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HPDL laser alloying of heat treated Al-Si-Cu alloy

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ABSTRACT

Purpose: There are presented in this paper the investigation results of microstructure of the cast aluminium alloys in the as cast state as well after laser treatment used for alloying with carbide and oxide ceramic powders like aluminium oxide and silicon carbide, titanium carbide, vanadium carbide and tungsten carbide. 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 for the microstructure determination. By mind of the transmission electron microscopy, especially selected area diffraction method appliance it was possible to determine the phases occurred in the alloy in the as cast state. The morphology and size of the Mg_2Si was also possible to determine as well the lattice parameters for this phase.

Findings: Concerning the laser treatment conditions for surface hardening the scan rat as well as the laser power influence was studied. It was used a power in the range between 1.0 and 2.0 kW 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 in an important manner, crucial for further investigation.

Research limitations/implications: The aluminium samples were examined metallographically using optical microscope with different image techniques as well as transmission 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 for cast aluminium alloys – including electron microscope investigation – and HPDL treatment parameters makes the investigation very attractive for automobile, aviation industry, and others where aluminium alloys plays an important role.

Keywords: Laser treatment; Surface treatment; Aluminium alloys; Alloying

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Laser Surface Alloying - LSA is one of the methods of surface treatment, consisting in the introduction to the matrix material small amount of alloying additions into the surface layer in form of ceramic particle powder (Table 1). The laser treatment as a part of the new generation techniques applied in metal surface technology is discussed in this paper. Large power densities (109 W/cm^2) allow precise control of heating and cooling of small material amount at scan rates exceeding 108 K/s. 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.

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.

High-power diode lasers usually come in the form of bars (approximately 10 mm×0.6 mm) comprising about 25 monolithic groups of up to 20 parallel single-laser stripes. A major drawback of high-power broad-area diode lasers is their satisfactory beam quality. This allows focusing of the total beam as it is the addition of many single beams. Hence, power density at the workpiece is limited as well, leaving high-power diode lasers with restricted application opportunities. Crucial for reliability and lifetime of bars is proper heat sinking. Although power efficiency is extremely high, one half of the absorbed pump power has to be removed as waste heat. 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 [1-9].

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.

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.

Properties of the surface layer depend also on the substrate, the alloying material and the alloying process parameters, but almost always, rich in the alloying layer obtained is characterized by a greater than the substrate hardness, fatigue strength, better corrosion properties and tribological increasing surface roughness, which results in the alloying elements, often the performed treatment is intended to smooth the surface. Example for this are investigations performed on laser alloyed the 32CrMoV12-28 hot-work tool steel surface layer with the vanadium carbide, tungsten carbide, titanium carbide, niobium carbide, tantalum carbide using the high power diode laser. There are revealed structure refinement and influence of the mentioned factors on the mechanical properties of surface layer, and especially on its hardness, abrasive wear resistance, and roughness. Development of the surface layer was observed in which the remelted zone, whose thickness is ca. 0.7 mm, heat-affected zone with thickness ca. 1.2 mm, and the transient zone [10-17].

The conditions determined by the process of laser alloying: laser beam power density and exposure time of laser beam on the material, which varies between thousands and decimal parts of seconds. Proper selection of these conditions provides the required characteristics of geometric and mechanical properties of the resulting surface layer. 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. 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. Achieved under these conditions the cooling rate to reach 1011 K / s, while the solidification velocity often exceed 20 m / s, which in the case of some materials may cause quenching of thin layer of substrate material. Plasma affects the casting of two ways, on the one hand, it shields the lake from 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. While intensifying the effect of plasma is carried out using a plasma cloud blowing, but at the same time re-directing to the work area primarily reflected laser radiation by a system of flat mirrors or mirror dish [18-26].

Table 1.
Properties of the ceramic powders using for alloying

Properties	WC	VC	TiC	SiC	Al_2O_3
Density, kg/m^3	15.69	5.36	4.25	3.44	3.97
Hardness, HV	3400	2850	1550	1600	2300
Melting temperature, °C	2870	2830	3140	1900	2047

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 [27-37].

Laser treatment is presented with remelting of cast aluminium alloys AlSi7Cu4 and AlSi9Cu4. The basic laser treatment parameters is the practical aim of this work, as well as improvement of hardness. Special attention was devoted to monitoring of the surface layer morphology of the investigated material and on the laser tray quality - the roughness, flatness, width and porosity.

