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Influence of Silicon and Cobalt Laser Alloying on the Microstructure and Nanomechanical Properties of the Gray Cast Iron Surface Layer

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The aim of the research was to modify the surface layer of flake iron by laser alloying with composition of elements: Si and Co and the evaluation of the obtained effects (regarding the changes in the surface layer microstructure and its chosen properties). In the first part, the treatment consist on covering the cast iron surface with the alloying composition layer, and in the second part – heating of this surface with laser beam using molecular laser. The treatment effects were estimated with: SEM, EDS, hardness tester, nanoindentation tester and surface profile device. It was stated (among others), that the alloyed zone in the surface layer flake iron after performed laser treatment was gained and it was characterized by following features (in comparison to the core material): fine and homogeneous microstructure with some similarities to the hardened white cast iron, presence of Co and increased amount of Si. It was noticed that such properties as hardness and Young's modulus have been increased.

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1. Introduction

Gray cast iron, including flake cast iron, in the automotive industry or agricultural machinery (and many others) finds constant interest. While the global production of steel in 2014 amounted to over 11,300 thousand tons, the production of flake gray iron is almost 48,000 thousand tons (nodular cast iron almost 27,000 thousand tons, and malleable cast iron over 1,000 thousand tons) [1]. Cast iron with graphite is characterized by better vibration damping ability than steel, higher thermal conductivity, 10% lower density, lower sensitivity to the notch effect, while at the same time (taking into account many applications) sufficient mechanical properties.

Flake cast iron is used in many areas, such as elements of means of transport or elements of agricultural machinery, which are exposed to tribological wear and corrosion. In the case of means of transport, cast iron is used, for example, for cylinder liners, piston rings, as well as brake discs and drums, brake pumps and cylinders, valve lifters and valve guides. In case of elements of agricultural machinery many parts working in the soil are made of grey cast iron. As examples could be coulter flaps or parts of disc harrows.

The surface layers of some fragments of this type of parts should be characterized by high resistance to tribological wear and very often also corrosion resistance. In order to meet the requirements, various methods of surface modification have been developed, such as diffusion: nitriding [2] and boriding [3]. One of the surface treatments used in case of surface layers of metal alloys, that allows to the modification of only those

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fragments of machine parts that are most exposed to wear during operation, is laser heat treatment (LHT) [4–21].

Previous studies have shown that after laser remelting, a fine and homogeneous microstructure and high hardness of the surface layer of gray cast irons can be obtained [11]. The properties of the surface layer can be changed not only by heating with a laser beam, but also by implementing alloying substances during this treatment (e.g. individual elements, compounds, and also their compositions). Laser alloying is a method chemical heat treatment that is easier to apply in case of many components because of no need of furnace usage as in case diffusive methods. It needs only covering the paste using a brush or sparing gun on chosen part of the treated component before laser heating. One of the problem could be post machining requirement because of increase of surface roughness after laser remelting. Nevertheless, such processing is need only in case of friction pairs (like a shaft and a pan). In case of agricultural components working in the soil (like coulter flaps made of flake iron) there is no need to perform such additional post processing. Previous studies [13] have shown that in the case of cast irons, the hardness of their surface layer can be increased by implementing silicon by laser alloying. Moreover, in the case of steel, it has been proven that thanks to this treatment, wear [14] and corrosion [15] resistance can also be increased. On the other hand, by implementing cobalt into steel with this method, it is possible to increase the heat resistance [16]. However, in already carried out research [17] on cast iron, the possibility of strengthening its surface layer with the use of cobalt was proven. However, these studies also showed that improperly selected parameters of the laser beam, i.e. in a way that does not guarantee the appropriate cooling velocity, result in the formation of a perlite-rich microstructure (due to the increase of the critical cooling velocity by cobalt). Therefore, it seems appropriate to investigate the effect of laser alloying with the use of another alloying element, e.g. silicon, with cobalt, which will counteract this phenomenon.

The aim of this exploratory research was the formation of a modified surface layer of flake cast iron by laser alloying with a mixture of silicon and cobalt and the evaluation of the effects of this treatment. In particular, the research was aimed at determining the changes in the microstructure of the obtained surface layer and its selected properties.

