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Laser surface treatment of cast Al-Si-Cu alloys

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ABSTRACT

Purpose: The test results presented in this chapter concern formation of the quasi-composite MMCs structure on the surface of elements from aluminium cast alloys AC-AlSi9Cu and AC-AlSi9Cu4 by fusion of the carbide or ceramic particles WC, SiC, ZrO_2 and Al_2O_3 in the surface of alloys. In addition, within the scope of the tests the phase transformations and precipitation processes present during laser remelting and fusion at appropriately selected parameters: laser power, the rate of fusion and quantity of the ceramic powder fed have been partially examined.

Design/methodology/approach: In general, the laser surface processing should result in achievement of the surface layer with the most favourable physical and mechanical properties, in particular enhancement of surface hardness, improvement of abrasion resistance and resistance to corrosion is assumed in relation to the selected aluminium alloys after standard thermal processing.

Findings: The presented results of the surface layer include analysis of the mechanisms responsible for formation of the layer, and particularly concern remelting of the substrate and its crystallisation at various parameters of the High Power Diode Laser (HPDL) and the technological conditions of the surface processing, remelting and fusion of the particles in the surface of cast alloys ACAlSi9Cu and ACAlSi9Cu4. For the purpose of testing the structure of the obtained surface layers the test methods making use of the light microscopy method supported with computer image analysis, transmission and scanning electron microscopy, X-ray analysis, X-ray microanalysis, as well as methods for testing the mechanical and usable properties have been used.

Practical implications: What is more, development of the technology of surface refinement of cast alloys Al-Si-Cu with the laser fusion methods will allow for complex solving of the problem related to enhancement of the surface layer properties, taking into account both economic and ecological aspects.

Originality/value: On the basis of the test result analysis it has been pointed out that in case of the analysed aluminium cast alloys the applied laser surface processing, and the thermal processing preceding it, ensuring occurrence of the mechanisms responsible for material strengthening, enable enhancement of the mechanical and usable properties of the examined alloys. An essential objective is also to indicate the multiple possibilities for continuation of the tests, regarding the light metal alloys aluminium, magnesium and titanium, broadening the current knowledge within the scope of elements and light structures.

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

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1. Introduction

While analysing the given element in terms of its internal structure as well as possible, future working conditions it should be remembered that the product properties depend mainly on two factors: internal structure of the material, from which it has been made and on the condition of the external surface having both direct mechanical and chemical contact with the environment, including inter alia with the tools processing the given element, as well as during exploitation with the surfaces of other co-operating elements. The character of the surface, its morphology and properties often have direct impact on the product manufacturing, and in the most cases the surface quality decides just on its functional qualities. The surface layer of the material is characterised not only by its shape, roughness and appearance (colour, transparency), but also by a number of other properties that are completely different from the properties of the inside of the material, which in a significant manner influence the various types of mechanisms occurring around its area, i.e.: friction, fatigue, corrosion, erosion, diffusion, conductivity and determine the usability and fitness of the surface processed elements for possible uses. Despite the fact that the surface layer of the engineering materials may not be formed independently from the substrate, nevertheless the requirements set to the inside of the product are usually different from the conditions that are expected from the manufactured surfaces. Often due to economic, technological or even practical reasons it is more advantageous to select the substrate in such a way that it would conform to the general resistance assumptions anticipated for the given element, and as a next step to apply one of the techniques for its surface treatment in order to protect it against destruction or to enhance its usable properties. Therefore the material selection constitute such an important stage of design, which is often executed due to destructive processes present during the given work environment. Attention should also be paid to the fact that formation of the new materials, including also the ones with the applied coating, carries the possibility of discovering the pioneering, previously unidentified structural and wear mechanisms or specification of broader scope of the already existing mechanisms.

In relation to the current market demand for light and reliable constructions, aluminium alloys, belonging to the group of the construction materials, characterised by a number of good mechanical and usable properties, good castability and resistance to corrosion play an important role. Aluminium alloys, constituting the combination of the low density and high strength are more and more often used in situations, where reduction of the subassembly element masses is significant, desired and feasible.

Characteristics of the mentioned mechanisms and their dependency has not only cognitive significance, but also enables to specify broader methodological and application perspectives of the presented aluminium cast alloys, which has a particular importance when the necessity of manufacturing of the engineering materials and elements that are executed on their basis on the request is clearly discussed. The analysis of the test results of the mechanical and usable properties as well as tests of the structure of the surface layer of aluminium alloys after thermal and surface processing will allow for specification of the conditions of the laser surface processing of the aluminium alloys, such as the rate of scanning, laser power, used within the scope from 1.0 up to 2.2 kW, type and rate of the powder feeding, in order to produce the best possible surface layers on the surface of the processed alloys.

The highest demand for the aluminium alloys has been indicated and is still currently indicated by the automobile industry. The specific features of certain types of Al-Si alloys result in their particular fitness for strictly set applications, related to working conditions of the given elements e.g. for manufacturing of the pistons intended for internal-combustion engines and engines with high loads. Moreover, the aluminium alloys, the participation of which in the total mass of the motor vehicle presently amounts to circa 200 kg, are also used, inter alia, for the elements of the drive mechanism (pistons, transmission shafts, cylinder heads, cylinder blocks, gearboxes), elements of the body (vehicle frames and constructions, driver's cabs, bonnets, doors, seat constructions, bumpers, cargo roof guides), elements of the chassis (braking systems, hoops, axles: rear and front) and other as semi-trailers, petrol tanks or heat exchangers. An example of relatively new applications of aluminium alloys are body constructions that are entirely made of this kind of material, as e.g. spatial construction of Audi A8 body, enabling reduction of the vehicle mass by 40% in relation to the traditional frame made of steel [95]. In addition, 125 kg of the sheet metal, 70 kg of bars, 150 kg of casts and 40 kg of other aluminium forms accrue to the mass amounting to 385 kg of elements made of aluminium alloys used in the given vehicle. The priority goal of nearly all the companies, global consortiums and research centres along with the leading companies from China, USA and Europe is at present set to radically reduce emissions of the carbon oxide in the atmosphere, and what follows, to aim at reduction of the mass of construction and elements with simultaneous preservation or enhancement of their present properties. The need for reduction of the basic mass of the vehicles becomes so much more significant, that more and more transportation means are equipped with the so-called additional accessories (such as airbags, additional seatbelts, power window systems, etc.) increasing their mass, which aims not only at improvement of the traffic safety, but also at enhancement of the usable attractiveness of such vehicles. Every kilogram of Al (2.7 g/cm3) substituting around 3 kg of steel (7.86 g/cm3), in the entire vehicle lifespan, makes economy amounting to approx. 20 kg CO2. Reduction of the weight of the average car size weighing 1400 kg results in reduction of the fuel consumption by 0.6 l at the distance amounting to 100 km [1]. Increased tests and multiple applications of the aluminium alloys in the constructions and other vehicle elements in the automobile industry will result in the possibility to reduce the average vehicle weight by around 300 kg, which, at average consumption of 7.2 l/100 km, gives economy in the amount of 3000 l in the entire lifespan of the given product and reduction of the exhaust fumes emissions by around 20%.

Aluminium alloys are at present one of the most frequently used construction materials of our century [2-4, 5-8], therefore it is very important to maintain high rate of the tests related to problems of the light alloys. Increasing the properties, particularly of the surface layer is however inextricably combined with application of appropriate technologies and methods for their formation. The methods making use of lasers are included within such technologies. Laser technologies play a vital role in the engineering of the surface of aluminium alloys. Lasers are type of devices that for many years have already been inextricably combined with improvement of the quality of our lives. What is more, their constant development, finding more recent forms of their applications as well as their undoubted advantages (energy efficiency, good quality of the processed elements, selectivity, ease of automation of the processes using lasers), result in the fact that they become comparable alternative to traditional processing methods, also including other surface technologies [9-15]. The advantages related to their application result in more frequent use of the laser radiation, also within the scope of surface processing.

The requirements set for the present engineering materials, also including the aluminium cast alloys, force the materials experts, designers and engineers to seek new methods for formation of the surface layers properties, due to the fact that materials have to be characterised by the required exploitation period and high resistance to corrosion. Nevertheless, in most frequent cases the economic reasons determine manufacturing and application of the new, better materials, therefore the expensive raw materials are replaced with cheaper ones after appropriate processing of their surface. The properties of the surface layer are most often obtained by means of thermal processing, thermal-chemical, thermal-mechanical and mechanical processing as well as by their mutual combinations [16-23]. With regard to the above-mentioned prerequisites, new technologies for formation of the surface layers of aluminium alloys started to be implemented, which found broad application during modification and processing of the engineering materials, ensuring the possibility of substantial increase of the mechanical and usable properties of the processed elements.

The newly-developed and currently designed techniques particularly aim at manufacturing, testing and using the surface layers with properties that are different, better than the core (substrate), they concern mainly the abrasion resistance, anti-corrosive and decorative properties. Problems of use of the new methods particularly regards enhancement of the strength properties and assurance of high resistance to chemical influence. High hardness and castability as well as high fatigue resistance and resistance to mechanical impact, and resistance to high and low (creeping and frail creeping) temperatures (including the thermal shock) and adequate thermal conductivity are mainly required from the manufactured surface layer. The above-mentioned properties depend mainly on the structure of the obtained surface layers. Recent surface engineering technologies, particularly including laser techniques and methods for application of thin coatings from hard materials, resistant to abrasive wear and corrosion should also ensure appropriate durability at low manufacturing costs.

In order to prepare the basis material for the laser techniques different kinds of supportive technologies are used, which for example aim at increasing the absorption of laser radiation of the processed aluminium surfaces, improvement of anti-corrosive and decorative properties of the surface layers of aluminium alloys.

Laser surface processing denotes mainly the laser. The types of lasers and their modifications are all different in terms of physical state of the active medium, its chemical composition, type of the used pipes, resonators, length of the light emitted and many other properties. The main aspect limiting their use is the economic issue. The laser is used in the material engineering (Fig. 1) and has to be characterised by high power, efficiency and precision of operation. Constructing of such a laser is neither easy, nor a cheap task, due to the fact that it requires application of expensive component materials, at the same time increasing final costs of the material processing with the use of the source of energy in the form of the laser. Among lasers that are most often used for processing of the engineering materials the active medium is a solid body or gas, and their main types are the following ones [15,24,25]:

- solid state lasers (crystalline (ruby), glass (neodymium),
- gas lasers (atom, molecular, ion, excimer, copper vapour lasers),
- semiconductor lasers (diode lasers),
- liquid lasers (dye, chemical),
- plasma lasers,
- free-electron lasers,
- X-ray and gamma ray lasers.

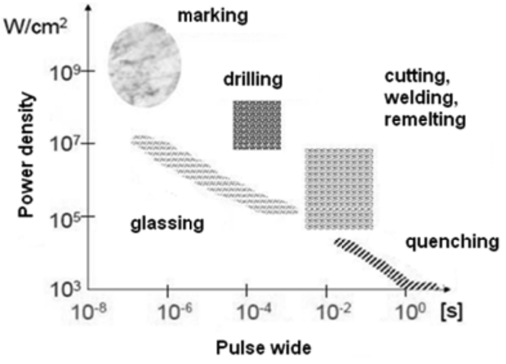

Fig. 1 Laser techniques used for material treatment [26-31]

In case of laser processing of the materials the most frequent application, as high as 37% falls to cutting of the materials, then 21% to marking, 18% to microprocessing, 16% to welding, 6% to soldering, hardening and surfacing and 2% to perforation. The main advantage of the lasers is concentration of energy amounting as much as 1030 W/cm2, such extensive power is particularly used for cutting, marking and perforation. In case of welding, soldering and surface processing power density does not exceed 106 W/cm^2. One of the most recent variants of lasers is semiconductor laser, also called diode laser, which is a specific type of device, characterised by many differences in its construction, as well as in its functioning in comparison to other types of lasers. Despite the fact that these lasers are the ones from the first lasers that have ever been discovered (O.W. Łosiew, 1927, electroluminescence phenomenon), they have been developed and modified all the time, in particular due to the possibility of miniaturisation and very precise modification of the chemical composition of the semiconductors used.

Diode lasers, also including HPDL lasers (High Power Diode Laser), due to their small dimensions and relatively low manufacturing costs (as for industrial conditions) and wide range of emitted lengths of the electromagnetic waves found application in many branches of everyday life and engineering. The lasers used for reading of data from optical drives CD, DVD, Blue-ray, pump systems for different types of lasers (e.g. Nd-YAG, fibre, disc), in stomatology and orthodontics in the treatments consisting in laser throughing and gingivectomy, shaping of the surface properties of the metal, polymer, composite, as well as ceramic materials belong to such applications.

Diode lasers are characterised by rectangular or linear shape of the beam focus with multimodal distribution of energy, they are stable and easy to control. Lack of complex optical systems causing substantial losses of energy from 10 up to 30%, high-energy efficiency reaching 50% and ease of robotisation of the manufacturing technology may also be included to consecutive advantages of HDPL laser. At the same time it is reliable, which makes it a very attractive tool in surface engineering. Uniform distribution of the laser beam focus on the surface of the processed materials and possibility to generate lower power density of the beam by HPDL lasers in comparison to other lasers are the basic advantages in favour of the semiconductor lasers in application of the material engineering. The above-mentioned advantages result in the fact that HPDL lasers are frequently used for modification of the surface layers of the engineering materials [32].

There are many possibilities of application of the semiconductor lasers in the material engineering, inter alia for cleaning the surfaces, soldering, welding, remelting (Fig. 2). Among the main techniques that are used for surface processing of the engineering materials with the use of diode laser the following ones may be included: remelting, alloying and/or fusion and surfacing. One of the most developing and innovative applications with the use of the diode laser is surface processing and particularly laser fusion and remelting of the light alloys.

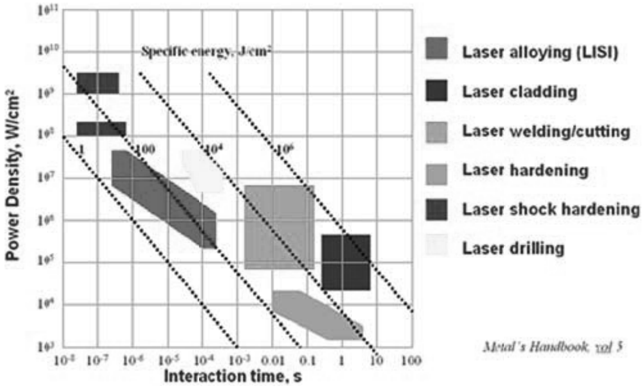

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Fig. 2 Classification of laser surface treatment,(according to Surface Treatment Technologies, Inc)

The majority of lasers used in the material processing make use of absorption of the focused radiation through various non-transparent materials. The radiant flux while falling on the surface of such a material is often subject to partial reflection and partial absorption. The amount of heat absorbed by the material at the place of falling of the beam depends on the laser radiation wave-length, power density of the radiation falling on the surface, time of influencing the material by the beam and radiation absorption coefficient. Laser radiation enables to realise the presently known technologies, as for example hardening, in a better or quicker way, or introduce new technologies, e.g. laser fusion, impossible to be realised with the use of the devices with lower power density [32,33].