2. Experimental procedure

The material used for investigation were the AlSi7Cu4 and AlSi9Cu4 aluminium alloys. The chemical composition of the investigated aluminium alloys is presented in Table 2.

The heat treatment presented on Fig. 1 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. 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. Nozzle 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

As a result, the proper selection of feather conditions can be achieved on the surface, a single composite matrix consisting of (Al alloy). 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.

Table 2.
Chemical composition of the investigated aluminium alloys

Chemical composition of the investigated alloys, in mass %		
Elements	AlSi7Cu4	AlSi9Cu4
Si	7.45	9.27
Fe	0.17	0.34
Cu	3.6	4.64
Mn	0.25	0.01
Mg	0.28	0.28
Zn	0.05	0.05
Ti	0.13	0.09
Al	87.97	85.23
Rest	0.1	0.09

The micrographs of the micro- 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.

Microstructure investigation and phase identification was performed using transmission electron microscopy (TEM) JEOL JEM 3010 TEM with the bright and dark field image technique and SAD diffraction method. The diffraction pattern calculation was performed using the “Eldyf” software supplied by the Institute of Material Science of the University of Silesia.

The hardness was measured with Vickers hardness tester with a load chosen for the $HV_{0.05}$ scale, according to the PN-EN ISO 6507-1 standard, by a load of 60 Kgf. A minimum of 3 indentations was made on each of the tested samples.

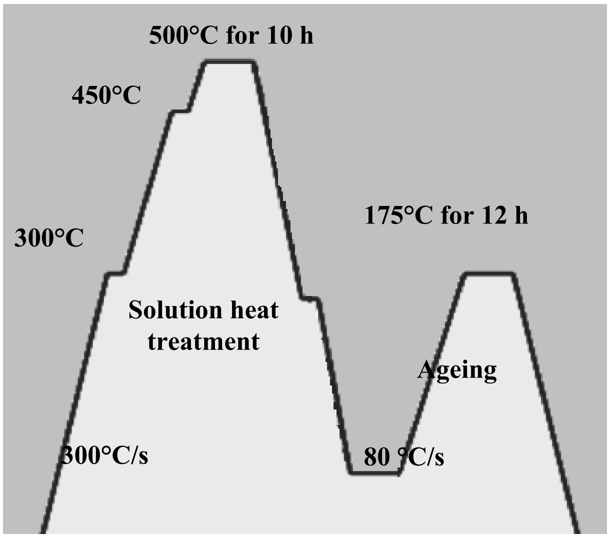

Fig. 1. Heat treatment parameters used for the investigated aluminium cast alloys

3. Results and discussion

Metallographic observations of the microstructure are presented on Figures 2 to 5. In this small range of magnification between 100 and 200 times there is visible the difference of the phase size and distribution in case of these two investigated alloys, where for the AlSi9Cu 4 (Fig. 4 and 5) there are more Si particles present in a more elongated form compared to the AlSi7Cu4 alloy (Figs. 2, 3).

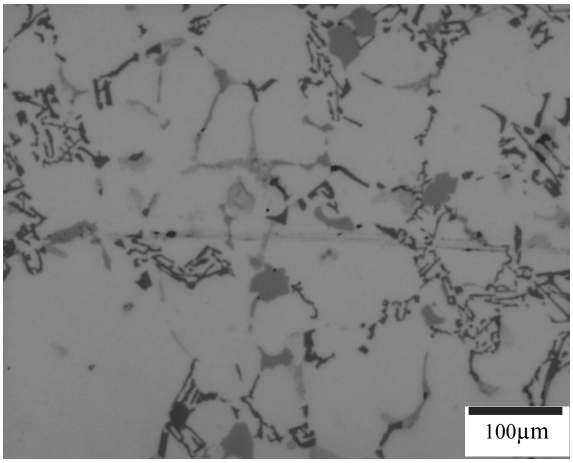

Fig. 2. Microstructure of the investigated AlSi7Cu4 alloy

As a result of metallographic investigations made on the light microscope (Figs. 2-5) it has been confirmed that the aluminium alloys in the cast state are characterized by a microstructure of the α solid solution constituting the alloy matrix as well as the Si, Al_2Cu and Mg_2Si phase in the forms of plates.

