microscope with different image techniques as well as scanning electron microscope.

Practical implications: Developing of new technology with appliance of Al alloys, High Power Diode Laser and diverse ceramic powders can be possible to obtain, based in findings from this research project. Some other investigation should be performed in the future, but the knowledge found in this research concerning the proper process parameters for each type of alloy shows an interesting investigation direction.

Originality/value: The combination of metallographic investigation, including electron microscope investigation and High Power Diode Laser (HPDL) treatment parameters makes the investigation very attractive especially for automobile industry, and transportation where parts manufactured of aluminium alloys are a very important because of its surface properties.

Keywords: Surface laser treatment; HPDL; Aluminium alloys; Alloying

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

One of modern methods for surface layer engineering in currently surface laser surface treatment especially Laser Surface Alloying - LSA, where to the matrix material there are introduced small amount of alloying additions into the surface layer in form of ceramic particle powders with different properties (Table 1) changing the surface layer appliance possibilities. The laser treatment as a part of the new generation techniques applied in metal surface technology is discussed in this paper. One of the intrinsic HPDL (High Power Diode Laser) properties is the rectangular beam shape, which can be profitably used in welding of large polymer parts. Polymer welding with a single moving HPDL beam was one of the earliest applications. Welding operations can be performed simultaneously when a single scanable beam is replaced by several larger rectangular beams. The rectangular beams are aligned along the whole weld track. For polymer-based windows, the length of the weld track is favourable for simultaneous weld processing as there are no moving parts. Beyond reduced handling costs, the residual mechanical properties of the weld governed by the thermal cycle can be controlled by the pulse shape and are no longer constrained by the welding speed. With increased pulse duration, also a larger lateral extent of the molten zone evolves and experimental experience showed improved adaptive gap bridging performance. In general, the additional degree of freedom for the processing parameters enables a more flexible process, and therefore investigation of new processes should be fruitful. Large power densities allow precise control of heating and cooling of small material amount. This makes it possible to obtain amorphous structure with a thickness of about 20 microns. Diode lasers have long been used as light emitters in fiber-optic telecommunications, as barcode readers, and for implementing the write–read functions of optical disks. Diode lasers are increasingly found in applications such as materials processing (welding, cutting, drilling, surface hardening, etc.) as well as in printing and graphical arts, in displays, and medical applications.

Industry component manufacturer successfully use HPDLs for simultaneous hardening of the springs of door hinges. Flexible adaptation to a variety of geometrically different parts, minimized distortion by simultaneous hardening, and pyrometric monitoring of the quality are additional features to these low-cost and high-productivity laser system. Relatively low intensities in are sufficient for these applications. Experimental results on metal working with higher intensities were obtained using industrial HPDLs at proper focusing conditions with an output power of 1.3 and 2.5 kW, respectively. While these HPDLs are built on the basis of commercial diode laser bars with 40 W output power for each diode, in the meantime a record continuous-wave output power of 267 W per bar has been achieved, of course like it seems to be not the physical limit for these achievements and we can expect further enhancement of these values.

In fact, since the advent of the high-power diode laser, laser technology is experiencing a fundamental structural change, as this semiconductor device has become the key element of a new breed of laser systems that are competing with gas lasers and lamp-pumped solid-state lasers. Power performance is so far restricted to wavelengths about 940 nm.

Hence, power density at the work piece is limited as well, leaving high-power diode lasers with restricted application opportunities. Mounting high-power diode-laser bars on cooling elements requires high precision and the complete mastering of the electrical, thermal, and mechanical junction process. This is the fundamental concept for direct-diode applications. The major concern of laser alloying is to avoid defects after treatment such as cracking, bubbles and unacceptably rough surface. The second concern is to achieve a maximum hardness in the surface layer to ensure good working parameters [1-16].

High-power diode lasers are continuously making inroads into industrial applications, as they are compact, easy to cool, yield a power efficiency beyond 50%, which is about five times higher than any other kind of laser has to offer, and their costs are becoming increasingly attractive. To exploit the tremendous application potential of high-power diode lasers, research and development programs are performed in many industrial countries.

The top layer obtained in the laser alloying process has a different structure and properties compared to the structure and properties of the substrate material and the alloying material. The morphology of the resulting quasi-composite layer tends to be not homogeny, and entered the correct dispersion of particles throughout the depth of penetration with the exception of a very thin layer of diffusion saturation [17-29].

Today aluminium alloys plays an increasingly role in the world constructional material production, because of the availability and properties which are possible to obtain. Mechanical properties of the Al-Si alloys are connected to the size, shape and distribution of the Si eutectic present in the microstructure, for the reason of the improvement of the mechanical properties, these alloys are in general modified, for the reason of change of the fibrous Si morphology what makes it possible to achieve better mechanical properties of the Al-Si alloys. In real conditions the crystallization of the Al alloys shows departures of the crystallization process resulting from the Al-Si equilibrium diagram, which is a double system with an eutectic and limited solubility of the components in a solid state. The reason of these deviations is fir of all the considerably higher alloy crystallization, compared to this occurred in equilibrium conditions, but also the change in the initial alloy structure in the liquid state, caused by impurities, or specially added modifiers for the reason of structure modification and morphology changes of the $\alpha+\beta$ eutectic or shifting of the characteristic equilibrium diagram temperature points, because of the pressure increase during the alloy crystallisation process. In this area also the HPDL laser treatment with ceramic particle feeding is of big importance for changing the structure of aluminium.

