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Thermal fatigue influence of laser treated tool steel surface

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Abstract

This research project presents the investigation results of laser remelting and alloying especially the laser parameters and its influence on the structure and properties of the surface of the 32CrMoV12-28 and X38CrMoV5-3 hot work steels, using the high power diode laser (HPDL). As a result of the performed research structure changes were determined concerning the grain size and reinforcement ceramic particle distribution in the steel surface layer. The reason of this work was to determine the optimal laser treatment parameters, particularly the laser power applied to achieve good layer mechanical properties for protection of this hot work tool steel from losing their work stability and to make the tool surface more resistant to action in hard working conditions. For alloying the tantalum carbide TaC, niobium carbide NbC as well as titanium carbide TiC powders were used. For investigations of the alloyed samples hardness and microhardness measurements of the different remelting areas were performed. The remelted layers which were formed in the surface of investigated hot work steel were examined metallographically and analyzed using light and scanning electron microscope as well as the investigations concerning ear resistance of the produced surface layer were carried out.

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1. Introduction

Tool steels still feature the widely used group of tool materials, especially interesting because of their low price and very good functional properties. Big interest in these steels gives basis for carrying out investigations focused on improvement of the functional properties of these materials [1-3].

In this paper there is presented the laser treatment as a new technique applied in laser surface technology as a possibility for remelting, feeding and alloying of hot work tool steels grade 32CrMoV12-28 and X38CrMoV5-3 with selected ceramic carbide powders like for example titanium carbide TiC, tantalum carbide TaC and niobium carbide NbC. This treatment seems to be a plausible alternative of other surface treatment techniques as there are for example the vacuum techniques like PVD/CVD methods [12-17] or anodisation method [18]. For layer treatment the HPDL (High Power Diode Laser) laser (Fig. 1) was applied, where diode lasers have long been used as light emitters in fibre-optic telecommunications, as barcode readers, and for implementing the write-read functions of optical disks [3-6].

The structure and improvement of fatigue resistance and mechanical properties is the most important aim of this work; because the improvement of mechanical wear of the surface layer of a tool operating at real service conditions is a critical factor for practical use. Hence, power density at the work piece is limited as well, leaving high-power diode lasers with restricted application opportunities. Crucial for reliability and lifetime of bars is proper heat sinking. Although power efficiency is extremely high, one half of the absorbed pump power has to be removed as waste heat. Mounting high-power diode-laser bars on cooling elements requires high precision and the complete mastering of the electrical, thermal, and mechanical junction process. This is the fundamental concept for direct-diode applications. This type of surface treatment is used for improvement of hardness, wear resistance and thermal fatigue resistance by changing the structure and improvement of the thermal fatigue resistance as well as abrasion wear resistance, mostly by introduction of carbide or other ceramic particles to the material matrix. Rapid changes in the thermal condition connected to mechanical load occurred in real service conditions leading to development of the surface layer with sufficiently resistance against these factors [7-10].

Ceramic powders are a rarely used tool material used in metal machining because of its high wear resistance as well as its valuable influence to thermal fatigue improvement at high service temperature of the tool made from the investigated tool steel. Entering of powder is done using the conveyor directly during remelting, or else the powder is being applied as paste which dries up on the specimen surface, and only next is subjected to alloying. This makes it possible developing the alloy with the bi- or multi-component structure, and also of the composite or gradient type with the intermetallic phases. Thanks to the rapid cooling because of heat removal to the cold substrate an advantageous, fine-grained structure develops, which may also display the gradient morphology. The surface layers obtained with laser alloying may have the heat-resisting and anti-corrosion properties, may also be characteristic of the high abrasion wear and erosion resistance [11-18].

Tool life is an important parameter to be considered in tool selection since it will affect tool change scheduling and production planning. The tool life of a hot work tool is commonly determined with an actual machining operation by using the tool with a particular work material under certain working conditions to reach the maximum allowable life time. However, this is also an expensive process since a lot of work material is consumed in the test. The major concern of laser alloying is to avoid defects after treatment such as cracking, bubbles and unacceptably rough surface. The second concern is to achieve a maximum hardness in the surface layer to ensure good working parameters.