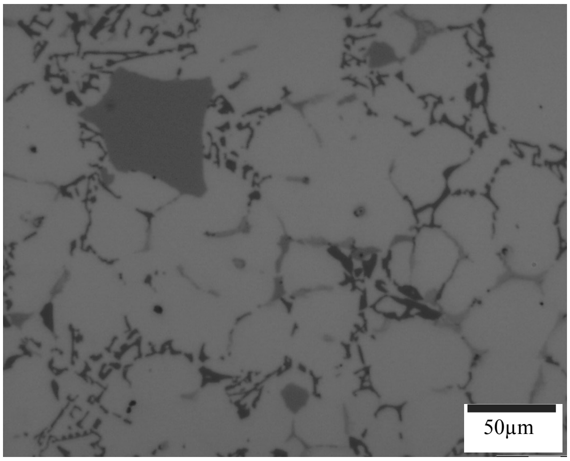

Fig. 3. Microstructure of the investigated AlSi7Cu4 alloy

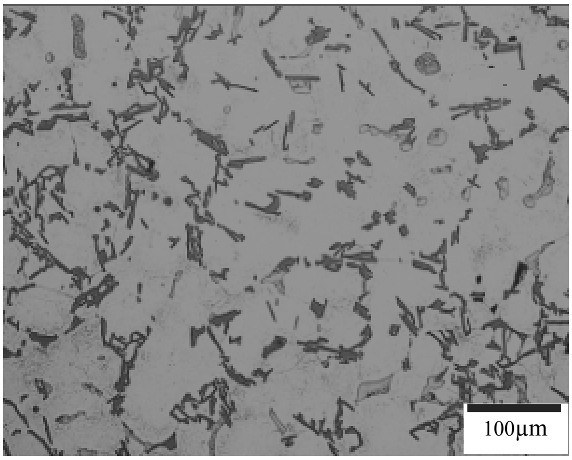

Fig. 4. Microstructure of the investigated AlSi9Cu4 alloy in as cast state

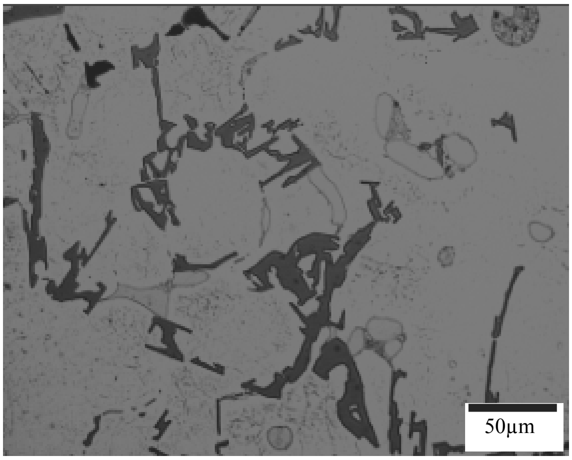

Fig. 5. Microstructure of the investigated AlSi9Cu4 alloy in as cast state

Investigations results performed on transmission electron microscope, Figs. 6-13 presents the microstructure details of the cast aluminium alloys. There can be found structures- Figs. 6, 7 - with different dislocation density inside the sub grains. Places with high dislocation density are visible as black areas, where as uniform light grey areas are free of dislocations.