Four basic methods for laser surface processing can be differentiated: remelting, alloying, fusion and surfacing.

- Remelting consists in melting of the material by energy of laser beam radiation without using additional materials. This method allows for substantial modification of the crystalline structure in the surface layer of the materials by means of formation of chemically uniform and fine-crystalline surface layer with no modification of the chemical composition as a result of total melting of the processed material and, as a consequence, enables to achieve high resistance to abrasion, erosion and corrosion.
- Laser alloying consists in introduction of the alloying elements to the material being subject to processing by means of hydrodynamic mixing of both materials. A necessary condition is the fact that at least one of these materials is in a liquid state. The laser beam affecting the material causes its melting and formation of a pool, in which, as a result of gravitational movements, convections and pressure of the laser beam the materials mix with each other and a new layer of material is formed at the periphery of the pool. Alloying of the body in the solid state depends mainly on the temperature gradient, gradient of the concentration of the diffusing element, as well as on the time of diffusion [9,12-15].
- Fusion is a one-stage method, which aims at achievement of a surface layer in the form of a quasi-composite or improvement of the properties of the layer of the alloyed material. Fusion is realised by means of continuous-operation lasers, due to the fact that the strengthening material may be fed to the melted zone only at the moment of laser heating, fusion is not performed during the breaks between the heat impulses.
- During melting (surfacing) additional material is melted in the form of the powder or wire by means of energy of the laser beam radiation in the gas shield. Argon or a mixture of argon and hydrogen is most often used as a shielding gas and at the same time as a gas for feeding the powder to the surfacing area. Gas lasers CO_2, continuous Nd:YAG lasers and HPDL lasers are most frequently used for laser surfacing. High power density (up to 10^7 W/cm^2) enable very precise heating and melting, allowing for practical evaporation of all the known construction materials [34-37, 29-32].

The works related to technologies for modification of the surface layer of materials, including light metal alloys, with the use of HPDL laser, are substantial at a global scale. The rate of development of technology and laser devices at the global industry increases systematically, therefore it is very important to maintain high rate of research over this problems and to point out new research areas (Fig. 3).

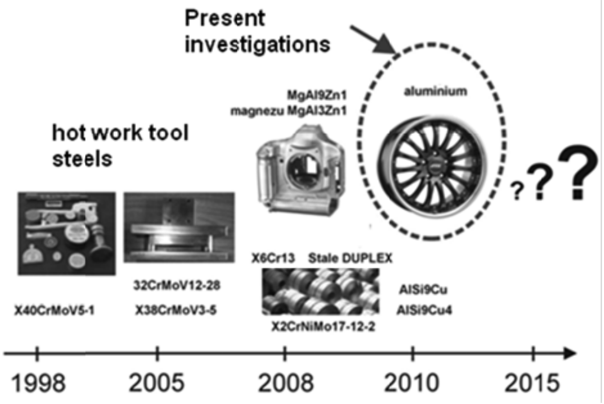


Fig. 3. Time axis presenting the “mile stones” of laser surface treatment development in relations to the applied substrate material

2. Material vel. investigations

The presented test results concern experimental aluminium alloys AlSi9Cu and AlSi9Cu4 with the chemical composition given in the Table 1. As a reinforcing material carbon powders have been used (Figs. 5-8).

The tested alloys have been melted in the induction furnace with ceramic mixing the basic components at proper ratios: aluminium cast alloys with silicon, two-component basic alloy AlSi49 and two-component alloy AlCu55. After melting of the basic components the alloy has been heated to the temperature of 850±10 ºC, and then kept in this temperature for 2 hours. Melting and heating of the alloy has been made in the protective atmosphere of argon for limitation of the diffusion of hydrogen, oxygen and nitrogen from the atmosphere. Immediately before pouring the ingots intended for the tests every melted material has been additionally subject to carbonisation by mean s of argon.

The samples have been poured with constant, continuous stream to the entire volume of the ingot. From each melted material 3 ingots have been made with an average mass of 15 kg, which have been subject to thermal and mechanical treatment. The standard thermal processing of the aluminium alloys has been used in the electric resistant furnace U117, with heating rate 5°C/min, along to the established scheme (Fig. 4).

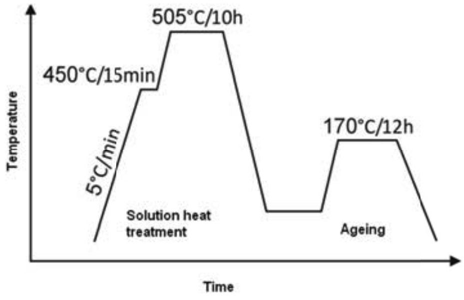


Fig. 4. Scheme of the heat treatment of the investigated aluminium alloys

During heating isothermal break has been used at the temperature of 450°C for 15 minutes. After solution heat treatment quenching at water has been used, whereas after ageing the material has been quenched on air at the room temperature. The withstand temperature amounted respectively for solution heat treat 505°C for 10 hours, and for the subsequent ageing 170°C for 12 hours (Table 2). Alloys after the thermal treatment constituted a reference point in relation to the alloys that have been surface processed.

Aluminium cast alloys AlSi9Cu and AlSi9Cu4 (Figs. 9-12) are characterised by the structure of the solid solution α constituting the matrix and discontinuous phase β-Si forming eutectic grains $\alpha+\beta$, which morphology depends on the mass concentration of silicon and copper. It has been proved that in the alloys AlSi9Cu and AlSi9Cu4 a phase β-Si occurs in the form of large irregular plates with sharp-edge corners located in the matrix at high distance in relation to each other in a disorganised manner. What is more, the structure of the tested alloys is characterised by occurrence of acerous formations of the phase Al_5FeSi, which are usually located near eutectics $\alpha+Al_2Cu+AlCuMgSi+\beta$, which eutectics may additionally include the phase with ferrum and manganese, presumably $Al_{15}(FeMn)_3Si_2$. In the tested cast alloys Al-Si-Cu the phase Al_2Cu occurs as a component of triple eutectics and as separate formations of irregular shapes, which with the used reagents dyes brown.

The target laser fusion and remelting has been executed by means of the technique of feeding the powder at rate within the range 1-10 g/min in a continuous manner to the area of the pool of the melted metal by means of dosing the granulate with the use of the fluidisation or gravitational feeder. The powder feeder has been connected to the transporting gas cylinder and powder-feeding nozzle. Fusion has been made in the argon shield, in order to protect the substrate against oxidising. The surface processing of laser fusion has been made so as to improve the usable properties of the tested alloys, ceramic powders WC, SiC, Al_2O_3 and ZrO_2 with the properties given in the Table 3 have been used as alloying material.

Table 1.
Chemical composition of the analysed aluminium alloys

Alloy	Mass concentration of the alloying elements in the investigated alloys in %							
	Si	Cu	Fe	Mn	Mg	Zn	Al	Rest
ACAlSi9Cu	9.09	1.05	0.72	0.36	0.27	0.14	88.17	0.15
ACAlSi9Cu4	9.27	4.64	0.17	0.01	0.28	0.05	85.4	0.18

Table 2.
Heat treatment conditions for the investigated aluminium alloys

Description of the heat treatment step	Heat treatment conditions		
	Temperature, °C	Time, h	Cooling type
Solution heat treatment	505	10	water
ageing	170	12	Air (temperature of the environment)

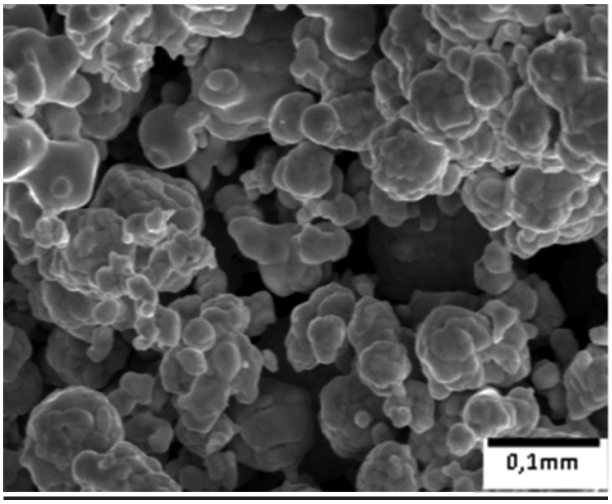


Fig. 5. Surface morphology of the tungsten carbide powder (SEM)

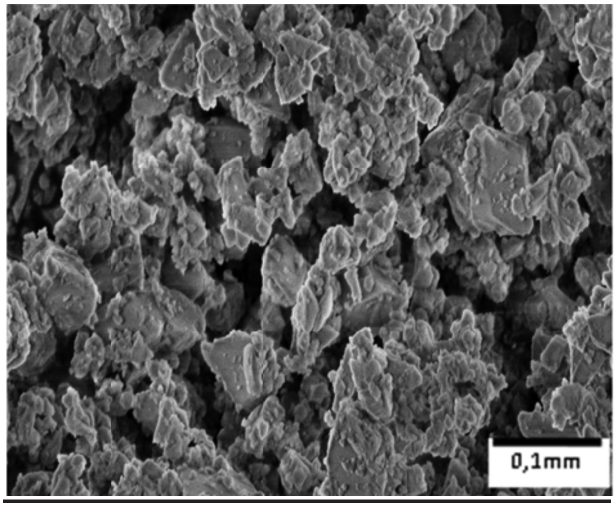


Fig. 6. Surface morphology of the silicon carbide powder (SEM)

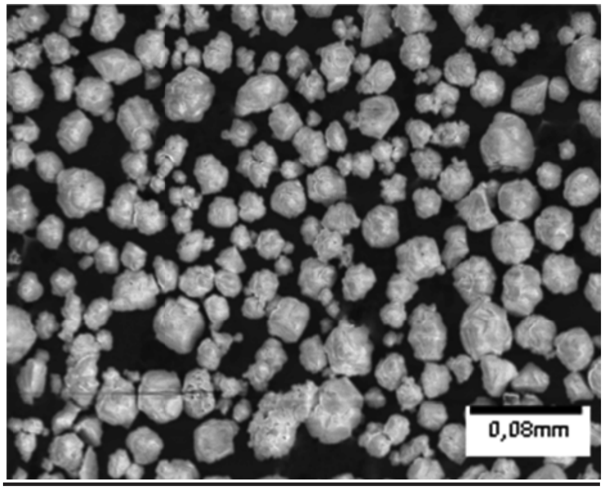


Fig. 7. Surface morphology of the aluminium oxide powder (SEM)

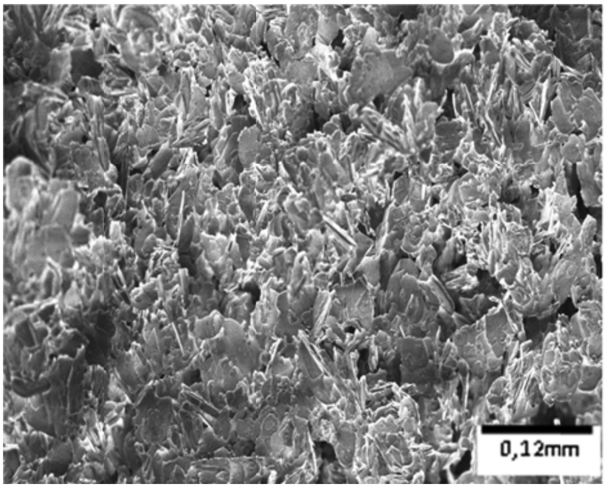


Fig. 8. Surface morphology of the circonium oxide powder (SEM)

In case of directing too excessive blow of the protective gas in the melted area, blowing of the liquid metal pool took place and as a consequence of achievement of the remelting face with very irregular shapes, with characteristic new layers of the liquid metal at the sides of the stitch, which automatically eliminated the executed samples for further stage of tests. Therefore within the scope of the experiments adequate distance of the nozzle from the surface of the sample has been selected, amounting to 20 mm. With regard to the above-mentioned assumptions and continuity of feeding the additional material to the liquid pool, the minimum amount of flow of the carrier has been experimentally established to 3 l/s. On the basis of the preliminary tests it has also been proved that the shape of the applied nozzle has a substantial impact on the correct fusion of particles of the ceramic powders.

Based on the visual inspection of the macro structure of melting of the surface layer the optimum values of the laser power for the substrate material of the aluminium alloy AlSi9Cu4 have been established within the range from 1.0 kW up to 2.0 kW, and adequate rate of fusion and remelting of the surface layer of the tested aluminium alloys (Figs. 9-12) within the range from 0.5 m/min up to 1.0 m/min. It has been stated that the optimum rate of remelting and fusion amounts to 0.5 m/min, therefore after preliminary trial runs the laser power within the range 1.5-2.0 kW and the rate of powder fusion 0.5 m/min have been adopted for the tests. The increase of the rate of fusion causes reduction of the time, during which the laser beam influences the material, and at the same time results in limitation of the amount of energy absorbed by the substrate and as a consequence leads to limitation of the extent of the structural changes. Using too high laser power and too low scanning rate causes evaporation of the surface and formation of craters, whereas using too low power and too high fusion rate may be the reason for inadequate remelting characterised by inhomogeneous distribution of the particles fused in the matrix of the aluminium cast alloys Al-Si-Cu, or may result in lack of interfusion.