High-power diode lasers are continuously making inroads into industrial applications, as they are compact, easier to cool, compared to other materials [21-23], yield a power efficiency beyond 50%, which is about five times higher than any other kind of laser has to offer, and their costs are becoming increasingly attractive. To exploit the tremendous application potential of high-power diode lasers, research and development programs are performed in many industrial countries [19-27].
This study was carried out to investigate the effect of chosen carbide powders including TiC, NbC, TaC powder addition into the steel surface layer and the solidification rate on structure and properties in the laser melted metal surface of the hot work tool steels 32CrMoV12-28 and X38CrMoV5-3. On the other hand, the solidification in the weld metal was changed from the primary ferrite to the primary austenite, as the solidification rate was raised. The purpose of this work is to study the effect of a HPDL laser remelting of the hot work tool steel, especially on their structure, hardness and microhardness. Special attention was devoted to monitoring of the layer morphology of the investigated material surface and on the particle occurred in the steel matrix.

Experimental conditions

The material used for investigation were two types of hot work tool steel; it has been supplied annealed in form of rods 76 mm in diameter and in the length of 3 m. Samples of this material were of the plate form, of the rectangular shape, with dimensions 70 x 25 x 5 mm. The chemical composition of the investigated steels is presented in Table 1. For the thermal fatigue samples were prepared of the form presented in Fig. 2.

Table 1. Chemical composition of the investigated hot work tool steels 32CrMoV12-28 and X38CrMoV5-3

| Steel          | C      | Si    | Mn    | V     | Cr    | Mo | Rest |
|---------------|--------|-------|-------|-------|-------|----|------|
| 32CrMoV12-28  | 0.308  | 0.25  | 0.37  | 0.535 | 2.95  | 2.70 | 0.022 |
| X38CrMoV5-3   | 0.372  | 0.42  | 0.43  | 0.420 | 4.95  | 2.72 | 0.024 |
The 32CrMoV12-28 steel was heat treated according to the steps for this steel type, at first tempering was performed and then annealing. Austenisation was performed in a vacuum furnace at a temperature of 1040°C, the heating time was 0.5h. During the heating to the austenitic temperature two isothermal holds were applied. The first one at the temperature of 585°C, the second at 850°C. After tempering two annealing operations were performed for the time of 2 h, the first at 550°C and the second at 510°C. After heat treatment the samples surfaces were grind on a magnetic grinding machine. Special care was set to avoid micro cracks, which can disqualify a sample on future investigation.

The austenitising for the X38CrMoV5-3 was carried out in the vacuum furnace at the temperature of 1040°C, with the soaking time of 0.5h. Two isothermal holds were used during heating up to the austenitising temperature, the first at the temperature of 585°C and the second one at 850°C. The specimens were tempered twice after quenching, each time for 2 hours, at the temperature of 575°C and next at 560°C.

Thermal fatigue test was carried out on a special stand, developed at the Faculty of Mechanical Engineering, where the steel discs are heated by induction heating coil - connected to a power generator (Fig. 3) and cooling water supply - to the austenisation temperature and by a set rotation speed immersing in in cooling water. A constant cycle rate were chosen of 6000 cycles, for the reason to simulate real service conditions of material exploitation as a mould form.
The carbide powders (Fig. 4) was put to the so prepared and degreased samples. The powder was initially mixed before with the inorganic sodium glass in proportion 30% glass and 70% powder. A paste layer of 0.5 mm in thickness was put on. A high power laser diode HPDL Rofin DL 020 with process rate of \( v = 0.5 \text{ m/min} \) was. All other work parameters are presented in Table 2. The laser power was chosen in a range of 1.2÷2.3 kW.

Table 2. HPDL laser parameters

| Parameter                          | Value          |
|-----------------------------------|----------------|
| Laser wave length, nm             | 940 ± 5        |
| Peak power, W                     | 100 + 2300     |
| Focus length of the laser beam, mm| 82/32          |
| Dimensions of the laser beam focus, mm | 1.8 x 6.8 |

The samples were mounted in the laser holder for remelting. On each sample surface four laser process trays were made of a length of 25 mm, with the power 1.2; 1.6; 2.0; 2.3 kW. It could be determined experimentally, that the full protection of the remelted area can be achieved by means of the argon protective atmosphere with the gas flow rate of 20 l/min through a circular nozzle with diameter of 12 mm, which was directed inversely to the direction of the remelting process.