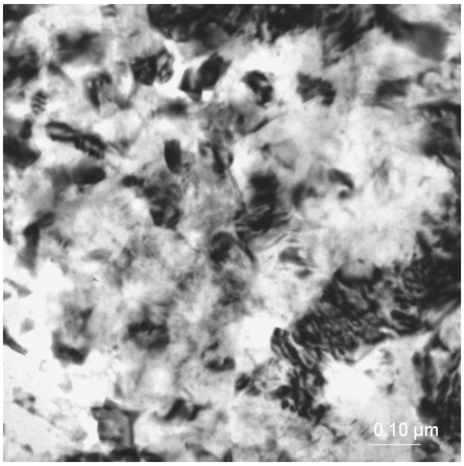

Fig. 6. Al_α phase microstructure, bright field, TEM

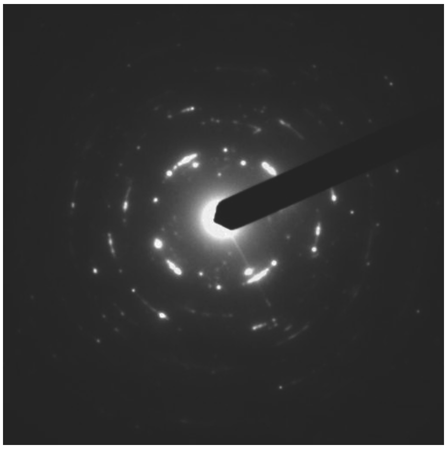

Fig. 7. Diffraction pattern of the area in Fig. 6

The visible subgrains have an average width of 0.1 to 1 µm in length. The observed structure presents this considerable density of dislocations affects favourably the mechanism of strengthening of the aluminium alloy. Diffraction pattern measurement (Figs. 10 and 12) performed for phase identification give as a result a polycrystalline diffraction pattern for the Alα matrix as well the cubic phase with the group symbol 227 - (F d -3 m) with zone axis [111] and d-spacing of 0,635 nm for the Mg_2Si phase (Figs. 8 and 11).

The shape of the laser tray of the cast aluminium alloys AlSi7Cu4 and AlSi9Cu4 using high-power diode laser HPDL are presented on Figs. 14-16. There is visible a clear relationship between the laser power applied and the achieved quality of the laser treated surface. If was found that the optimal laser power is ca 1.5 kW.