2. Methodology

The laser heat treatment consisted of alloying the surface layer of EN-GJL-250 flake cast iron. The chemical composition of the material is presented in Tab. 1. The modification of the layer consisted in applying a coating on the cast iron surface and then heating the surface with a laser beam. A molecular CO_2 laser by TRUMPF with a maximum power of 2600W and TEM01 mode was used for the treatment. Such parameters of the laser beam have been selected to enable melting in the cast iron surface layer according to the diagram prepared for this purpose [11]. The alloying coating consisted of a composition containing silicon and cobalt in a 1:1 ratio. The parameters of the elements to be laser alloyed are presented in Tab. 2.

Tab. 1.The chemical composition of EN-GJl-250 flake iron (weight percentage)

C	Si	Mn	P	S	Cr	Cu
3.34	2.15	0.64	0.03	0.02	0.04	0.047

Tab. 2. Elements used in laser alloying

Element	Particle size	Purity
Silicon	325 mesh	99%
Cobalt	2 μm	99,8%

After the laser heat treatment, microstructure analysis, element identification, selected nanomechanical properties and surface stereometry were tested. For these purposes, a scanning electron microscope (Tescan Vega 5135), an X-ray microanalyzer (PGT Avalon EDS), a profilographometer (ZAISS) and a hardness tester (3212 ZWICK Vickers) were used. A NHT nanoindentation tester (Anton Paar) with a Berkovich diamond indenter was also used (which enable to analyze selected nanomechanical properties). Thanks to this method (used in the research on gas boriding [3]), it was possible to evaluate such properties (apart from hardness) as the elasticity modulus, creep modulus, and to estimate the value of plastic and elastic work of modified layer. The maximum load was 100.00 mN during 5 s. 5 repetitions were performed.

3. Research results and analysis

After laser heat treatment of flake cast iron by alloying, an alloyed zone was obtained in its surface layer (Fig. 1), which was formed by remelting a part of the parent material (flake cast iron) with a previously applied coating containing an alloy composition consisting of silicon and cobalt. A fine-grained and homogeneous (compared to the base material) alloyed zone was characterized by a microstructure with properties similar to hardened white cast iron (Fig. 2). Grains of the matrix could achieve nanoscale even. It is also worthy to emphasize that in case of laser remelting of flake iron, graphite is diluting in the liquid matrix during heating, saturating the matrix with carbon.

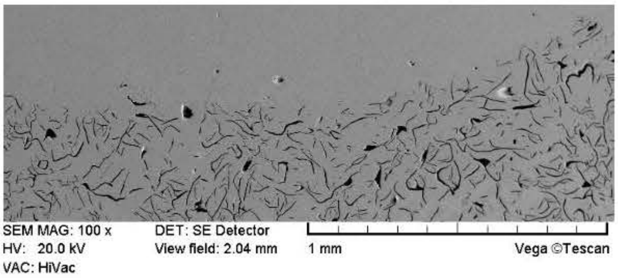

Fig. 1. The part of the surface layer microstructure (remelted zone with unremelted material) of flake iron after laser alloying, SEM image

The implemented elements were identified in the alloyed zone (Fig. 3). The presence of cobalt and an increased silicon content in relation to its initial level in cast iron were noted (Tab. 1). Cobalt and an increased silicon content in the alloyed zone were recorded along entire depth of the zone (Fig. 4). The identified concentration of silicon and cobalt suggests that these elements were primarily dissolved in solid solutions (martensite and residual austenite). Cobalt atoms can replace iron atoms in the crystal lattice due to their similar size.

The measurement of nanoindentation within the microstructure of the silicon and cobalt enriched surface layer obtained in this way allowed not only to find an over 3-fold increase in its hardness (which was noted in the case of the Vickers value (HV_{IT}) and the universal value (H_{IT})) in relation to the core of the material, but also the change of other nanomechanical properties. Results revealed a 2-fold increase in the modulus of elasticity (E_{IT}) and a nearly 2-fold reduction of the elastic modulus (Er) (maximum depth during the measurement: h_{max} for the layer was almost twice smaller than the starting material).