It is known that the coarseness of the microstructure clearly affects the solution treatment time needed to dissolve particles and obtain a homogenous distribution of copper in the matrix. A short solution treatment time of 10 min is enough to achieve a high and homogenous copper concentration for a material with a fine microstructure (secondary dendrite arm spacing, SDAS of 10 μm), while more than 10 h is needed for a coarse microstructure (SDAS of 50 μm). Models are developed to describe the dissolution and homogenisation process. The model shows good agreement with the experimental results. The eutectic silicon morphology, viz., particle size and shape, plays an important role in determining the mechanical properties in A1-Si alloy castings. The silicon particles, present as coarse, acicular needles under normal cooling conditions, act as crack initiators and lower the mechanical properties. Their morphology is therefore modified through the addition of small amounts of strontium (Sr) or sodium (Na) to the melt, which alters the structure from acicular to fibrous, that is considerably more beneficial to the resultant properties. Modification of the silicon particles can also be achieved thermally, through solution heat treatment, where the silicon particles are initially broken down into smaller fragments that are then gradually spheroidized. Prolonged solution treatment leads to undesirable coarsening of the particles [30-47].

Table 1.
Physical properties of the ceramic powders

Properties	WC	TiC	SiC	Al_2O_3
Density, kg/m^3	15.69	4.25	3.44	3.97
Hardness, HV	3400	1550	1600	2300
Melting temperature, °C	2870	3140	1900	2047
Thermal expansion	23.5	8.3	4.0	7.4÷ 8.5
Grain size, μm	80	5	100	120

Laser treatment is presented with remelting of cast aluminium alloys AlSi7Cu, AlSi7Cu4, AlSi9Cu and AlSi9Cu4. The basic laser treatment parameters is the practical aim of this work, as well as improvement of hardness. Special attention was payed to studying of the surface layer morphology of the investigated material especially the surface layer structure.

2. Experimental procedure

The material used for investigation were the AlSi7Cu, AlSi7Cu4 as well AlSi9Cu and AlSi9Cu4 aluminium alloys. The chemical composition of the investigated aluminium alloys is presented in Table 2. For feeding the Al_2O_3 aluminium oxide powder was used (Fig. 2).

The heat treatment was carried out in the electric resistance furnace U117, with a heating rate of 80 °C/s for the ageing process and 300 °C/s for the solution heat treatment process with two holds at 300°C and 450 °C performer for 15 minutes. Cooling of the samples after heat treatment was performed in air for the ageing process and in water for the solution heat treatment process. The solution heat treatment temperature was 505°C for 10 hours, and then ageing was performed at 175°C for 12 hours.

For remelting it was using the high power diode laser HPDL Rofin DL 020 (Fig. 1). The used laser is a device with high power, used in materials science, including for welding. The laser equipment used included such as: rotary table and moving in the XY plane, the nozzle of the powder feeder to the enrichment or welding, shielding gas nozzle, laser head, power and cooling system, and the computer system controlling the operation and location of the laser the working table.

Remelting was performed in argon, in order to protect the substrate from oxidation. The sample was subjected to laser fusing the protective gas blowing the cover of the two nozzles, one directed axially to the laser-treated sample and the other directed perpendicular to the weld area. Flow rate of shielding gas (Argon 5.0) was 10 l/min.

Fig. 1. HPDL Rofin DL 020 laser stand used for alloying

Table 2.
Chemical composition of the investigated aluminium alloys

Chemical composition of the investigated alloys, in mass %		
Alloys	AlSi7Cu	AlSi9Cu4
Elements	Chemical composition	
Si	7.166	7.449
Fe	0.1384	0.1655
Cu	0.9901	3.595
Mn	0.11	0.2544
Mg	0.268	0.2829
Zn	0.0461	0.0515
Ti	0.082	0.1265
Al	rest	rest
Alloys	AlSi9Cu	AlSi9Cu4
Elements	Chemical composition	
Si	9.094	9.268
Fe	0.1792	0.3379
Cu	1.049	4.64
Mn	0.3608	0.0143
Mg	0.2682	0.2838
Zn	0.1409	0.0478
Ti	0.0733	0.0899
Al	rest	rest

Distance from the sample was set in the range of ca. 20 mm. On one surface of the rectangular samples was performed by one track by fusing laser at different laser power and at a laser scan rate of 0.25 m/s.

The micrographs of the structure and macrostructure investigation was performed using the light microscope Leica MEF4A supplied by Zeiss in a magnification range of 50 - 500x. The micrographs of the microstructures were made by means of the KS 300 program using the digital camera equipped with a special image software.

The obtained results from the microstructure investigation were performed on the scanning electron microscope ZEISS Supra 35 with a magnification up to 500 times. For microstructure evaluation the Back Scattered Electrons (BSE) as well as the Secondary Electron (SE) detection method was used, with the accelerating voltage of 20 KV.