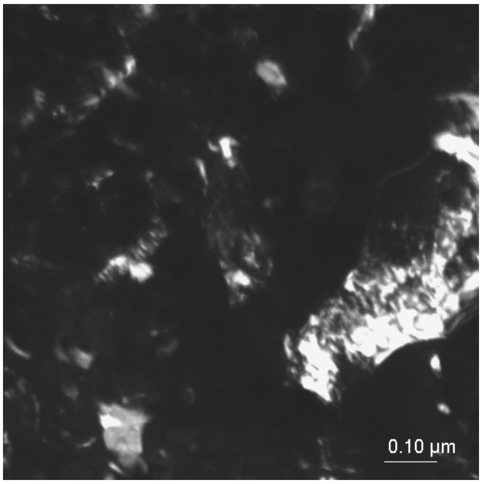

Fig. 8. Al_α phase microstructure, dark field, TEM

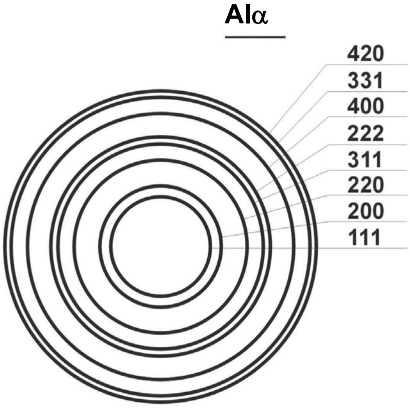

Fig. 9. Solution of the diffraction pattern presented in Fig. 7

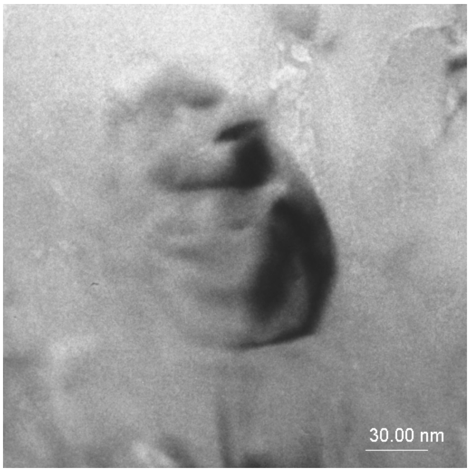

Fig. 10. Mg_2Si phase microstructure, bright field, TEM

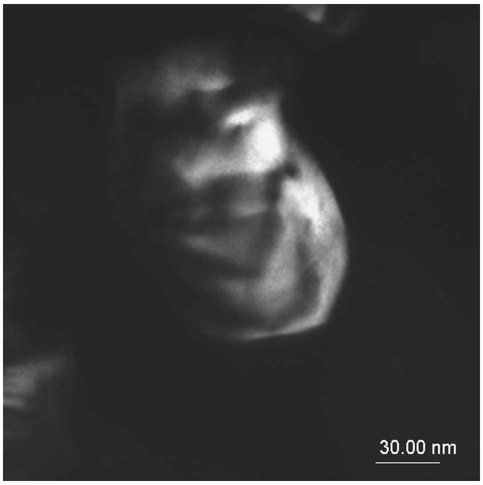

Fig. 11. Mg_2Si phase microstructure, bright field, TEM

Fig. 12. Diffraction pattern of the particle in Fig. 10

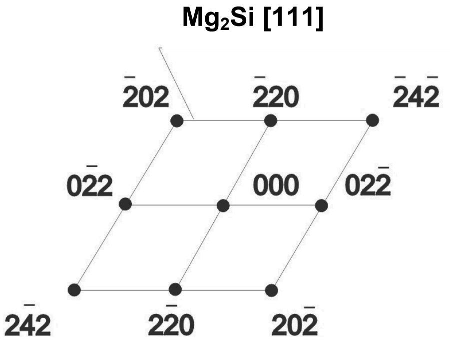

Fig. 13. Solution of the diffraction pattern presented in Fig. 12

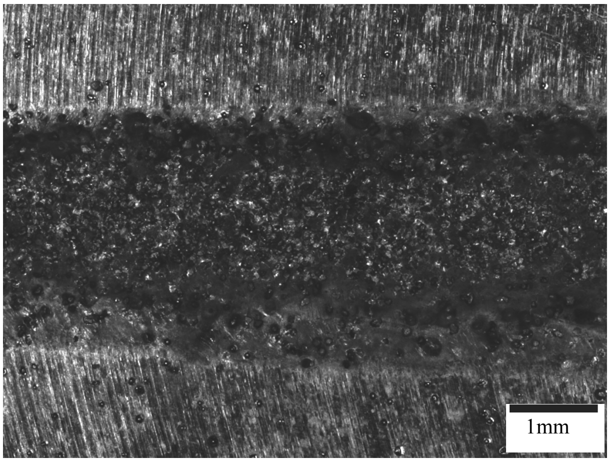

Fig. 14. Surface of the laser tray face after remelting with 1.0 kW laser power, AlSi9Cu4 cast alloy

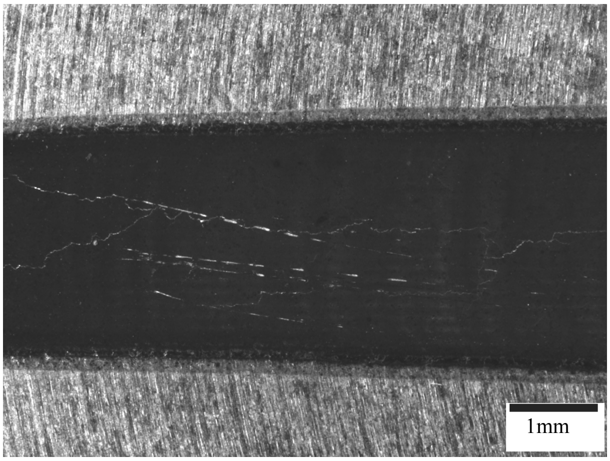

Fig. 15. Surface of the laser tray face after remelting with 1.5 kW laser power, AlSi9Cu4 cast alloy

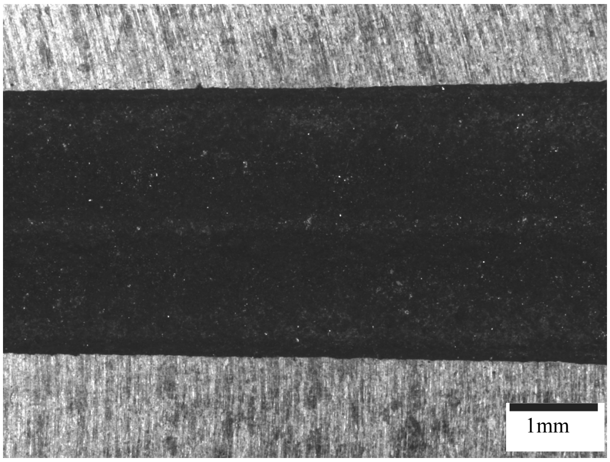

Fig. 16. Surface of the laser tray face after remelting with 2.0 kW laser power, AlSi9Cu4 cast alloy