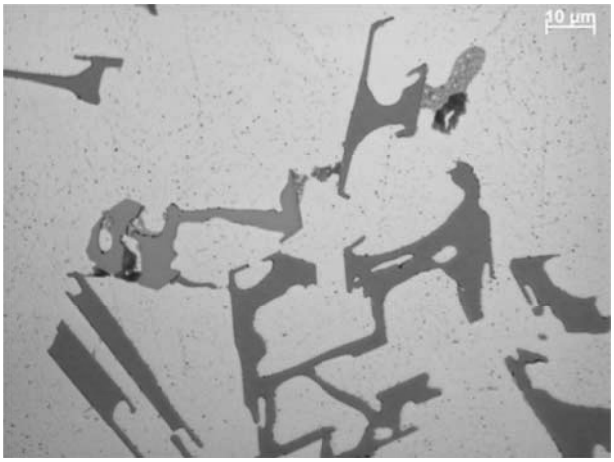


Fig. 9. Microstructure of the cast aluminium alloy AlSi9Cu in as cast state

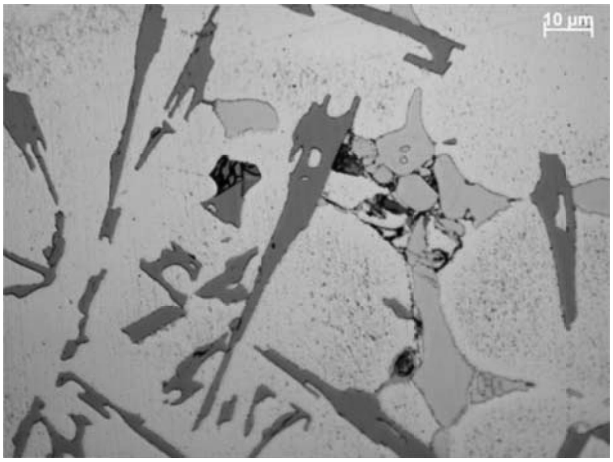


Fig. 10. Microstructure of the cast aluminium alloy AlSi9Cu4 in as cast state

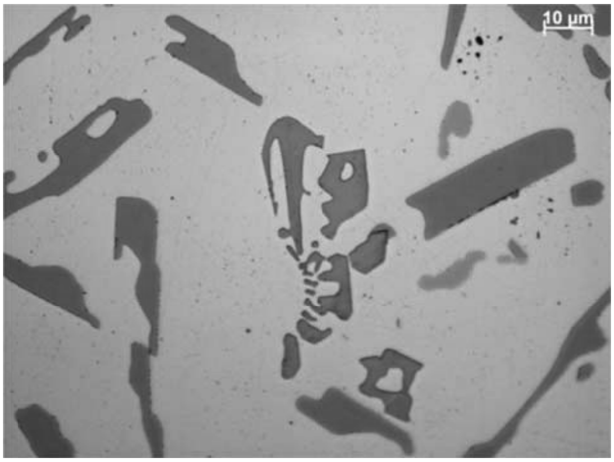


Fig. 11. Microstructure of the cast aluminium alloy AlSi9Cu after ageing

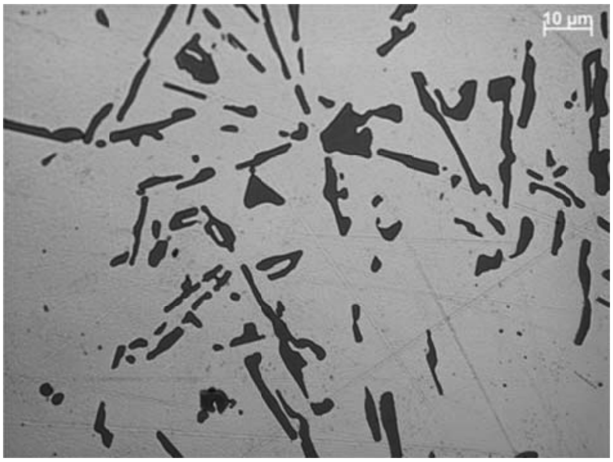


Fig. 12. Microstructure of the cast aluminium alloy AlSi9Cu4 after ageing

Table 3. Properties of the ceramic powders used for feeding

Properties	WC	ZrO_2	SiC	Al_2O_3
Density, g/cm^3	15.69	5.68	3.44	3.97
Hardness HV, Kg/mm^2	2400	1100	2800	2300
Melting temperature, °C	2870	2715	Decomposition in 2700	2047
Boiling temperature, °C	6000	4300	sublimation	2977
Radiation refraction coefficient, n_D	3.19	2.13	2.55	1.76
Thermal transmition, Wm^{-1}K^{-1}	84	2	120	30
Crystallographic structure, unit cell	heksagonal regular	monocrlinic tetragonal, gularna	regular	trigonal
Colour	black	white	gray	white

In particular realisation of the described problematics is related to laser processing of the product surfaces for the purpose of development of quasi-composite surface layer of the cast alloys Al-Si-Cu by means of fusion with the use of HPDL laser in the surface of the aluminium elements of fine particles and fast micro-nanocrystallisation is related to presentation of the results of the following tests regarding:

- specification of the parameters for manufacturing of the surface layers,
- selection of the ceramic powders used for fusion, conforming to the imposed requirements,
- preliminary specification of the structure of the developed surface layers in relation to the applied technological parameters with the use of the method of scanning microscopy with EDS attachments, X-ray analysis,
- determination of the mechanical and usable properties, particularly hardness and roughness,
- complex tests of the structure of the developed laser surface layers with the use of the light microscopy methods, scanning electron microscopy, X-ray analysis and EDS spectroscopy,
- tests of the transformation zone and the connection zone between the core and the surface layer made by the laser with the use of the methods of scanning electron microscopy, EDS spectroscopy and X-ray microanalysis,
- tests of the usable and exploitation properties, in particular of the resistance to tribological wear and resistance to electrochemical corrosion in three-electrode chamber in the classified corroding mediums, in relation to the platinum and calomel electrode.

3. Analysis of the results

Due to the occurrence of the high temperature gradient on the border of the melted surface layer and the substrate, rapid quenching and solidification of the liquid metal takes place. Due to properties of the laser beam depth of the partial melting of the substrate's metal may be adjusted with high precision, at the same time ensuring achievement of properties of the surface layers with the desired chemical composition and adjusted participation of the specific structural components. It is also possible to obtain the metal layers e.g. with nanocrystalline structure, layers including hard intermetallic phases in the soft metal matrix, cermetal and ceramic layers with very high hardness, resistance to corrosion, scaling and abrasive wear. Occurrence of homogeneity and uniformity of distribution of all the phases along the entire thickness is a characteristic feature of a well-formed layer, apart from the presence of a very thin layer of diffusion saturation. After solidification a layer with a different chemical composition, structure and properties in comparison to the initial material is formed. Properties of the surface layer depend on the substrate, fusion material and fusion parameters, however the obtained surface layer almost always rich with fusion particles is distinguished by hardness and fatigue strength higher than the substrate, better tribological and anticorrosive properties, with a simultaneous increase of roughness. As a result, processing on the elements is frequently made after fusion, aiming at smoothing of the surface. Impact of the ceramic powders introduced into matrix may result in occurrence of the dispersion strengthening, nevertheless depending on the size of the alloying material introduced to the matrix of the metal material. Formation of the surface layer by means of a laser fusion method of ceramic powders on the surface of the described aluminium cast alloys with silicon with the use of the HPDL laser aimed at increase of the usable properties of the surface layer made of this group of the light alloys, that is: hardness and abrasion resistance.

Metallographic analysis of the cross-sections of the samples from aluminium alloys in the surfaces of which ceramic powders WC, SiC, Al_2O_3 and ZrO_2 have been subject to fusion with the use of laser 1.5 kW and 2.0 kW confirms occurrence of the characteristic type of topography of the surface of the samples for every one applied for fusion of the ceramic powder, as well as clear influence of the laser power on the shape of the face of the stitch (Figs. 13-16). The surface layer of the aluminium alloys melted by means of laser, without the use of the ceramic powder indicates more regular and flat shape of the melting area in comparison to the surface layer obtained after fusion of the ceramic powders, in case of which typical fluctuations of the additional material on the surface of the sample have been observed. Such types of fluctuations are caused by the change of the surface tensions, as well as absorption of the laser radiation energy by the powder used during laser processing, which in turn has a substantial impact on increase of roughness on the surface of the samples.

Analysis of the results of the structural tests carried out in high-resolution scanning electron microscope of the laser processed aluminium alloys AlSi9Cu and AlSi9Cu4 with ceramic powders WC, SiC, Al_2O_3 and ZrO_2 confirmed occurrence of the melted zone with visible dendrite structure for all the used ceramic powders (Figs. 13-16). The zone character of the obtained surface layer is also recognisable for this type of technology, which is also confirmed by the structural tests, for the selected group of powders, composed by: melted zone, heat impact zone and transformation zone combining the heat impact zone with the substrate material. After laser fusion of the surface layer of aluminium alloys AlSi9Cu and AlSi9Cu4 with ceramic powder of aluminium oxide Al_2O_3 (Fig. 13) occurrence of the solid burnt surface layer of aluminium oxide and lack of presence of the particles of the powder used in the melted zone for the entire scope of the used laser power has been revealed. Increase of the amount of the fed powder from 4.0 g/min even up to 6.0 g/min did not ensure fusion of Al_2O_3 powder to the matrix, increase of thickness of the obtained surface layer of aluminium oxide has only been confirmed (Fig. 17). However the formed layers of the aluminium oxide indicate substantial unevenness, they are folded, and the visual cracks attest to high fragility of the obtained layer. The surface layer visible on the drawings 21-28, formed during fusion of the powder Al_2O_3, most probably consisting in amorphous phase of the aluminium oxide may also be classified as a coating, due to the fact that the performed tests so far have not provided evidence for fusion of the powder Al_2O_3 in the aluminium matrix. Testing of the transformation zone between the formed amorphous coating and the aluminium substrate also constitutes an essential aspect, so that it would be possible to specify, whether the amorphous coating is strictly separated from the substrate, or if the zone of fusion of the discussed coating in the substrate Al occurs.

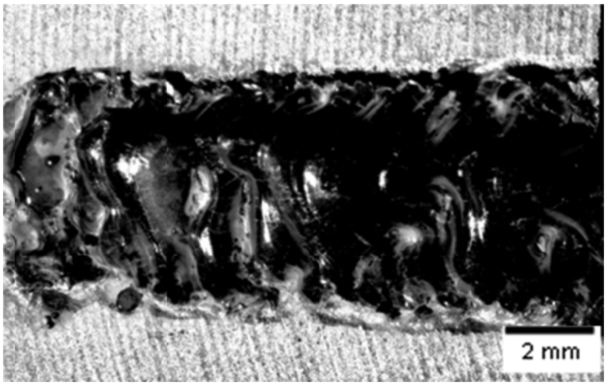


Fig. 13. Surface structure after feeding of the powder Al_2O_3 into the surface layer of the AlSi9Cu, laser power 2.0 kW, 1g/min, scan rate 0.5 m/min

Fig. 14. Surface structure after feeding of the powder ZrO_2 into the surface layer of the AlSi9Cu, laser power 2.0 kW, 8.0 g/min, scan rate 0.25 m/min

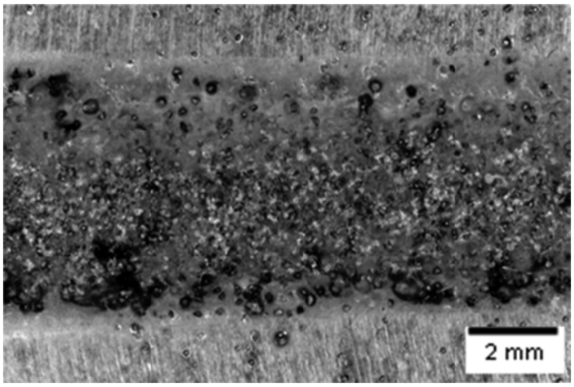


Fig. 15. Surface structure after feeding of the powder WC into the surface layer of the AlSi9Cu, laser power 1,5 kW, 1.5g/min, scan rate 0.25 m/min

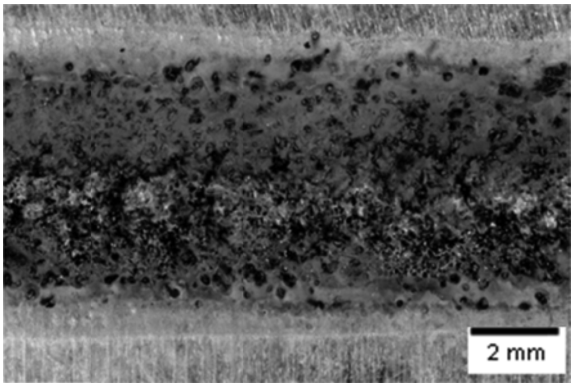


Fig. 16. Surface structure after feeding of the powder SiC into the surface layer of the AlSi9Cu, laser power 1.5 kW, 1.5 g/min, scan rate 0.25 m/min

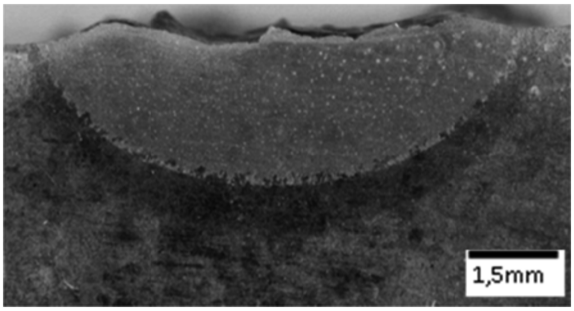


Fig. 17. Surface structure after feeding of the powder Al_2O_3, alloy AlSi9Cu, laser power 2.0 kW1g/min, scan rate 0.5 m/min

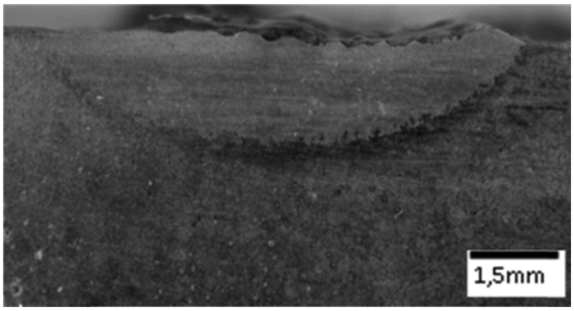


Fig. 18. Surface structure after feeding of the powder ZrO_2, alloy AlSi9Cu, laser power 2.0 kW, 8.0 g/min, scan rate 0.25 m/min

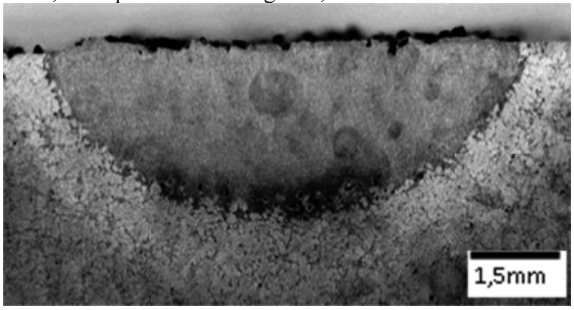


Fig. 19. Surface structure after feeding of the powder WC, alloy AlSi9Cu, laser power 1.5 kW, 1.5g/min, scan rate 0.25 m/min

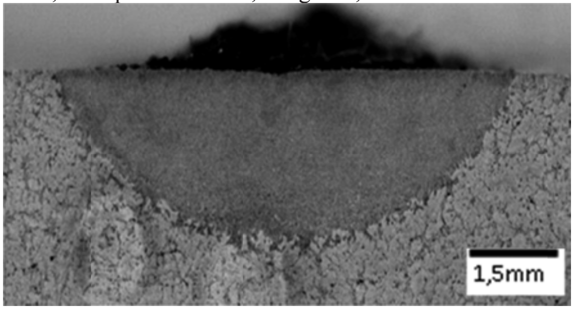


Fig. 20. Surface structure after feeding of the powder SiC, alloy AlSi9Cu, laser power 1.5 kW, 1.5 g/min, scan rate 0.25 m/min

Analysis of the surface layers obtained as a result of fusion with the use of powder of the zirconium oxide ZrO_2 indicated melted character similar to interfusions obtained for the used powder of aluminium oxide, indicating occurrence of the burnt surface layer with no presence of the particles of the alloying material in the melted zone. Increase of the amount of the fed powder in the range up to do 8g/min (Fig. 18) did not ensure achievement of the expected structure of the surface layer with visible fusion of the particles in the melted zone. The formed surface layer of ZrO_2 is folded with irregular thickness, however as opposed to the layer obtained after fusion of the powder Al_2O_3, no cracks or defects have been in its structure. For the purpose of testing of the possibility of fusion of the powder of zirconium oxide to the matrix of the tested aluminium alloys, fusion has been executed by means of maximum amount of the powder fed in the amount of 10 g/min, nevertheless also in this case presence of the powder in the matrix has not been discovered, and most importantly, occurrence of the melted zone has not been stated, due to significant absorption of laser radiation by the phase ZrO_2.