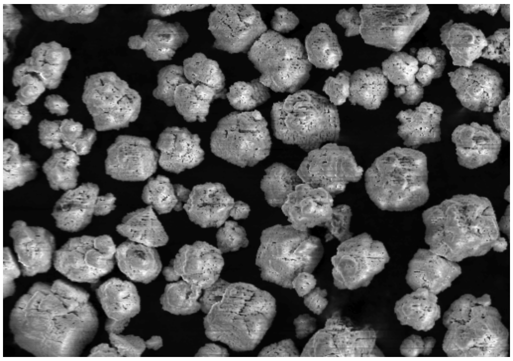

Fig. 2. Al_2O_3 ceramic oxide powder used for alloying

Chemical composition investigations using EDS microanalysis on the scanning electron microscope Zeiss Supra.

The hardness was measured with Rockwell hardness tester with a load chosen for the HRF scale, with a load of 60 Kgf.

3. Results and discussion

The obtained results from the microstructure investigation performed on scanning electron microscope ZEISS Supra 35 with a magnification up to 500 times reveals the cross section structure of the surface layer as well as the presence of the used Al_2O_3 powder (Fig. 3-6). For microstructure evaluation the Back Scattered Electrons (BSE) detection method was used, with the accelerating voltage of 20 KV. Based on these investigation the distribution of the powder particles in the surface layer of the aluminium-silicon-copper cast alloys was presented, it was also found, that in the laser treated surface layer there are no pores or cracks in the produced coating or any defects and failures occurs in this layer; this finding is valid for all of the investigated alloys (AlSi7Cu, AlSi7Cu4, AlSi9Cu and AlSi9Cu4). Occasionally occurred discontinuity of the layer can be seen as a product of the heat transfer process and may be neutralised by properly adjusted powder quality and powder feed rate. It is also possible on the basis of these cross-section micrograph to evaluate the thickens of the surface layer depth, which is ca. 2.13 µm (Fig. 7) in case of the AlSi9Cu alloy, for the AlSi7Cu4 alloy the obtained structure investigation results allow to confirm only a minor amount of the Al_2O_3 powder on the surface of the treated alloy In case of the Al_2O_3 powder the particles are sintered building a layer on the top of the laser treated aluminium surface. It was also found that the examined layers consists of three subzones - the remelted zone, the heat influence zone and the substrate material. Further investigations will be needed to revealed the morphology and nature of these zones, occurring after alloying with different process parameters and different ceramic powders.

The uneven areas and hollows in the surface layer of the Al-Si-Cu alloys with laser alloyed aluminium oxide particles are produced as a result of intensive heating of the surface. Depending on the type of substrate, laser power, feed rate and the powder applied, the surface on which high gradient of surface tension is produced, is unevenly heated, which has a direct influence on the formation of the melted material in the remelting lake. Some of the alloy and ceramic parts embedded in the remelting zone is evaporated under high temperature occurring during laser treatment, therefore the characteristic hollows appear on the remelting surface. It was also found that, disregarding the ceramic powder used, in the laser bundle power range from 1.2 to 2.0 kW the porosity of the composite layers obtained increases, in comparison to that of the raw cast surfaces of aluminium alloys.

The shape of the laser tray of the cast aluminium alloys AlSi7Cu4 and AlSi9Cu4 using high power diode laser HPDL are presented on Figures 14 and 15. There is obvious a clear relationship between the laser power applied and the achieved quality of the laser treated surface, the particular investigation concerning laser power influence were carried out in former works [3, 4]. If was found that the optimal laser power is ca. 1.5 kW.

As a result, the proper selection of feeding conditions there can be generally achieved on the surface, a single composite matrix material consisting of Al alloy and ceramic powder particles [2-7, 15]. In determining the conditions of the process should take into account several important factors, including the following: the beam energy, absorption differences between the cast of aluminium alloys, laser scan rate. As it can be found for all investigated alloys the used alumina powder forms after laser alloying a sintered layer on the surface, confirmed be the EDX analysis of the chemical composition Fig. 8, 9 and Table 3. There is also no evidence for alloying of the Al_2O_3 phase into the alloy matrix, Figs. 10, 11, 12 and Table 4.

For a lower laser power of ca. 1.0 kW there is not a linear remelting present on the whole length of the treated sample surface. Where for a higher laser power of ca. 2.0 kW the laser tray is very uneven. There was investigated also the influence of the laser speed on the remelting of the aluminium surface. The range was chose from 0.25 m/min to 0.75 m/min (Figs. 13-14), the optimal value was set as 0.5 m/min for both of the investigated aluminium alloys groups.

The investigations of the cross section has revealed also the nature of the structure of the surface layer, Figs. 15-20. Based on the AlSi7Cu4 alloy, there was investigated the influence of the laser power on the cross section of the obtained surface. The idea was to found if the laser power will change nature of the alloying of the alumina powder. But for 1.5 kW and 2.0 kW the Al_2O_3 powder forms a sintered layer on the surface of the laser treated aluminium.