This was accompanied by a 2.5-fold reduction in plastic work (W_{plast}). The value of W_{elast} remained at a similar level. It can be expected that the obtained alloyed layer will be characterized by a reduced value of the creep parameter (C_{IT}), which in the examined case was on average 1.47, while for the parent material it was 1.72. The results of the mean values from the nanoindentation measurements for the parent material and the alloyed zone were shown in Tab. 3. Fig. 5 shows an example of the curve of the depth of the indentation changes during loading with a change in the load value, and Fig. 6 shows an example of the curve of loading and unloading in the parent material and the alloyed zone during the nanoindentation test.

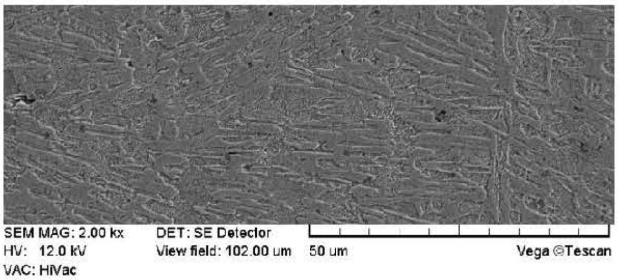

Fig. 2. The example of the alloyed zone microstructure area in the surface layer of flake iron, SEM image

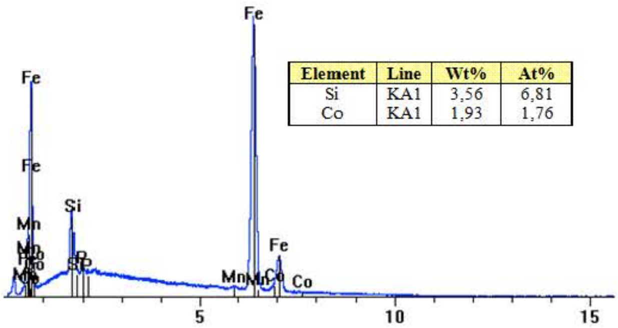

Fig. 3. EDS spectrum of the alloyed zone

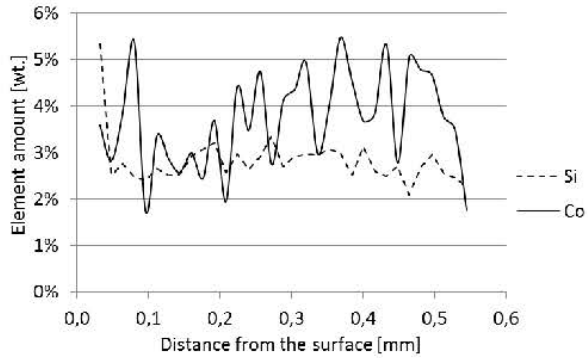

Fig. 4. The profile of silicon and cobalt amount in the surface layer from the surface to core material

Tab. 3. The chosen nanomechanical properties evaluated by the nanoindentation test for the core material and the laser alloyed zone

Parameter		HV_{IT}	H_{IT} [GPa]	E_{IT} [GPa]	E^* [GPa]	Er [GPa]	h_{max} [μm]	C_{IT} [%]	η_{IT} [%]	W_{elast} [nJ]	W_{plast} [nJ]
Bulk material	**Average**	263,4	2,82	91,4	100,5	91,8	1,33	1,72	20,4	10,8	42,1
	½$L_{0,9}$	41,3	0,45	26,3	28,9	24,1	0,10	0,41	2,1	2,1	5,4
Alloyed zone	**Average**	907,0	9,80	178,2	201,2	171,1	0,77	1,47	33,5	9,3	18,6
	½$L_{0,9}$	90,0	0,97	16,1	10,2	7,4	0,03	0,12	2,0	0,6	1,3