It should be emphasised that the surface layers formed on the surface of the tested alloys, with participation of the aluminium and zirconium oxides, due to their specific nature of solid burnt surface layer may also be classified as certain type of quasi coating. Difficulty in description of the character of this type of formed surface layers results from the fact that there is lack of explicit evidence specifying the nature of connection between the substrate and the formed surface layer. However it should be evidently emphasised that the formed quasi coating in few cases is clearly separated from the substrate, which is confirmed by the structural tests carried out in the scanning microscope (Figs. 21, 29, 30), as well as it is morphologically connected to the melted zone of the substrate material (Figs. 24, 26).

Similar analogy, consisting in achievement of the burnt surface layer in the fused material has not been observed in case of laser processing with the use of WC powder (Figs. 31-34). Both for the amount of the fed powder amounting to 1.5 g/min and 3.0 g/min the presence of WC particles has been stated in the matrix of the melted alloy, however the distribution of the strengthening material in the matrix limits only to the upper and lower zone of the melted layer, where the used WC powder falls gravitationally during fusion (Figs. 31, 32, 41, Tables 4, 5). While establishing the laser power value during laser fusion per 1.5 kW and the amount of the fed powder per 1.5 g/min, then the optimum distribution of the fused WC powder into the structure of the surface layer has been obtained, at the same time avoiding occurrence of the central zone of the formed layer not filled with the powder. For the purpose of obtaining of the uniform distribution of the fused powder and filling of the entire area of the melted zone the attempts have been made to increase the amount of the powder fed to the value of 4.0 g/min, 6.0 g/min and 8.0 g/min, stating that for the amount of the powder fed constituting 4.0 g/min and 6.0 g/min an increase of the depth of the melted zone occurs in turn with no improvement of the dispersion of the WC powder in the matrix. In case of maximum value of the fed powder amounting to 8.0 g/min, occurrence of new layers and substantial irregularity of the surface of the stitch has been stated, which is caused by the excessive amount of energy absorbed by the WC powder, as a result of which violent thermal reaction in the melted metal pool takes place, causing occurrence of the substantial irregularity of the obtained surface layer after solidification of the melted metal. Whereas increase of the laser power up to 2.0 kW at the amount of the fed powder from 6 up to 8 g/min caused disintegration of the WC particles (Figs. 33, 34), therefore further increase of the laser power turned to be unjustified due to the nature of the structural changes of the ceramic powder fused, which could influence reduction of its mechanical properties.

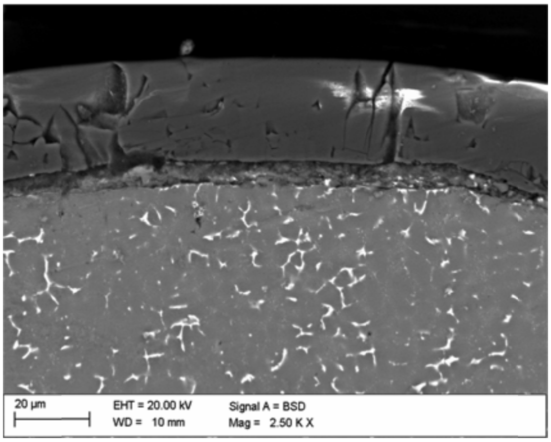


Fig. 21. Surface layer of the AlSi9Cu4 alloy after feeding of the Al_2O_3 powder , laser power 1,5 kW, 1g/min, scan rate 0,5 m/min

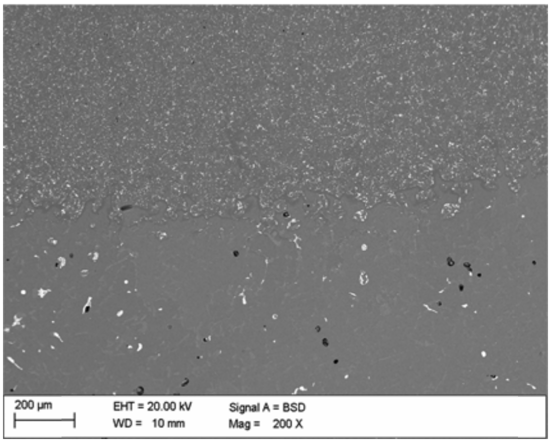


Fig. 22. Surface layer of the AlSi9Cu4 alloy after feeding of the Al_2O_3 powder, laser power 2.0 kW, 1g/min, scan rate 0.5 m/min

Similar character of the structure of the surface layer as in the case of fusion of the WC powder has also been stated after application of the SiC powder, confirming occurrence of the powder in the matrix in the entire scope of the melted zone. In case of the SiC powder the optimum distribution of the powder melted in the matrix of the surface layer has been obtained with the following fusion parameters used: laser power 2.0 kW, and amount of the powder fed 1.5 g/min, (Figs. 35-36).

Analogical to the WC powder, an increase of the amount of the fused powder fed to 2.0 g/min with the laser power 2.0 kW caused formation of the characteristic new layers and agglomerates on the surface of the melted area, including particles of the SiC powder (Fig. 39), with a simultaneous lack of presence of the powder in the material matrix (Fig. 40). In such a case an essential role is played by proper ability of absorption of the laser radiation, which in the case of Al_2O_3 and ZrO_2 powder causes formation and burning of these materials into irregular coating.

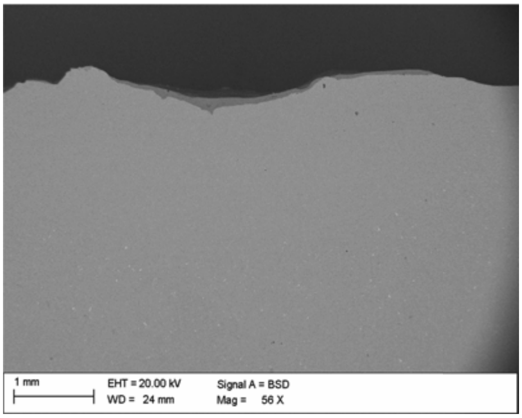


Fig. 23. Surface layer of the AlSi9Cu alloy after feeding of the Al_2O_3 powder, laser power 2.0 kW, 1 g/min, scan rate 0.5 m/min

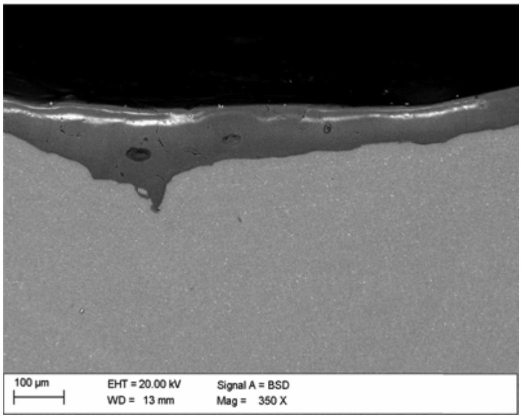


Fig. 24. Surface layer of the AlSi9Cu alloy after feeding of the Al_2O_3 powder, laser power 2.0 kW, 1 g/min, scan rate 0.5 m/min

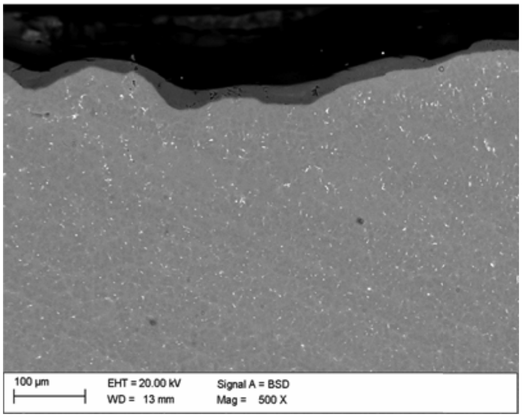


Fig. 25. Surface layer of the AlSi9Cu alloy after feeding of the Al_2O_3 powder, laser power 1.5 kW, 1 g/min, scan rate 0.5 m/mi

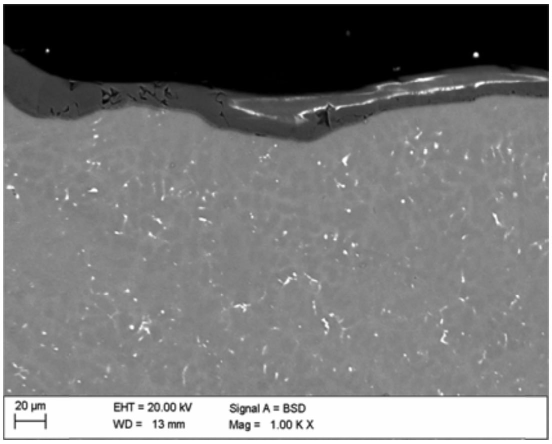


Fig. 26. Surface layer of the AlSi9Cu alloy after feeding of the Al_2O_3 powder, laser power 1.5 kW, 1 g/min, scan rate 0.5 m/min

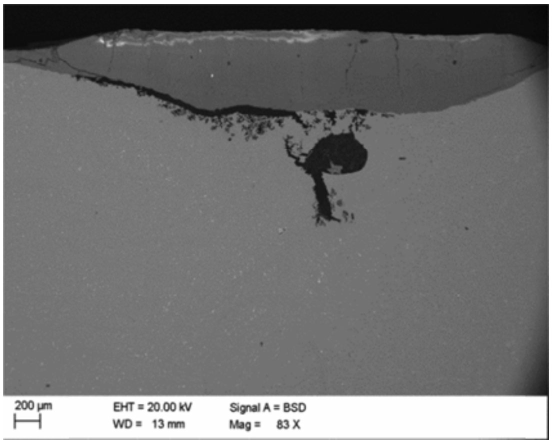


Fig. 27. Surface layer of the AlSi9Cu alloy after feeding of the Al_2O_3 powder, laser power 2.0 kW, 4 g/min, scan rate 0.5 m/min

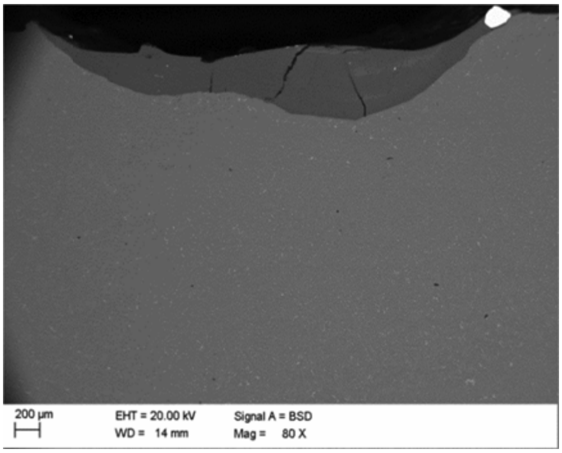


Fig. 28. Surface layer of the AlSi9Cu alloy after feeding of the Al_2O_3 powder, laser power 2.0 kW, 6 g/min, scan rate 0.5 m/min

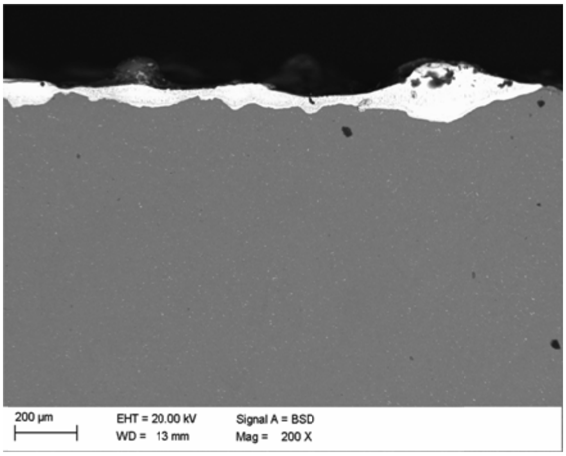


Fig. 29. Surface layer of the AlSi9Cu4 after feeding of the ZrO_2 powder, laser power 2.0 kW, 8.0 g/min, scan rate 0.25 m/min

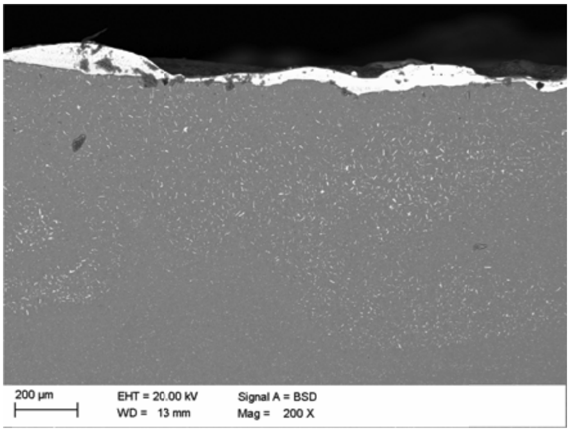


Fig. 30. Surface layer of the AlSi9Cu4 after feeding of the ZrO_2 powder, laser power 2.0 kW, 10.0 g/min, scan rate 0.25 m/min

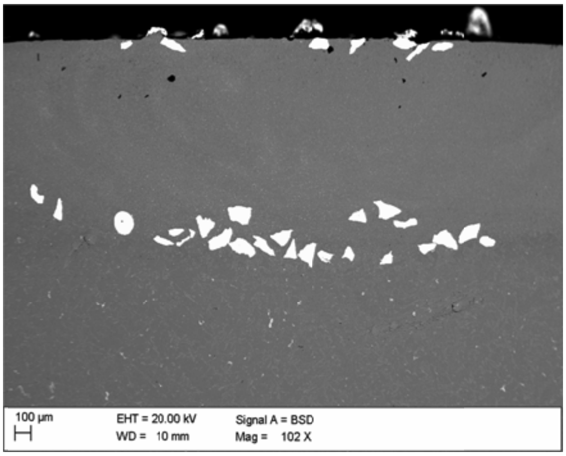


Fig. 31. Surface layer of the AlSi9Cu alloy after feeding of the WC powder, laser power 2.0 kW, 1.5 g/min, scan rate 0.25 m/min