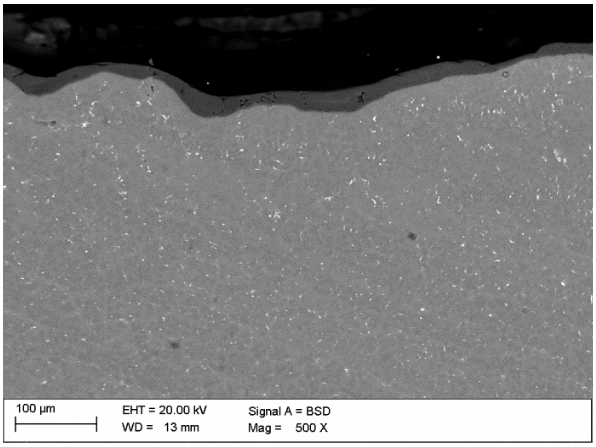

Fig. 3. Microstructure of the investigated AlSi9Cu alloy, 1.5 kW, 1g/min, 0.5 m/min

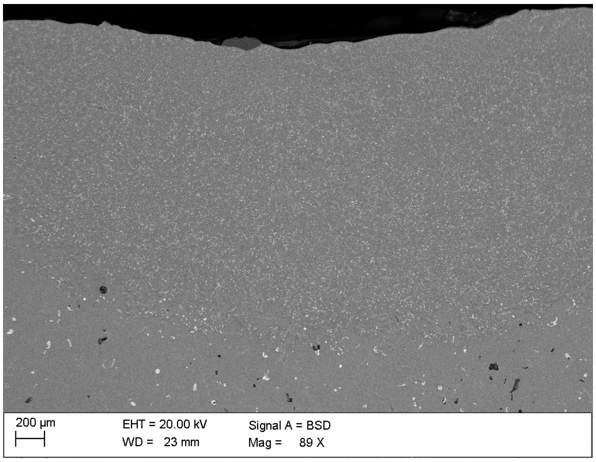

Fig. 4. Microstructure of the investigated AlSi7Cu4 alloy, 1.5 kW, 1g/min, 0.5 m/min

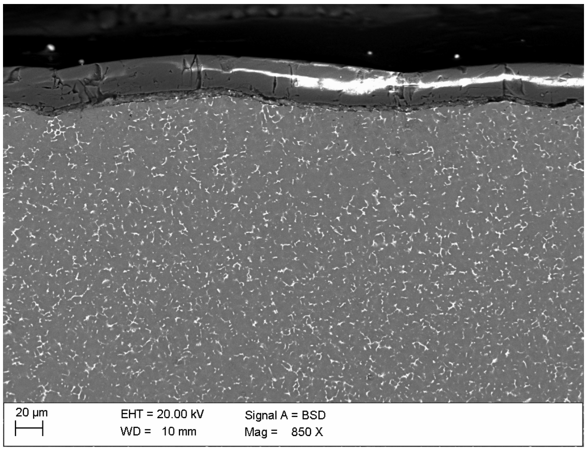

Fig. 5. Microstructure of the investigated AlSi9Cu4 alloy, 1.5 kW, 1g/min, 0.5 m/min

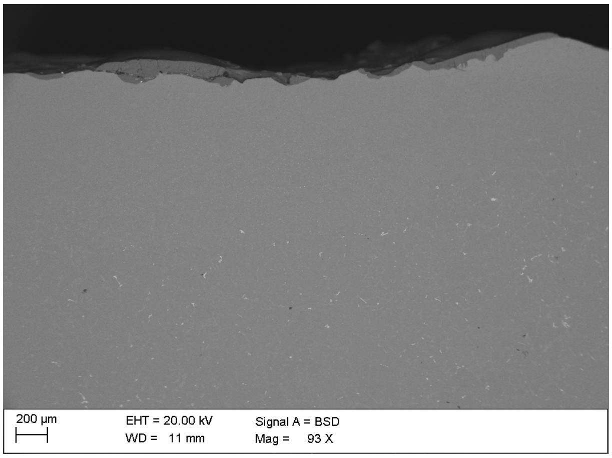

Fig. 6. Microstructure of the investigated AlSi7Cu alloy, 1.5 kW, 1g/min, 0.5 m/min

Beside the alumina powder feeding there was found a huge grain refinement in the remelted zone (Figs. 16-20) for the AlSi7Cu4 and both laser power used 1.5 kW and 2.0 kW.

En important factor for the right experiment condition settlements is the selection of proper powder scan rate during the remelting and alloying process. It was chose a range between 0.5 and 1 m/min for remelting only to have an reference value, because the appliance of ceramic powders can makes it necessary to change a little this reference value. On Figures 17-19 there are presented the optical micrographs of the laser treated surface of the aluminium alloy. It is clearly visible that for the 1 m/s scan rate the surface is very rough and cannot be used for future investigation because of too strong carrying gas influence on the surface. Whereas for the laser scan rates of 0.5 m/s the surface is flat enough, ensuring a minimal influence of the gas blow. It will be expected that in case of some ceramic powders, because of the absorption, the laser scan rate can reach even 0.25 m/s.