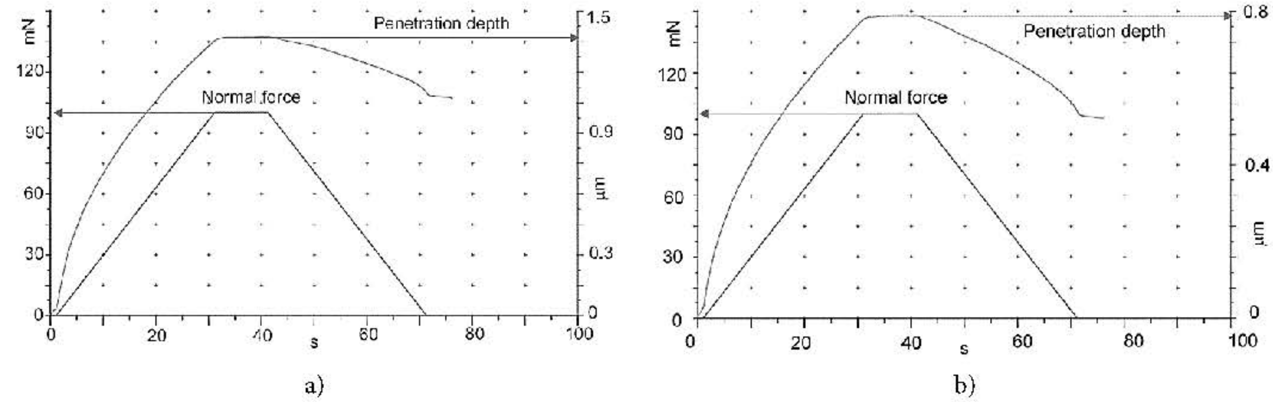

Fig. 5. The example of the indentation depth and load as a function of time during indentation testing of the core material (a) and the alloyed zone (b)

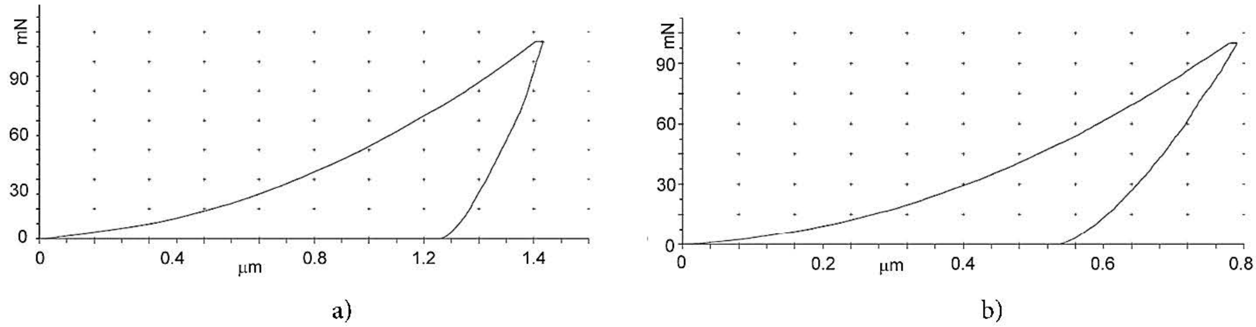

Fig. 6. The example of loading-unloading curve obtained by indentation testing of the core material (a) and the alloyed zone (b)

The mechanical properties of the formed alloy zones, however, may vary within certain value ranges depending on the used laser heat treatment parameters. The average hardness measured by the Vickers method in the remelted zones obtained in various laser alloying conditions changed in the range from 800 to 1000HV0.1 (Fig. 7).

It should be taken into account that the effect of strengthening the surface layer can be controlled not only by controlling the content of the added alloying elements, but also by the value of the parameters of the laser beam. It can be expected that the use of a higher fluency of the laser beam will result in a lower average hardness (because of formation of a larger alloyed zone). For example, the maximum width of the alloyed zone varied from less than 1 to 2 mm depending on used LHT parameters (Fig. 8).