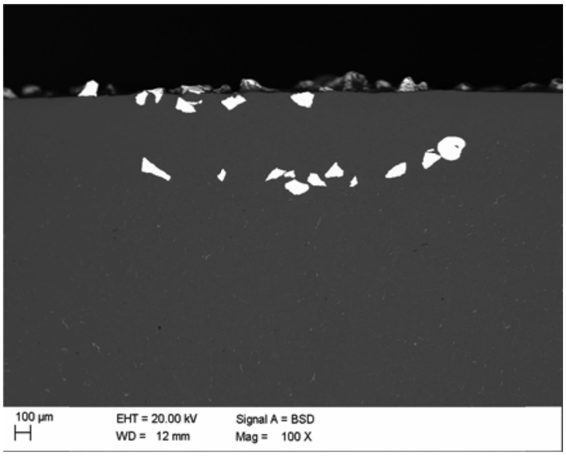


Fig. 32. Surface layer of the AlSi9Cu alloy after feeding of the WC powder, laser power 1.5 kW, 1.5 g/min, scan rate 0.25 m/min

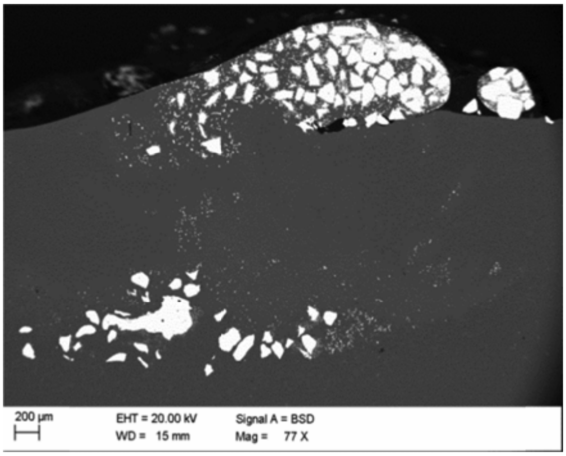


Fig. 33. Surface layer of the AlSi9Cu alloy after feeding of the WC powder, laser power 2.0 kW, 8.0 g/min, scan rate 0.25 m/min

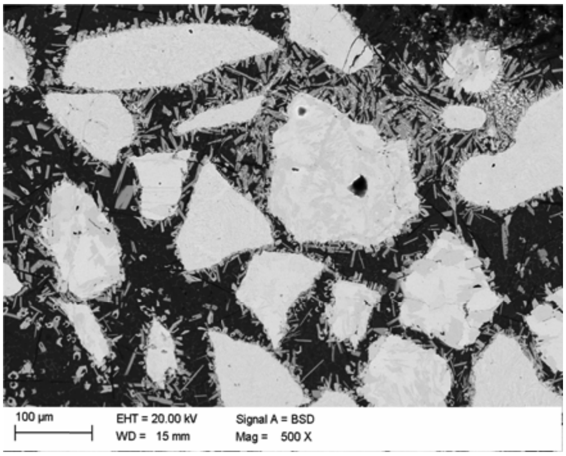


Fig. 34. Surface layer of the AlSi9Cu alloy after feeding of the WC powder, laser power 2.0 kW, 8.0 g/min, scan rate 0.25 m/min

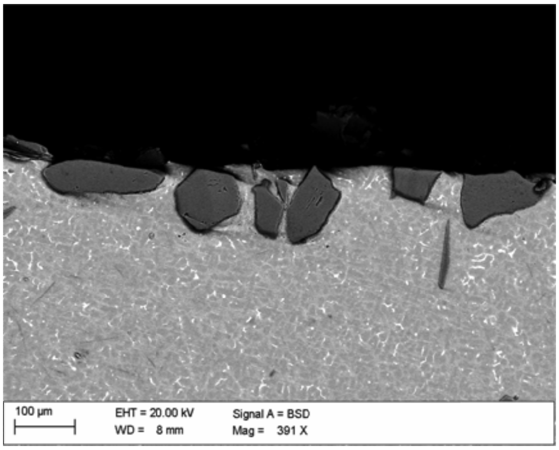


Fig. 35. Surface layer of the AlSi9Cu4 after feeding of the SiC powder, laser power 2.0 kW, 1.2 g/min, scan rate 0.25 m/min

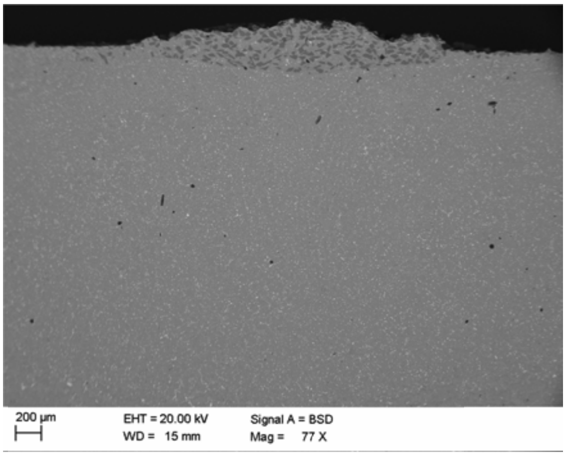


Fig. 36. Surface layer of the AlSi9Cu4 after feeding of the SiC powder, laser power 2.0 kW, 1.5 g/min, scan rate 0.25 m/min

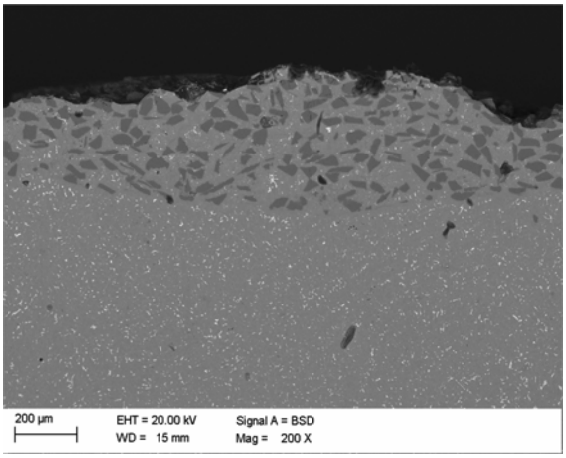


Fig. 37. Surface layer of the AlSi9Cu4 after feeding of the SiC powder, laser power 2.0 kW, 1.5 g/min, scan rate 0.25 m/min

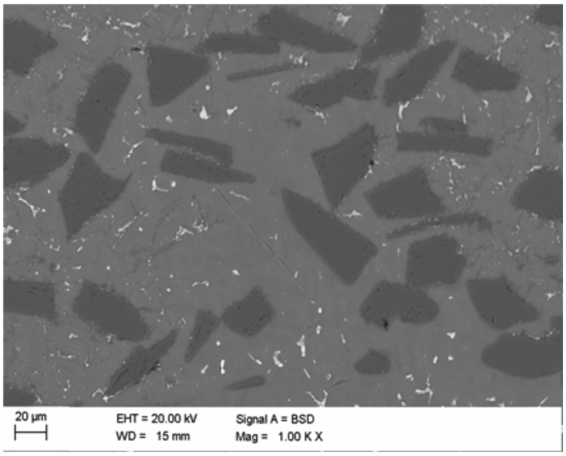


Fig. 38. Surface layer of the AlSi9Cu4 after feeding of the SiC powder, laser power 2.0 kW, 1.5 g/min, scan rate 0.25 m/min

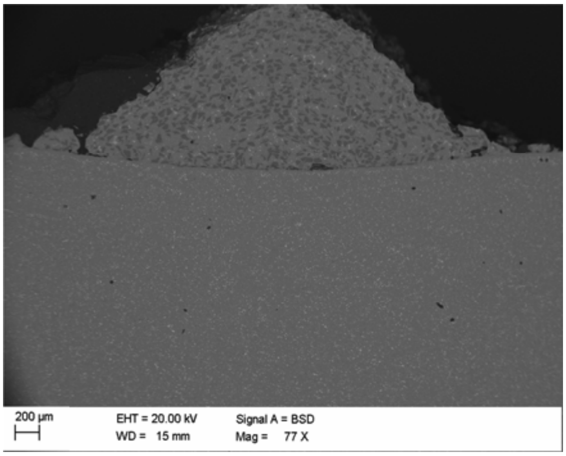


Fig. 39. Surface layer of the AlSi9Cu4 after feeding of the SiC powder, laser power 2.0 kW, 2.0 g/min, scan rate 0.25 m/min

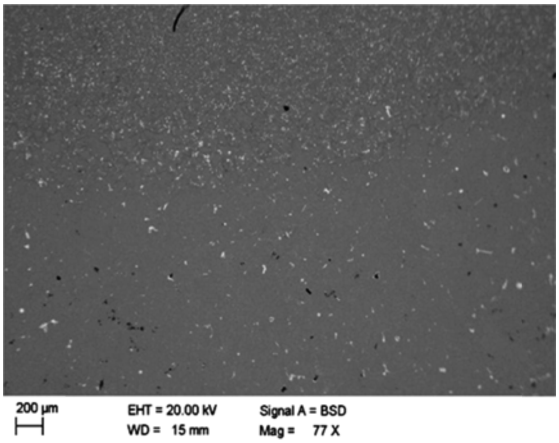
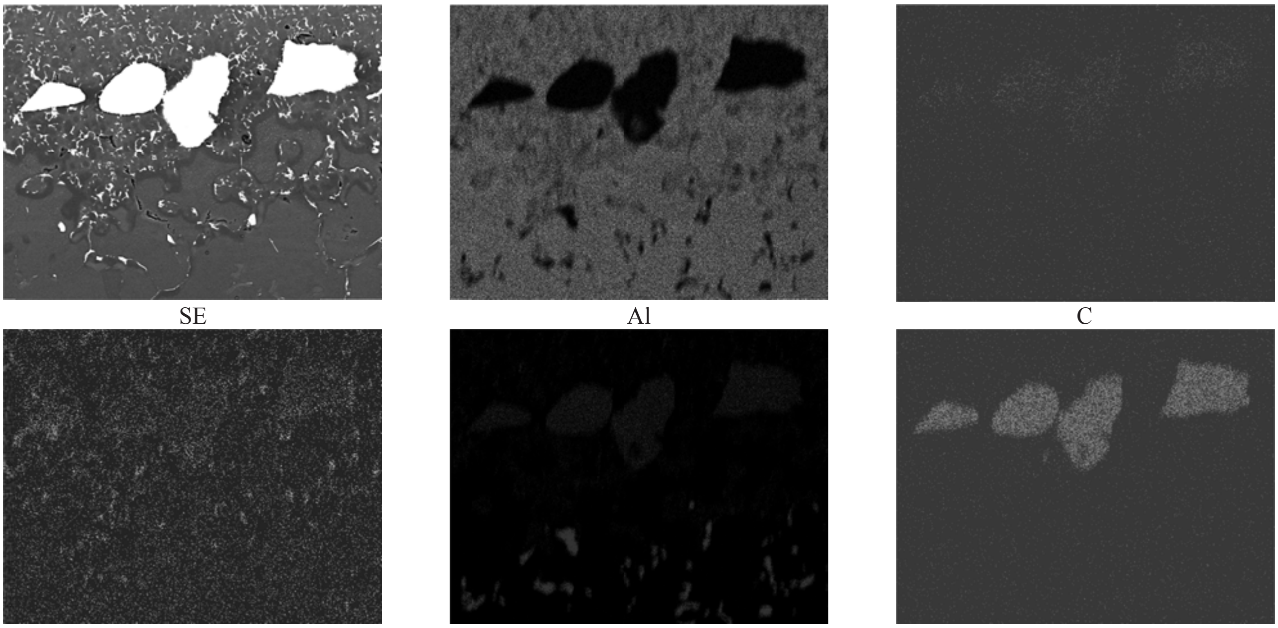


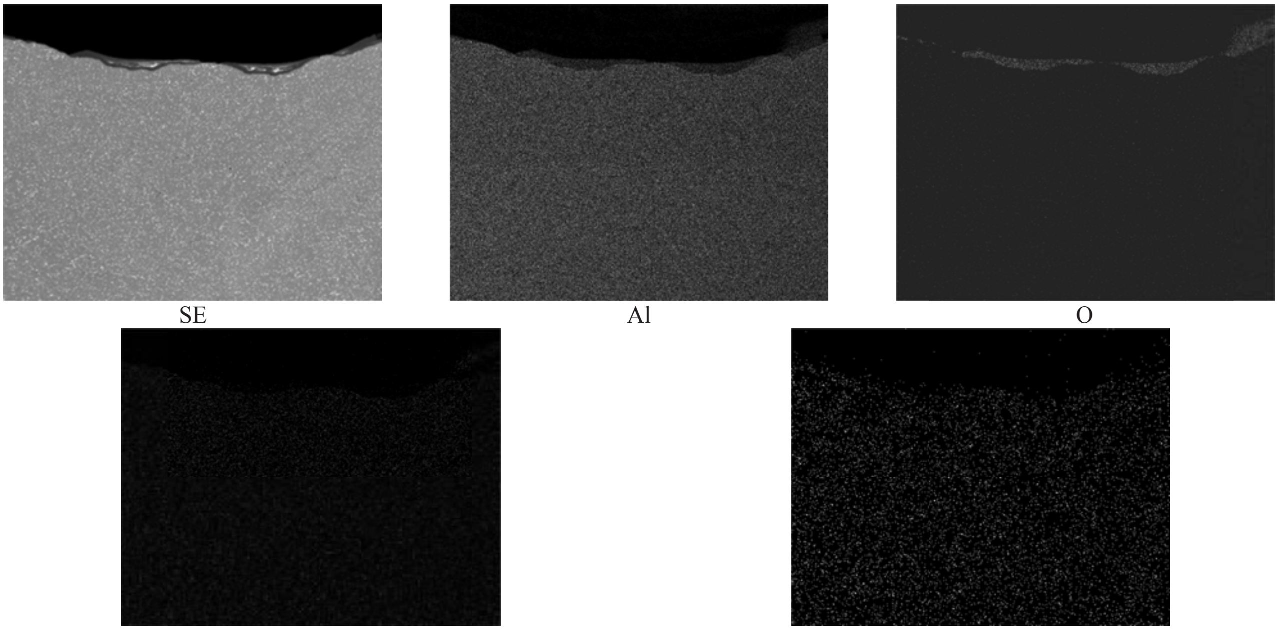
Fig. 40. Surface layer of the AlSi9Cu4 after feeding of the SiC powder, laser power 2.0 kW, 2.0 g/min, scan rate 0.25 m/min

Results of the X-ray quantitative and qualitative EDS microanalysis enable to confirm the presence of the alloying elements Al, Si, Cu as the component of the matrix of the aluminium cast alloys with silicone and the elements comprising the fused ceramic powders WC and Al_2O_3 (Figs. 41-46). Information on the mass and atomic concentration of the specific elements in the micro areas tested on the point-by-point basis of the surface layer after laser fusion has also been obtained.