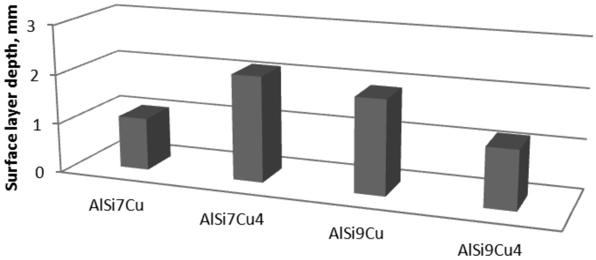

Fig. 7. Surface layer depth of the alloyed cast aluminium alloys with Al_2O_3 ceramic powder

Table 3.
Chemical EDS analysis results

Quantitative EDS microanalysis		
Element	Wt%	At%
OK	36.20	48.90
AlK	63.80	51.10

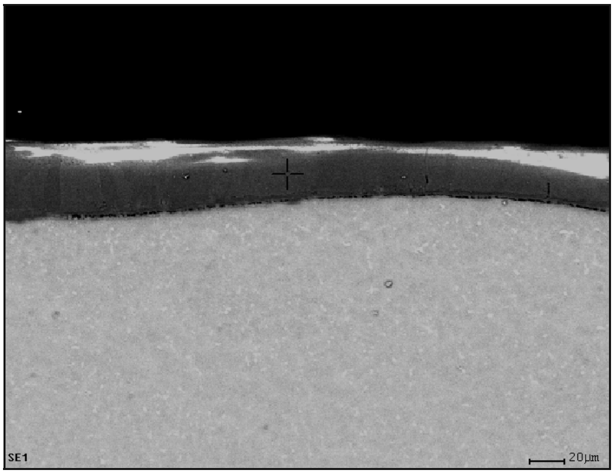

Fig. 8. Al_2O_3 Surface layer on the AlSi7Cu alloy

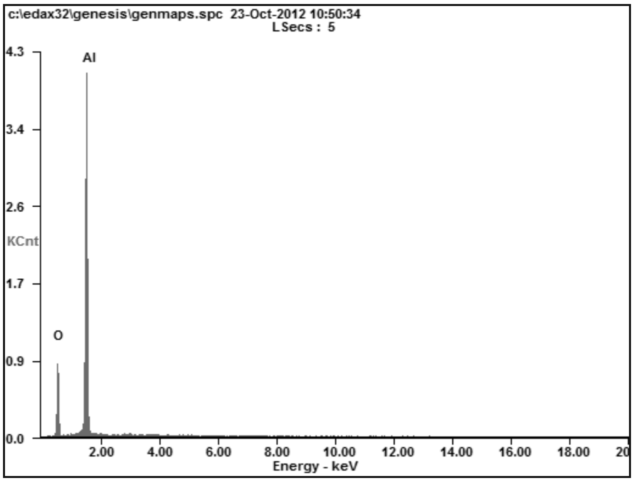

Fig. 9. EDS point-wise microanalysis

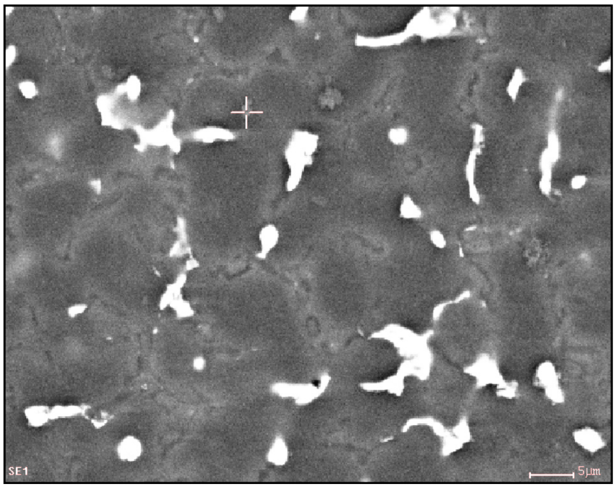

Fig. 10. Al_2O_3 Surface layer on the AlSi7Cu alloy

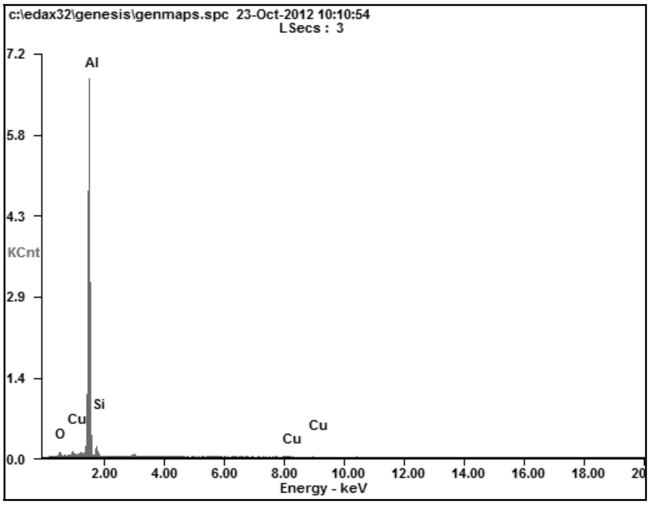

Fig. 11. EDS point-wise microanalysis

Table 4.
Chemical EDS analysis results

Quantitative EDS microanalysis		
Element	Wt%	At%
OK	4.48	7.44
AlK	87.77	86.45
SiK	5.43	5.14
CuK	2.32	0.97

Metallographic observations of the microstructure are presented on Figures 20 to 23. In this small range of magnification between 100 and 200 times there is visible the difference of the surface face size and roughness in case of these two investigated alloys groups with Si 9% and Si 7 % silicon content, where for the AlSi9Cu 4 (Figs. 20 to 22) there are more regular and uniform remelting face compared to the AlSi7Cu alloys with a weaker and more non-uniform laser face (Figs. 23 to 25).