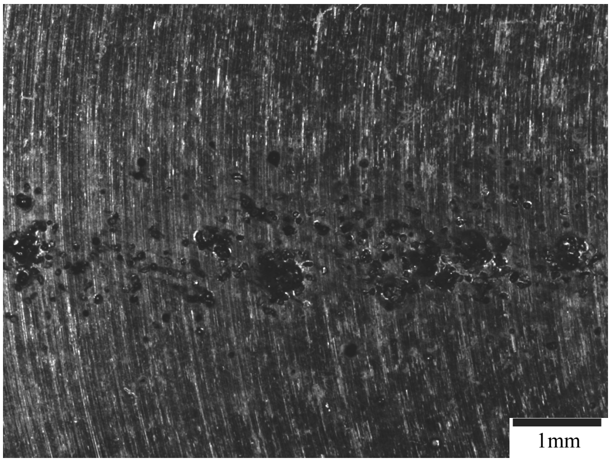

Fig. 17. Surface of the laser tray face after treatment with 1.5 kW laser power, scan rate 1 m/s, AlSi7Cu4 cast alloy

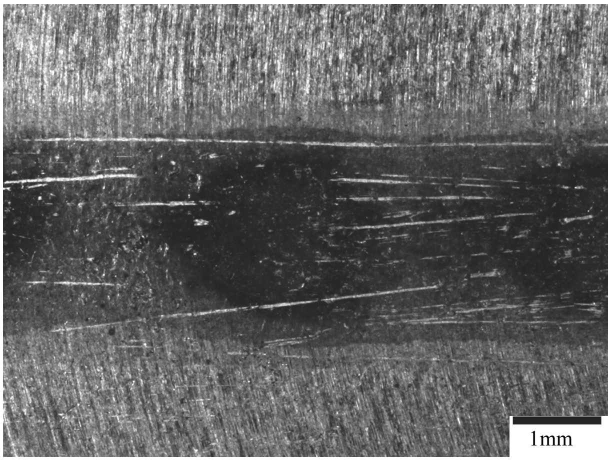

Fig. 18. Surface of the laser tray face after treatment with 1.5 kW laser power, scan rate 0.75 m/s, AlSi7Cu4 cast alloy

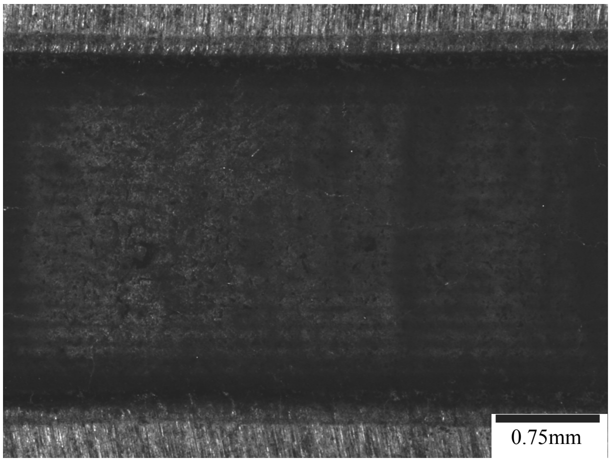

Fig. 19. Surface of the laser tray face after treatment with 1.5 kW laser power, scan rate 0.5 m/s, AlSi7Cu4 cast alloy

An 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/ 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 lase scan rate can reach even 0.25 m/s.

4. Conclusions

The performed investigations of the microstructure evaluation of the Al-Si-Cu alloys, carried out using light and transmission electron microscope, allow to confirm the occurrence of the phases present in the Alα- matrix. 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 laser power value of ca. 1.0 kW does not lead to the achievement of a completely homogeny remelting tray on the sample surface. Whereas a to high power of 2.0 kW produces an uneven, bumpy or hilly shape of the remelted area. Particularly it can be also found that:

1. the investigated Ag-Si-Cu alloy is characterised with a dendritic structure in the as cast state before heat treatment,
2. the investigated alloy has average hardness value of 40 HV after solution heat treatment and ageing and 35 HV in the as cast state,
3. 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 Al-Si7Cu4 alloy the Si precipitation are more elongated in the size up to 50 μm,
4. within the Al phase there are found place with very high dislocations density, revealed by mind of thin foils investigations on the transmission electron microscope,
5. the optimal laser power was determined as 1.5 kW, ensuring a proper surface roughness and width of the laser tray.

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