SE Al C

Cu Si W

Fig. 41. Structure of the cross-section of the surface layer after feeding of the WC powder into the surface of the cast AlSi9Cu4 aluminium lloys: image obtained using secondary electrons (A) as well as EDS mapping of the elements distribution Al, C, Cu, Si, W


SE Al O

Cu Si

Fig. 42 Structure of the cross-section of the surface layer after feeding of the Al2O3 powder into the surface of the cast AlSi9Cu4 aluminium alloys: image obtained using secondary electrons (A) as well as EDS mapping of the elements distribution Al, O, Cu, Si

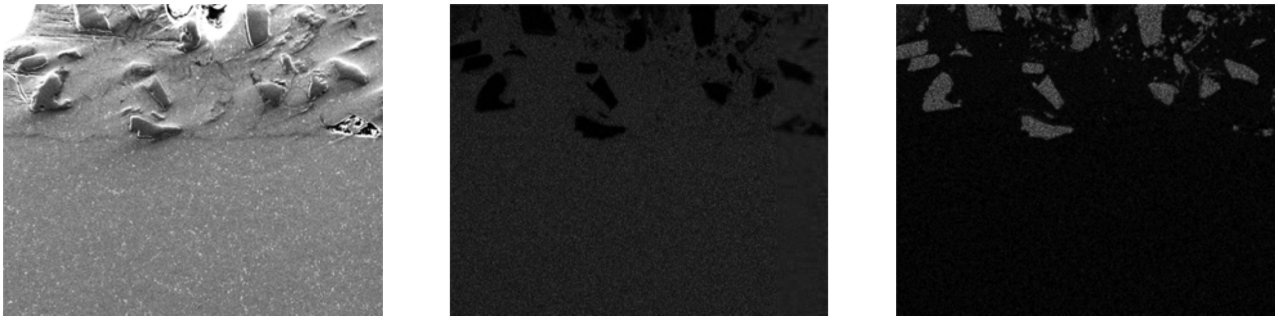

SE Al Si

Fig. 43. Structure of the cross-section of the surface layer after feeding of the SiC powder into the surface of the cast AlSi9Cu4 aluminium alloys: image obtained using secondary electrons (A) as well as EDS mapping of the elements distribution Al, Si

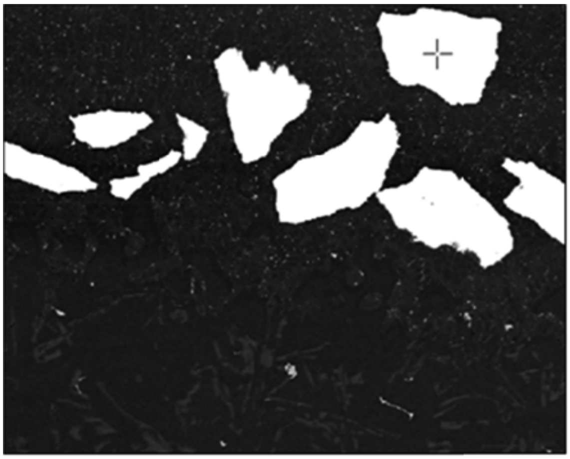


Fig. 44. Cross section of the surface layer after feeding of the WC powder into the surface of the cast AlSi9Cu4 aluminium alloy, laser power 1.5 kW

Table 4.
Investigation results of the chemical composition of the surface layer fed with WC powder into the surface of the cast AlSi9Cu4 aluminium alloy, laser power 1.5 kW

Analised element	Concentration of the elements, %	
	mass	atomic
C	10.31	63.75
W	89.69	36.25

Table 5.
kW Investigation results of the chemical composition of the surface layer fed with Al2O3 powder into the surface of the cast AlSi9Cu4 aluminium alloy, laser power 1.5 kW

Analised element	Concentration of the elements, %	
	mass	atomic
Al	38.30	51.14
O	61.70	48.86

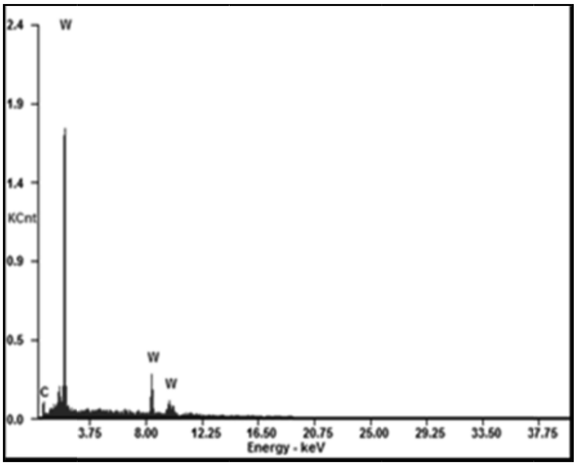


Fig. 45. EDS point-wise chemical composition analysis of the quasi-composite AlSi9Cu4 with fed particles of the WC powder, laser power 1.5 kW, analysis performed in point presented in Fig. 50

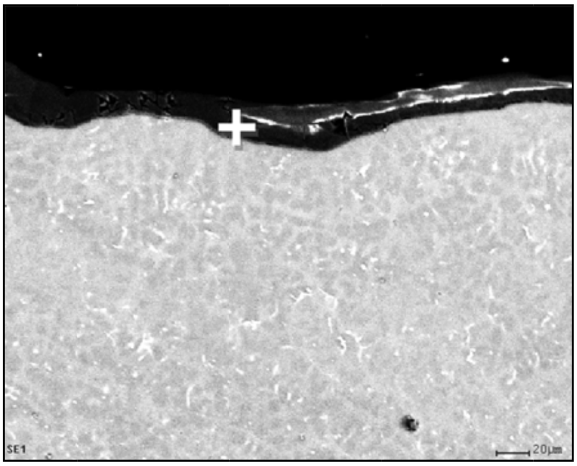


Fig. 46. Cross section of the surface layer after feeding of the Al_2O_3 powder into the surface of the cast AlSi9Cu4 aluminium alloy, laser power 1.5 kW

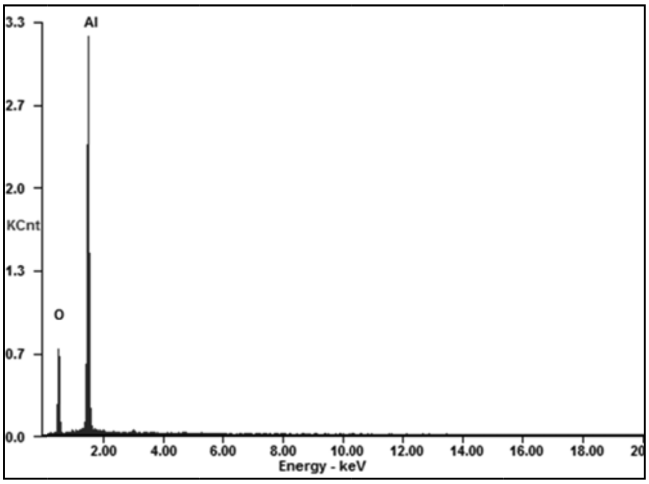


Fig. 47. EDS point-wise chemical composition analysis of the quasi-composite AlSi9Cu4 with fed particles of the Al_2O_3 powder, laser power 1.5 kW, analysis performed in point presented in Fig. 54

On Figures 48-50 there were presented X-Ray diffraction patterns of the investigated aluminium alloy after feeding with ceramic particles WC, SiC, and ZrO_2 with the laser power of 1.5 kW.

After conducted feeding, in each of the analysed cases the matric phase α-Al has been identified. Very slight participation of the phase Al_2Cu and Mg_2Si not exceeding the detection threshold in this method, amounting to approx. 3% does not allow for their explicit identification. The conducted tests of the X-ray analysis of the composite layers formed by fusion in the surfaces of the processed alloys of the particles of aluminium oxide have not confirmed occurrence of the phase Al_2O_3 in the tested micro areas, which may be caused by the change of the network structure of that phase from the crystalline into amorphous as a result of impact of the high temperature of the laser processing

The obtained depth of the heat impact zone has also extensive impact on the practical application of the formed surface layers. The measured depth of the heat impact zone consists in the range from 0.1mm in case of fusion of the ZrO_2 particles up to 1.3 mm for the Al_2O_3 powder. In the paper the measurement results of the depth of the heat impact zone have only been presented, as for the cases of fusion by means of aluminium and zirconium oxide powders no occurrence of the fusion has been stated, which at the same time excludes the presence of the melted zone. Changes in the depth of the heat impact zone related to the both tested alloys are relatively minimal for the powders WC, SiC and ZrO_2, the difference in the depth is only observed in case of aluminium oxide powder (Fig. 51) measured for the alloy AlSi9Cu - 0.8 mm and alloy AlSi9Cu4 - 1.3 mm, as well as very substantial difference in the depth of the heat impact zone has been stated (even 13-fold in case of ZrO_2), between the measured value for the powder Al_2O_3 and the other powders WC, SiC and ZrO_2.

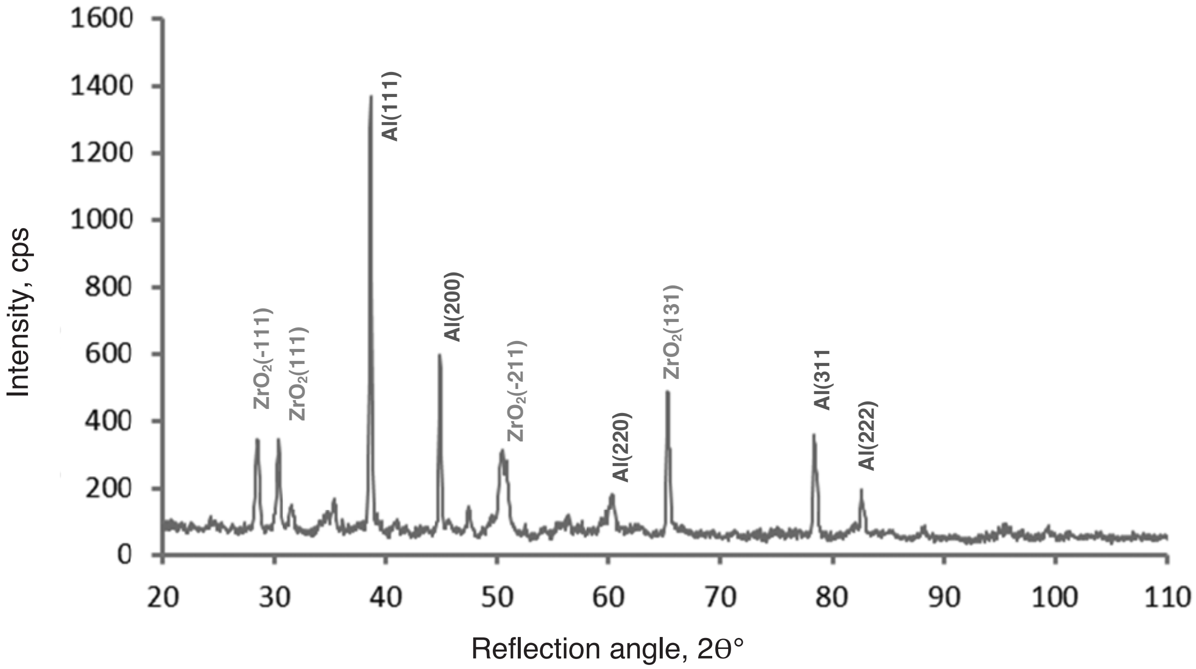


Fig. 48. X-Ray diffraction pattern of the cast aluminium alloy AlSi9Cu4alloyed with the ZrO_2 powder using the Bragg-Brentano method

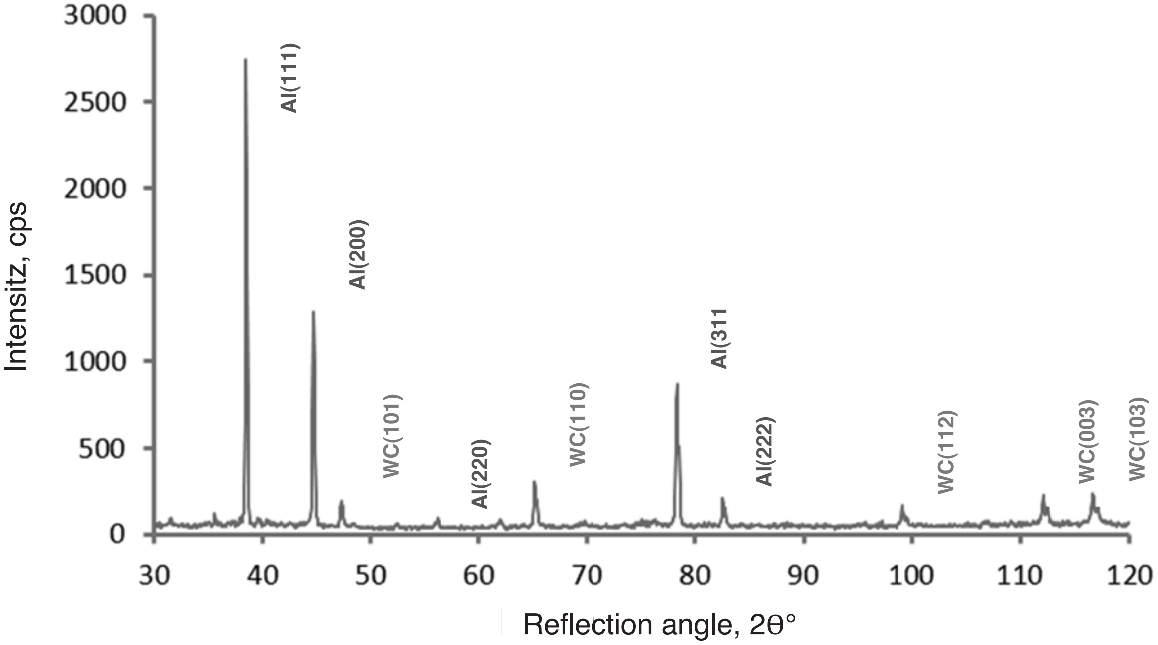


Fig. 49. X-Ray diffraction pattern of the cast aluminium alloy AlSi9Cu4alloyed with the WC powder using the Bragg-Brentano method