Before the alloying with Al_2O_3 there were performed preliminary tests allowing to find the proper laser scan speed as well as the optimal laser power used for alloying of this type of aluminium alloy substrate [4]. Of course the optimal laser powder and alloying speed using ceramic powder will differ slightly compared to the values used for remelting only of the aluminium alloy itself, but the range does not changes significantly.

With the increase of the laser beam power density, or decreasing the scanning speed increases the thickness of the resulting layer, for lower power density laser beam scan speed or greater, the depth of alloying and, consequently, the resulting surface layer thickness decreases. These values should be within the proper range, because for a high power density laser beam or a low-speed scanning, alloy material begins to sublimate, leaving small pits on the surface. If the laser beam power density is too low or too high scanning speed, alloyed layer structure may be heterogeneous.

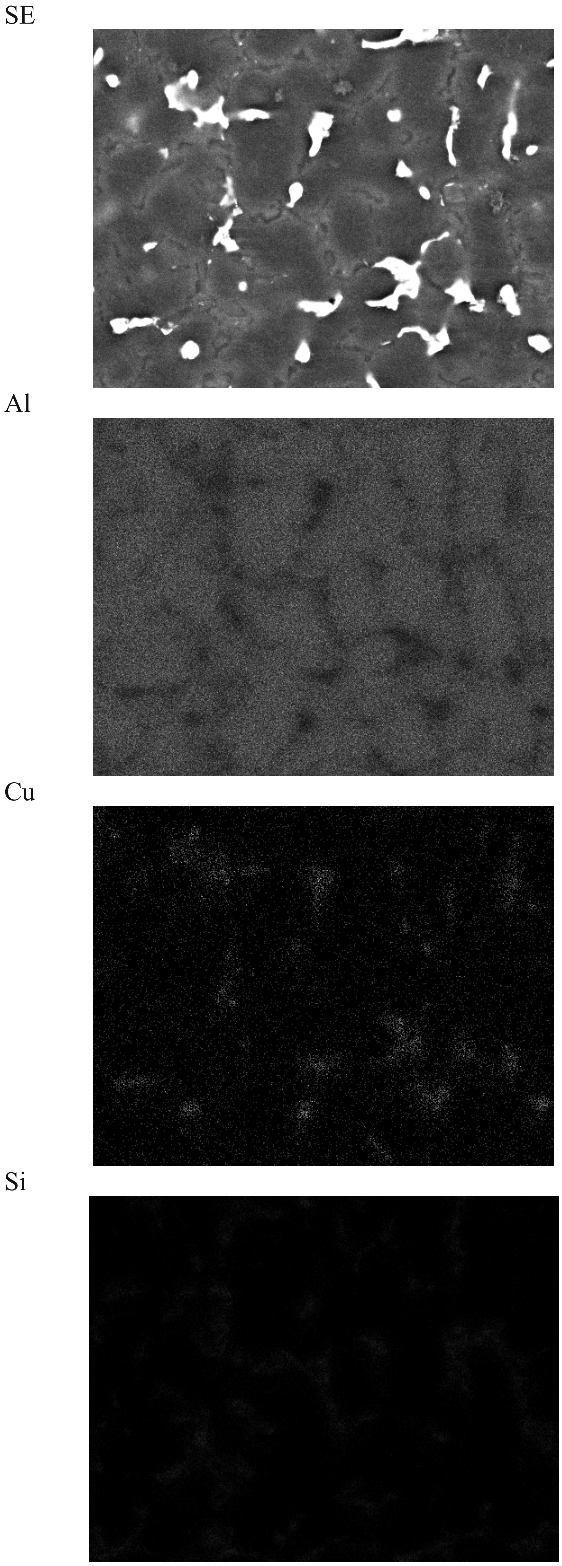

Fig. 12. EDS area analysis of the chemical elements distribution, AlSi7Cu4 alloy

What matters is the appropriate choice of alloying material to the ground, due to melting and sublimation, which for a homogeneous mix should be included in a narrow range of values. In fact, the plasma melting and evaporation occurs the material. A characteristic feature of the laser alloying process is the presence of the boundary layer and the substrate melted a large temperature gradient, which in turn leads to rapid cooling and solidification of molten metal. Further absorption of energy from the laser beam, which inhibits sublimation, on the other hand, by its own pressure leads to mixing of the molten components. The laser beam will also rise to funnel-like depressions in the lake of molten metal, which is ionized gas, and liquid metal at the border - plasma is maintained constantly disturbed, unstable equilibrium. In order to regulate the impact of plasma on the lake of molten metal, various technological methods of activation or levelling. One method of limiting the influence of plasma on a lake of molten metal by blowing a cloud of plasma stream of inert gas. Introduced gas (e.g. argon) is often additionally heated, which prevents deterioration of the energy effect.