As a result of laser heat treatment, the stereometric structure of the heated surface usually changes. In particular, if this treatment concerns surface layer remelting, as is the case during laser alloying. An example of a surface profile made across the obtained alloyed zone is shown in the Fig. 9. Although the values of surface roughness parameters (R_a, R_z) inside the remelted area did not increase significantly (their average values were R_a = 0.5 µm and R_z = 2.6 µm), on the border of the remelted and non-remelted area their value was increased by up to 10 times. It generates the necessity to carry out mechanical surface treatment after laser heat treatment with remelting of the surface layer in some applications of machine parts (it is not necessary, for example, in applications for agricultural elements working in soil [18]).

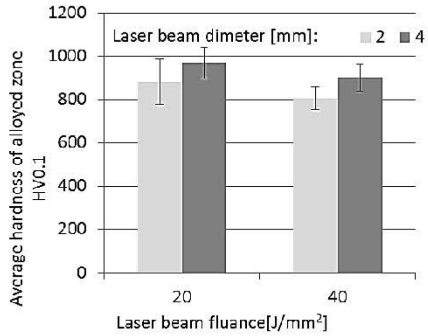

Fig. 7. The average hardness of the alloyed zone after laser treatment in case of using various values of laser beam parameters

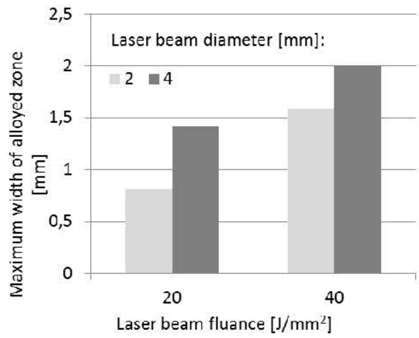

Fig. 8. The size of alloyed zone in case of using various values of laser beam parameters

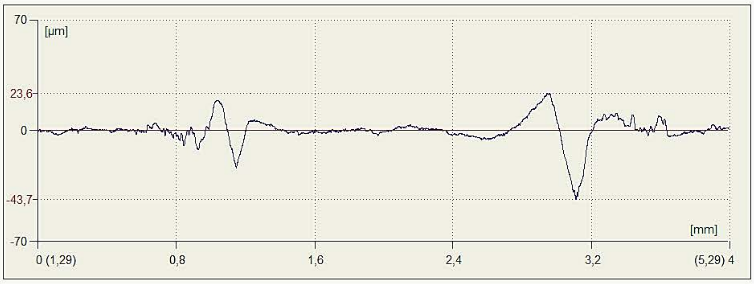

Fig. 9. The example of the surface profile after laser treatment

4. Conclusion

Based on the research carried out on laser alloying of flake cast iron with the use of silicon and cobalt, the following observations and conclusions can be formulated.

After laser heat treatment of flake cast iron it was possible to obtain in its surface layer an alloyed zone characterized by (compared to the bulk material):

- fine-grained and homogeneous microstructure with characteristics similar to hardened white cast iron;
- the presence of cobalt and an increased content of silicon;
- over 3-fold increased hardness, noted in the case of measuring the values of: Vickers (HV_{IT}), universal (H_{IT}), and also HV0.1 (it was accompanied by a 2.5-fold reduction of plastic work (W_{plast});
- 2-fold increase of modulus of elasticity (E_{IT});
- decrease of the creep parameter (C_{IT}).

As a result of the research, it was also found that the mechanical properties of the obtained alloyed zones may differ in certain ranges, depending on the parameters of the laser heat treatment used. The hardness of the alloyed zones obtained as a result of different values of the laser beam parameters ranged from 800 to 1000HV0.1. It has been found that a lower average hardness can be expected when a larger alloy zone is formed when a higher laser beam fluency is applied during processing.

The study of the stereometric structure of the heated surface showed an increase in the value of the surface roughness parameters, which makes it necessary to carry out a mechanical surface treatment of the surface layer in some applications of machine parts in case of LHT with remelting.

These exploratory studies in the field of silicon and cobalt alloying of the surface layer of flake cast iron justify further analysis of the nanomechanical properties of individual phases formed in the alloyed zones, and then tests to verify the resistance to tribological and corrosive wear during operation for subsequent application of the method to components of machines and devices.

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