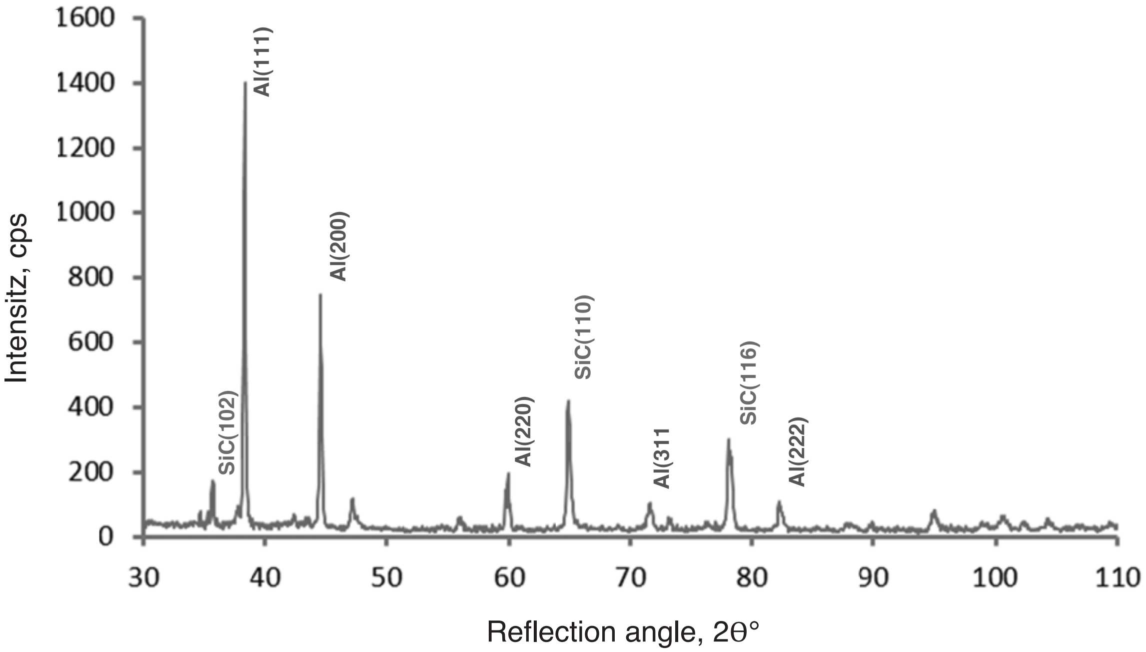


Fig. 50. X-Ray diffraction pattern of the cast aluminium alloy AlSi9Cu4 alloyed with the SiC powder using the Bragg-Brentano method

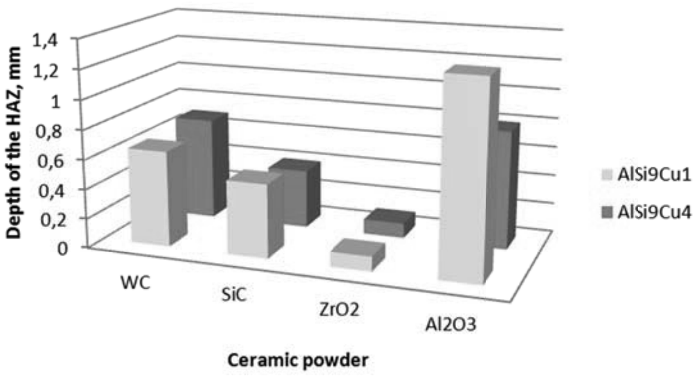


Fig. 51. Measurement results of the depth of the alloying and remelting zone in Al-Si-Cu cast alloy samples after the performer laser treatment

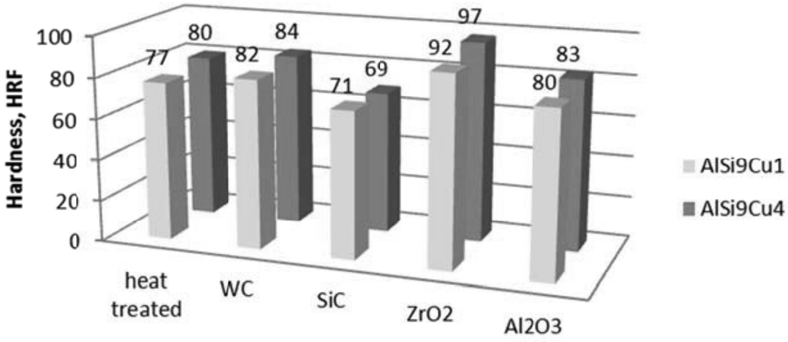


Fig. 52. Hardness measurement results of cast aluminium samples Al-Si-Cu after laser treatment

While analysing the mechanical properties of the surface layers processed by means of HPDL laser, particularly the results of measurements of hardness of the aluminium cast alloys subject to laser fusion it may be stated that for all the tested cases, except for fusion of the SiC powder, hardness of the surface layer had been subject to increase or remained on the unchanged level in comparison to hardness of the surface layer subject to standard thermal treatment (Fig. 52), where prior to fusion the measured hardness amounted to 77 HRF and 80 HRF respectively for the alloys AlSi9Cu and AlSi9Cu4. The cast alloy AlSi9Cu4 with the powder of zirconium oxide ZrO_2 - 97 HRF fused in the surface layer is distinguished by the highest increase of hardness, in comparison to the initial state. The lowest hardness for the melted surface layer has been stated for the powder SiC amounting only 69 HRF for the alloy AlSi9Cu4. However it is assumed that such a drop is caused by too small amount of the SiC powder introduced by means of fusion to the surface layer of the aluminium cast alloys, despite obtaining of very good dispersion and distribution of the SiC powder in the matrix. Whereas relatively high values of hardness for the composite surface layers formed with the use of the ZrO_2 and Al_2O_3 powder may be explained by formation of homogenous burnt coating on the surface of the processed alloys and the lack of presence of the diffused particles in the zone of the obtained melting. The highest measured hardness amounting to 97 HRF that is higher by 20% from the hardness measured for the alloy AlSi9Cu4 after thermal treatment has been obtained for the surface layer with the fused ZrO_2 powder. In case of fusion of the tungsten carbide powder hardness of the surface layer after laser processing achieves the values 84 and 82 HRF respectively for the alloy AlSi9Cu4 and AlSi9Cu, namely slightly higher from the values obtained for the substrate material being subject to thermal treatment.

Test results of the resistance to abrasive wear of the surface layers obtained by means of fusion of the ceramic powders into the surface of the aluminium cast alloys in the arrangement metal-ceramic material, allowed for assessment of the achieved results, enabling indication of the surface layer Al_2O_3 as the most resistant to abrasion. While analysing the obtained abrasion profiles of all the achieved surface layers (Figs. 53-56) it has been stated that the highest resistance to abrasive wear has been indicated by the burnt surface layers formed from the powder of aluminium or zirconium oxide, for which the mass loss expressed as a deviation from the average depth of the abrasion amounts to approx. 20 μm and is by 30% lower in comparison to the mass loss measured for the surface layer with the fused WC powder, characterised by the relatively low resistance to abrasion. The nature of the abrasion profile is characterised by diversified morphology depending on the applied powders and indicated regular shape corresponding to the beam of the applied WC bead as a counter sample with the 6 mm diameter for the oxide powders and irregular form with high profile roughness for the WC and SiC powders present in the melted surface layer in the form of the dispersion particles.

Tribological resistance of the formed surface layers has been registered based on the friction coefficient depending on the friction path (Fig. 57). Characteristics of the registered curves of the friction coefficient initially indicated rapid increase of the measured value. Such initial unfixed state has been registered for each tested sample is the result of relaxation and mutual adaptation of the arrangement tested substrate-ceramic bead. The lowest value of the friction coefficient 1.12 has been read for the unfixed state, in case of the surface layer obtained after fusion of the Al_2O_3 powder, lower by over 50% in comparison to the value of the friction coefficient obtained for the surface layer after laser processing with the use of the SiC and ZrO_2 powder, which indicates that the high friction coefficient corresponds to the low abrasion resistance.

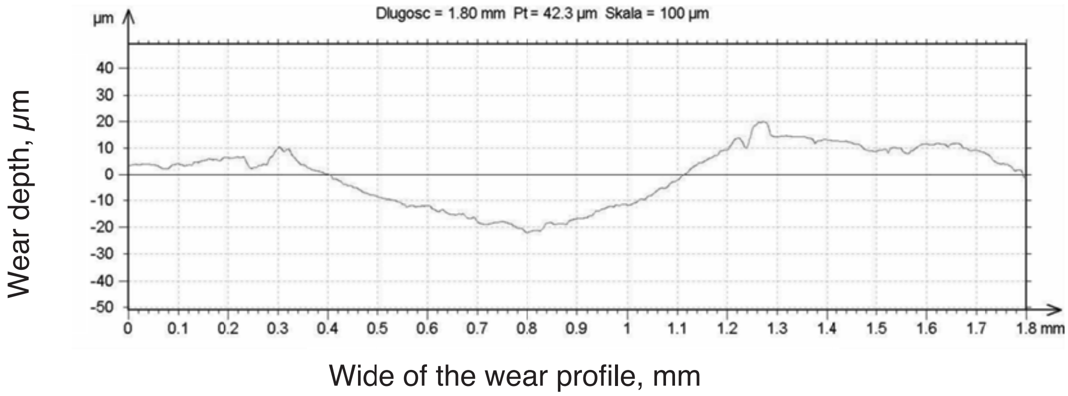


Fig. 53. Wear profile obtained for the AlSi9Cu alloy fed with the Al_2O_3 powder, 1 g/min laser power 1,5 kW obtained during the wear resistance investigation using the ball-on-plate method

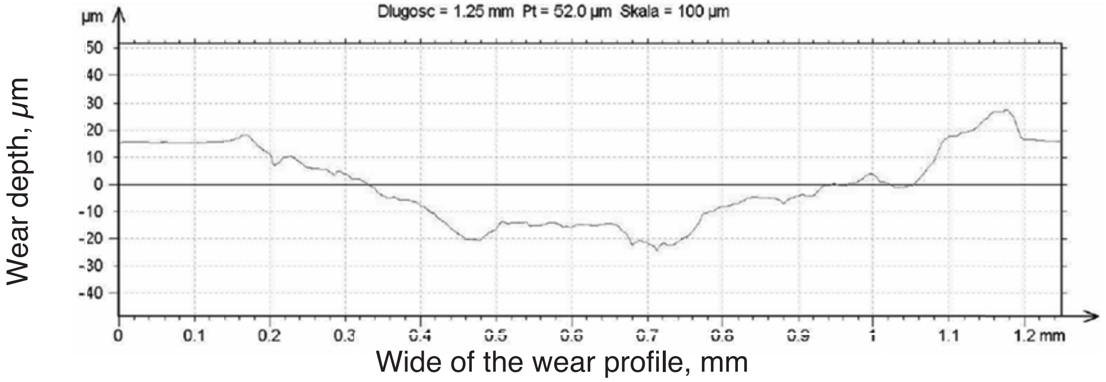


Fig. 54. Wear profile obtained for the AlSi9Cu alloy fed with the WC powder, 3 g/min laser power 2.0 kW obtained during the wear resistance investigation using the ball-on-plate method

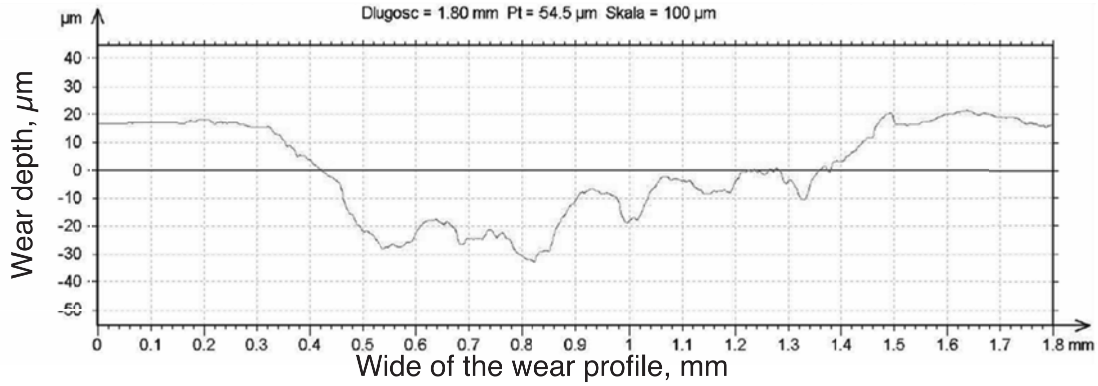


Fig. 55. Wear profile obtained for the AlSi9Cu alloy fed with the SiC powder, 2.0 g/min laser power 1,5 kW obtained during the wear resistance investigation using the ball-on-plate method

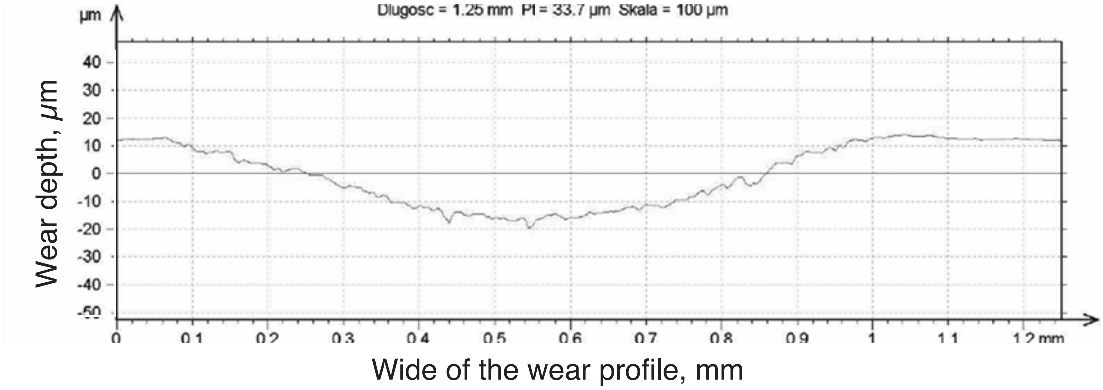


Fig. 56. Wear profile obtained for the AlSi9Cu alloy fed with the ZrO_2 powder, 8 g/min laser power 2.0 kW obtained during the wear resistance investigation using the ball-on-plate method

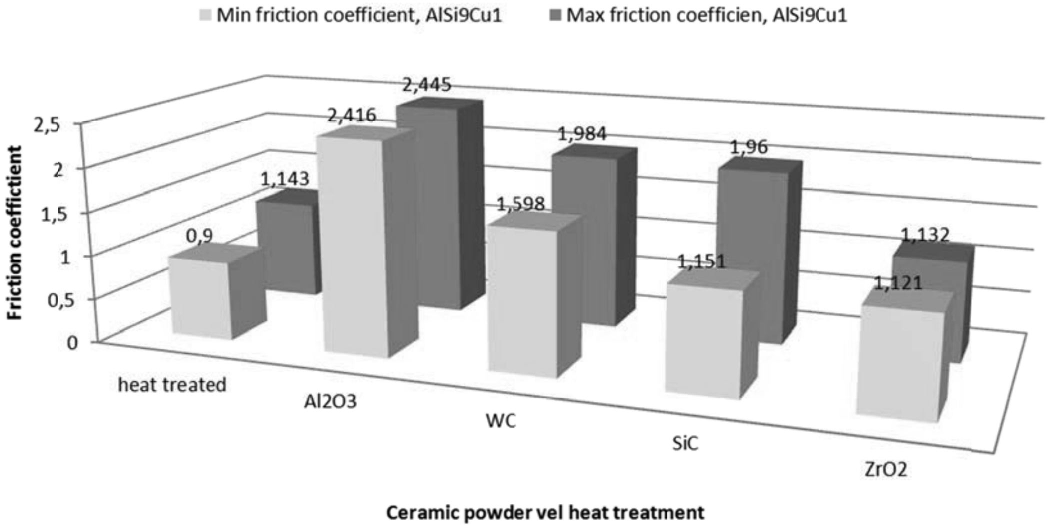


Fig. 57. Maximal and minimal wear coefficient measured during the investigations of the wear resistance with the ball-on-plate method for the surface layers obtained by mind of ceramic powder feeding

For the purpose of establishment of the impact of the surface processing on the corrosion resistance of the aluminium cast alloys Al-Si-Cu, corrosion tests with the use of electrochemical potential-dynamic method in 1-mol water solution of NaCl have been conducted. On their basis corrosion resistance of the surfaces of the tested materials has been specified, depending on the ceramic powders applied in the laser fusion method. As a result of the performed tests the anode polarisation curves have been obtained for the alloys with the fused WC, SiC, ZrO_2 and Al_2O_3 powders, which confirm that the tested materials are subject to very strong pitting corrosion, obtaining high values of the density of the corrosion current as soon as at the stage of slight corrosion potential (Fig. 58).