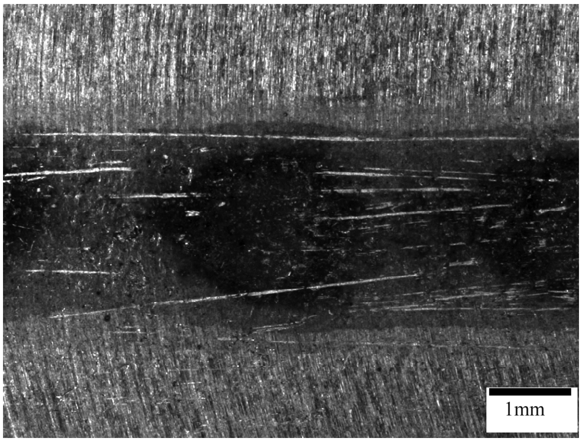

Fig. 13. Surface of the laser tray face after treatment with 1.5 kW laser power, scan rate 0.75 m/s, AlSi7Cu4 cast alloy

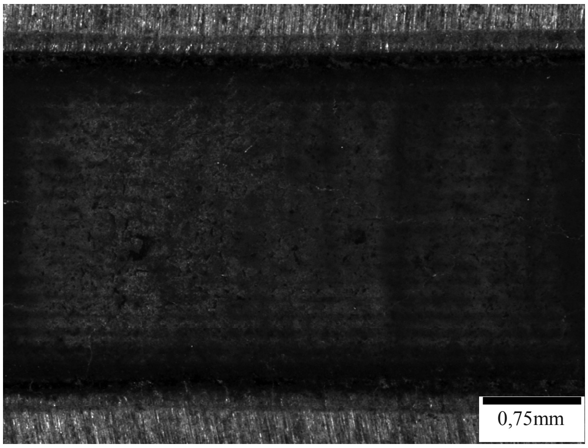

Fig. 14. Surface of the laser tray face after treatment with 1.5 kW laser power, scan rate 0.5 m/s, AlSi7Cu4 cast alloy

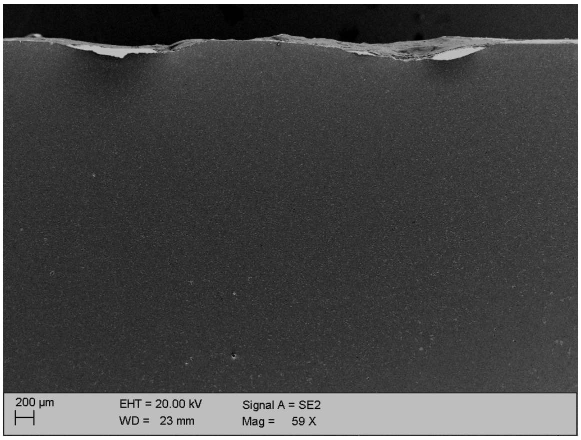

Fig. 15. Surface layer of the AlSi7Cu4 alloy, 2.0 kW laser power, powder feed rate 1g Al_2O_3/min, 0.5 m/min scan speed

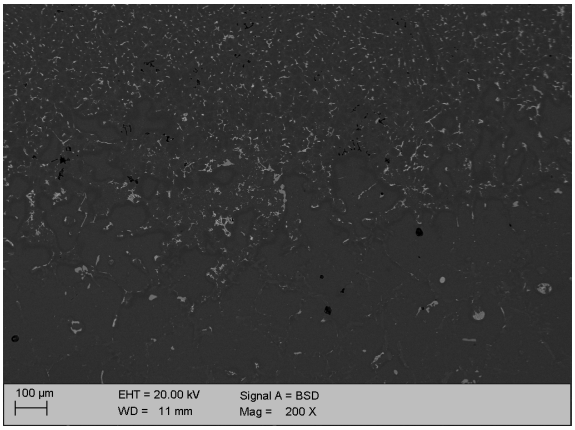

Fig. 16. Transition zone between surface layer and substrate of the AlSi7Cu4 alloy, 2.0 kW laser power, powder feed rate 1 g Al_2O_3/min, 0.5 m/min laser scan speed

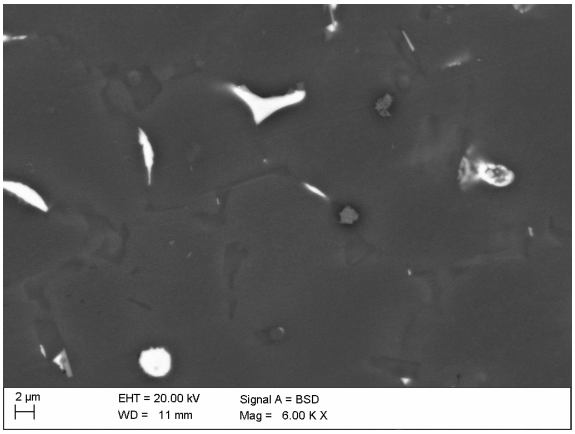

Fig. 17. Structure refinement of the surface layer obtained on the AlSi7Cu4 alloy, 2 kW laser power, powder feed rate 1 g Al_2O_3/min, 0.5 m/min laser scan speed