While considering the entire range of results from the corrosion tests of quasi-composite surface layers obtained with the use of various powders it should be stated that the differences in the value of the density of the corrosion current, present for the specifically fused ceramic powders may be revealed only in the slight scope. The layers obtained with the use of the aluminium oxide are distinguished by the highest corrosion resistance, however also in this case the corrosion resistance is relatively low, where the density of the corrosion current is at the level of approx. 3 mA/cm^2. The surface layer after fusion of the SiC particles indicates the lowest corrosion resistance, adopting the value of the density of the corrosion current amounting to approx. 5 mA/cm^2. In general the correctness of the adopted dependency may be confirmed, on the basis of which the analysis of the results has been conducted, namely that the higher corrosion current, the lower the corrosion resistance.

In case of the surface layers manufactured by means of the laser fusion technology with relatively slight corrosion resistance, occurrence of the extensive amounts of the corrosion centres is caused by numerous defects and irregularities of the obtained. Therefore assurance of the adequate corrosion resistance, particularly to the pitting corrosion, on which the aluminium alloys are vulnerable to after laser fusion is extremely difficult. Also for that reason fusion of the ceramic powders into the matrix of the aluminium alloys is disadvantageous from the point of view of assurance of high corrosion resistance, which obliges the scientific environment to continuous search for the best solutions to the encountered problems. Such a solution for improvement of the corrosion resistance of the tested alloys seems to be application of thin coatings imbedded from the gas phase, which according to the previous prerequisites may ensure better resistance to the pitting corrosion of the tested alloys in relation to the layers formed by laser.

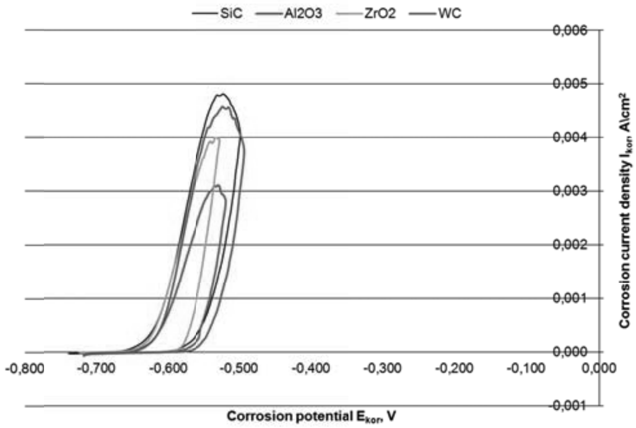


Fig. 58. Measurements results of the interdependence between the density of the corrosion current I_{kor} and the corrosion potential E_{kor} for the surface of the aluminium after feeding of the powders: SiC, WC, Al_2O_3 and ZrO_2

4. Summary

The most important result of the presented tests is specification of impact of the basic parameters of laser processing on the mechanical and usable properties of the tested materials in the conditions of tribological wear. An essential component of the obtained results is also analysis of the structural changes and changes in the chemical composition of the alloys Al-Si-Cu at the state after thermal treatment.

Despite emerging opinions on the lack of usefulness of formation of the hard surface layers or coatings on relatively soft substrate material such as aluminium, increasing interest around this issue has been observed. However, despite many undeniable advantages, by which the aluminium alloys may be characterised, they also have certain disadvantages, to which low hardness and resistance to abrasion should be included, particularly in relation to applications requiring high mechanical and usable properties of the surfaces of the manufactured element. Such a fact may quite effectively limit the possibility of application of the given material. Such state of affairs had been the reason for searching for the possible solutions, aiming at increase of the usable properties on the surface of the tested materials by means of application of the laser technology of surface processing of the substrate made of aluminium cast alloys with silicon. In addition, surface processing with the use of source such as laser has been a very innovative technology these days due to its possibilities, such as for example large economy of materials, precision of processing, substantial improvement of properties of the processed materials, possibility of applying complete automation, etc. Therefore, particularly the surface layers manufactured by the laser techniques, as well as the technology of laser surface processing have been characterised in the chapter. In addition, the mechanisms that take place during the laser forming of the surface, applications of the specific techniques, their advantages and disadvantages, possibilities and risks as well as anticipated development trends have been partially described. Such a processing also enables increase of the hardness and abrasion resistance of surfaces of relatively small dimensions, which may also be dictated by economic aspects. Application of laser surface processing is justified both from the economic point of view as well as due to the point of assurance in many cases of higher mechanical properties of the processed surfaces e.g. aluminium constructional elements exposed to tribological wear, tooth strips of the toothed wheels or blades of the cutting tools, which would not be able to be achieved while using conventional surface processing methods.

By fusion of the ceramic powders into the matrix of the tested aluminium alloys with laser power in the range up to 2.0 kW with the rate up to 0.5 m/min and the amount of the ceramic powders fed up to 10 g/min, occurrence of the zonal construction of the melting has been confirmed by separation of the obtained surface of the melted layer, heat impact zone and transformation zones (Figs. 17-20) with fragmented structure in comparison to the initial material after standard heat treatment. Such state of affairs is also confirmed by the tests conducted by the authors from other scientific centres, which mainly focuses on the possibility of fragmentation of the structure of the processed materials and at the same time on improvement of the exploitation properties of the manufactured elements. The performed structural tests confirm that the melted zone, with omission of the fine-crystalline grain is also characterised by occurrence of the dendritic structure, in which the directions of dendritic crystallisation are pursuant to the direction of heat abstraction from the impact zone of the laser beam.

Increase of the rate of fusion causes reduction of the time of reaction of the laser beam on the material, and at the same time results in limitation of the amount of the energy absorbed by the substrate and as a consequence leads to limitation of the extent of the structural changes. Application of too excessive laser power or too low rate of scanning causes evaporation of the material of the surface layer and formation of craters, whereas application of too small power or too excessive rate of fusion may be the result of inadequate melting characterised by inhomogeneous distribution of the particles fused into the matrix of the aluminium cast alloys Al-Si-Cu. Achievement of the homogeneous structure of the surface layer also depends on the linear energy of the beam. In case of the values adopted during conducted fusion its amount accounts for 4 kJ/mm for the power 2 kW. Too excessive value of the linear energy leads to reduction of the rate of quenching and as a consequence to lack of fragmentation of the grain in the surface layer of the melting and at the same time to reduction of the mechanical and usable properties of the material. Proper selection of the conditions for fusion enables achievement of uniform composite made of the matrix (alloy Al-Si-Cu) and hard ceramic particles fused on the surface of the material. While specifying the conditions of the surface processing several essential factors should be taken into consideration, among which the following are the most important ones: difference of the density and the surface tension (the so-called wettability) between the particles of the applied carbides or oxides (SiC, WC, Al_2O_3, ZrO_2) and the alloy matrix, differences in the adsorption of the beam energy between the used powders and aluminium cast alloys and differentiated thermal conductivity of the used powders, which substantially influences the amount of heat supplied from the outside (from the laser beam) to the substrate material at the same time allowing for achievement of better melting with uniformly distributed phases of the dispersion particles.

Application of the composite layers carried out by fusion into the surfaces of the processed alloys of the particles of tungsten carbide or silicon leads to increase of the resistance to abrasive wear, being one of the main intentions for shaping the properties of the surface layer of the alloys Al-Si-Cu. Not only the proper selection of the ceramic powder used for fusion, but also its distribution and voluminal participation in the matrix, modelled by various technological operations decides about the subsequent usable properties of the finished product.

While testing the surface layer after laser fusion clear differences in relation to the introduced ceramic powder have been stated. For example, the structure of the surface layer of the aluminium cast alloys obtained after fusion of the WC powder is characterised by high concentration of the additional material at the bottom of the melted zone, which is the result of gravitational decrease of the particles with relatively high density (15.69 g/cm^3) in the melted pool of the liquid metal. Whereas in case of fusion of powders of the oxides Al_2O_3 and ZrO_2 no melting in the structure of the used particles has been stated, which a s result of the influence of the laser beam formed burnt, thin layer of oxides on the surface of the processed material (Figs. 29, 30). The optimum distribution of the ceramic powder fused in the matrix of alloys has been confirmed after executed fusion of the SiC powder, characterised by uniform distribution of particles in the zone next to the surface of the surface layer (Fig. 37).

The surface layer was formed as a result of mixing of the additional material with the substrate, and is characterised by increased hardness, which is related to the structural changes in the transformation zone, including inter alia with the presence of extensively fragmented grains, new formation of the hard phases, presence of the saturated fixed solutions and favourable state of own tensions. While testing the dependency of the changes of hardness on the influence of the type of substrate and applied ceramic powder a maximum 15% increase of hardness has been stated in case of the layers manufactured with the use of the ZrO_2 powder, in comparison to hardness of the material after standard thermal treatment (Fig. 52). On the basis of the tests of the resistance to abrasive wear of the tested samples by means of the ball-on-plate method, measuring the friction coefficient and characterising the abrasion profiles a substantial increase of the abrasion resistance of the manufactured quasi-composite layers has been stated, particularly in the case of applied strengthening in the form of fine-grain tungsten carbide.

To sum up, it has been stated that as a result of the thermal treatment and the performed laser fusion of ceramic powders into the surface of the alloys Al-Si-Cu with the use of HPDL laser it is possible to obtain high-quality surface layer without any cracks and defects and with hardness exceeding the hardness valued achieved for the aluminium substrate. Improvement of the hardness may be obtained based on application of the optimum fusion parameters, which respectively amount to: rate of fusion 0.5 m/min for the aluminium oxide and 0.25 m/min for other powders, amount of the powder fed 1 g/min (Al_2O_3), 3 g/min (WC), 1.5 g/min (SiC), optimum laser power amounted to 2.0 kW (1.5 kW in case of Al_2O_3).

Nevertheless, the large minus of the technique of laser fusion of the ceramic powders, particularly the oxides, is premature sublimation and disintegration of extensive part of the material fused as a result of radiation by high-energy laser beam, even before the stage of introduction into the liquid pool. Apart from that, too extensive amount of powder, being at the same time absorbent of the laser radiation, and what follows, the heat carrier or too extensive blowing of the powder into the surface of the processed alloys Al-Si-Cu, causes extensive, undesirable reaction of the additional material, which is usually accompanied by intensive flame of the disintegration reaction. As a consequence of such influences on the path powder - laser beam - substrate material, on the surface of the processed alloy numerous holes and new layer of material occur outside the melted path, extensive turbulences of the melted material and undesired, irregular, high agglomerates may be formed, being a composition of the natural material and the melted powders.

Despite the fact that application of the laser fusion of ceramic powders, and particularly the carbides turned out to be conscious effort and substantially influencing the improvement of hardness (Fig. 52) and abrasion resistance (Figs. 53-56) in case of small surfaces, nevertheless this method indicates many disadvantages, to which extensive roughness of surfaces, disabling measurement of this parameter after laser fusion and low corrosion resistance mainly caused by numerous defects of the obtained layers should be included. Among the disadvantages the economic factors should also be classified, particularly consisting in the lack of validity for using laser fusion for processing of large surfaces, due to higher costs of the technology in comparison to the traditional methods e.g. painting techniques or plating.

5. Conclusions

1. The conducted tests enabled realisation of objectives of the hereby paper, namely that application of the laser surface processing for improvement of the exploitation properties of surfaces of the aluminium cast alloys allows for formation of the surface layer characterised by better mechanical and tribological properties in comparison as opposed to the core material.
2. It has been indicated that the surface layer obtained by means of laser fusion and remelting technology has greater hardness and resistance to abrasion in comparison to the aluminium material after conventional thermal treatment. What is more, laser fusion by means of the ceramic powders substantially influences fragmentation of the structure in the melted zone and heat impact zone within the tested scope of the laser power, at the same time increasing properties of the obtained layers.

3. Tests of the usable properties of the surface layers formed by means of laser indicate increase of hardness and resistance to abrasion of the surface layer with the fused powders of carbides WC and SiC and relatively low corrosion resistance. In case of powders of the aluminium and zirconium oxides the surface layer obtained by the laser fusion method has a form of oxide coating, composed by the elements present in the fused ceramic powders. In case of the surface layers after fusion of the oxide powders occurrence of the melted zone has not been confirmed, and at the same time presence of the particles fused in the matrix of aluminium alloys has also not been confirmed. The WC and SiC powder introduced into the matrix of the selected aluminium alloys during fusion has a form of particles uniformly distributed in the melted zone.

On the basis of the performed tests an interesting direction of further tests within the scope of surface processing has also been indicated, regarding absorption, combination of the basic fusion parameters and the resulting possibilities of optimisation of the usable properties of the surface layer of the aluminium cast alloys, related to design an application of new improvements of the types of feeders or nozzles, application of fluxes so at to minimise the negative influence of the radiation absorption of the laser beam. It is particularly anticipated that the future directions for development regarding the laser techniques and vacuum deposition of coating will include:

- testing the possibilities of intended application of laser fusion of the ceramic powders into the matrix of the light metal alloys based on use of other sources of the laser beam, particularly the fibre and disc laser, characterised by higher power density, smaller size of the spot in the beam focus, as well as more precise specification of the width and depth of fusion.
- development of the presently conducted tests, including laser fusion, while making allowance for the diversified granulation and shape of the ceramic powder introduced to the matrix, testing the properties of the surface layer depending on the size of the particles fused and their dispersion in the matrix,
- application of various possibilities for surface preparation prior the laser processing (anodising, etching, sand-blast cleaning, painting intended for increase of absorption of laser radiation) ensuring better dispersion of the powder particles in the matrix and application of fluxes, so as to reduce the surface resistance and improve the wettability of the ceramic powders.

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