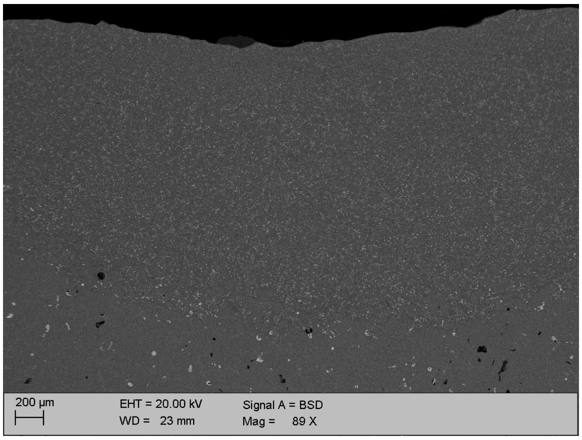

Fig. 18. Surface layer of the AlSi7Cu4 alloy, 1.5 kW laser power, powder feed rate 1g Al_2O_3/min, 0.5 m/min scan speed

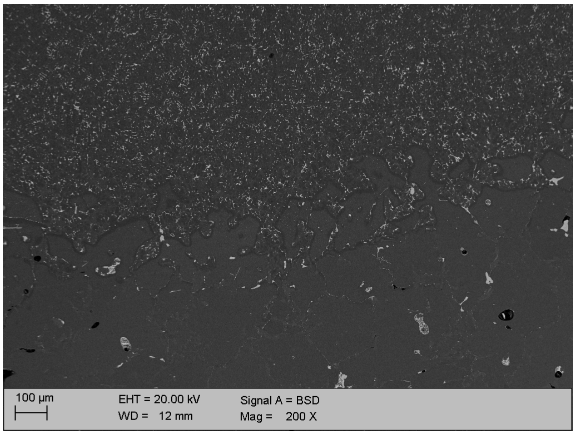

Fig. 19. Transition zone between surface layer and substrate of the AlSi7Cu4 alloy, 1.5 kW laser power, powder feed rate 1 g Al_2O_3/min, 0.5 m/min laser scan speed

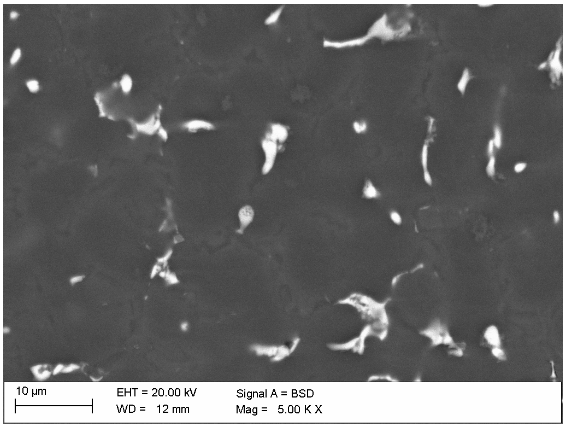

Fig. 20. Structure refinement of the surface layer obtained on the AlSi7Cu4 alloy, 1.5 kW laser power, powder feed rate 1 g Al_2O_3/min, 0.5 m/min laser scan speed

4. Conclusions

The performed investigations of the microstructure evaluation of the Al-Si-Cu alloys, carried out using light and scanning electron microscope, allow to confirm the zone-like nature of the surface layer obtained using HPDL laser for alloying of the AlSi7Cu, AlSi7Cu4, AlSi9Cu as well as the AlSi9Cu4 cast aluminium alloys. There were revealed the remelted zone (RZ), heat affected zone (HAZ) on the top of the substrate material, as well as a transition zone. Unfortunately there was not detected the ceramic powder Al_2O_3 particle in the substrate, but rather a sintered forth layer on the top of the samples consisting of Al_2O_3.

There are three phases which are of importance for achieving the require properties after properly performed heat treatment, these are: the primary Si phase, the Al_2Cu phase as well as the Mg_2Si phase. The laser power determination leads to the conclusion, that the optimal power range is ca. 1.5 kW, a lower value of ca 1.0 kW does not to achievement of an completely homogeny remelting tray on the sample surface, whereas a to high power of 2.0 kW makes an uneven, bumpy or hilly shape of the remelted area. in the range between Particularly it can be also found that:

- The primary Si phase has a more globular shape in case of the Al-Si7Cu4 alloy with a average size up to ca. 20 μm in diameter, whereas in the structure of the AlSi7Cu4 alloy the Si precipitation are more elongated in the size up to 50 μm.
- The optimal laser power is in the range of < 1.0 - 2.0 > kW.
- The optimal laser scan rate during treatment of the aluminium alloy surface was determined as 0.5 m/s. A to high scan rat leads to a non-homogeny laser tray on the surface.
- The Al_2O_3 powder particles does not fed into the aluminium alloy matrix during laser alloying, instead there is formed a sintered alumina layer onto the investigated aluminium cast alloy.
- The AlSi9Cu alloy has a more homogeny surface layer depth after alloying compared to the 7%Si aluminium alloy.

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