For surface preparation the standard metallographic procedure was applied in form of grinding using SiC paper, polishing with 1\( \mu \text{m} \) Al\(_2\text{O}_3\) polishing paste and drying, the samples were mounted in the thermo hardened resin supplied by Struers. Next the samples were etched in nital at room temperature for the experimentally chosen time selected individually for each remelted area.

Table 3 Properties of titanium carbide powder TiC

| Powder | Grain Size, \( \mu \text{m} \) | Melting temp. °C | Density, g/cm\(^3\) | Hardness, HV |
|--------|-------------------------------|------------------|---------------------|--------------|
| TiC    | 5                             | 3140             | 4.25                | 2800         |
| TaC    | 10                            | 3880             | 14.5                | 1725         |
| NbC    | 10                            | 3500             | 7.5                 | 2100         |

Structure investigation was performed using the light microscope Leica MEF4A supplied by Zeiss in a magnification range of 50 - 500x. The micrographs of the microstructures were made by means of the KS 300 program using a digital camera.

The observations were performed on the cross section (Fig. 5) of the sample on each of the remelting trays. Metallographic investigations were performed also using the scanning electron microscope ZEISS Supra 35 in a magnification range of 500 - 5000x.

Hardness measurements results were registered for each remelting area, for this reason the Rockwell hardness tester supplied by Zwick was used according to the PN-EN ISO 6507-1 standard, by a load of 147.2 N for 15 s. Microhardness measurements were performed using the DUH Shimatsu microhardness testing machine, using the HV\(_{0.01}\) scale.
3. Results and discussion

Preliminary investigations of the remelted hot work tool steels 32CrMoV12-28 and X38CrMoV5-3 show a clear effect of the laser power respectively 1.2; 1.6; 2.0 and 2.3 kW on the shape and thickness of the remelted material (Figs.5 and 6). It can be seen that with the increasing laser power the roughness of the remelted metal surface increases. The layers in cross-section view are presented on Figs. 5a and 5b.

Microstructure presented on Fig. 7, 8 shows a dendritic structure in the remelted area. There are also TiC, TaC and NbC particles present distributed in the steel matrix in the remelted zone. There is also a clear relationship between the employed laser power and the dendrite size, namely with increasing laser power the dendrites are larger Fig. 8.

The hot work tool steel has a ferritic structure with homogeny distributed carbides in the metal matrix in the annealed state. In areas, which are between the solid and molten state dendritic structure with large dendrites can be found. The required hardenability for this tool steel was achieving after a suitable tempering time, which assures melting of the alloying carbides in the austenite.
The structure of the laser treated surface layer consists mainly of dendrite (Fig. 7) with the dendrites directed to the heat transfer direction obtained during solidification of the remelted area of the remelting zone. It is worth to mention that the dendrite structure occurs in every remelting zone regardless the ceramic powder used for alloying, however the remelting zone reveals also small areas with grains, caused be a higher cooling rate that the dendritic structure.

The EDS exemplary point wise analysis shown in Figs. 8 and 9 confirms the presence of TiC particles in the matrix in form of small partially dissolved particle in the matrix. The small Ti particles are clearly shown on Fig. 8 as round whit particles a result of scanning microscope structural investigations. The structural investigations carried out using the high power diode laser allows to compare the surface layer as well as the shape and depth of the remelting area. It was noticed that the depth of remelting area grows together with the increasing laser power, which was confirmed by the results presented on Figs. 5a and 5b, generally this relationship is valid for all samples, alloyed with different ceramic powders or remelted only.
The major concern of these investigations is about the resistance to thermal fatigue, where the value is measured as the average and maximal crack depth in the laser alloyed surface layer of the tested steels. The lowest resistance to thermal fatigue measure as the crack depth on the surface layer is measured in case of the remelted steel without any ceramic powder used in both types of steel (Fig. 10).

Concerning the applied ceramic powders only the TiC and NbC powders have a reasonable appliance possibility (Fig. 13, 14).

The TaC powder due to its impact on defoliation in both types of the applied steels (Figs. 11 and 12) is not a satisfied solution. In case of the X38CrMoV5-3 there can be observed a lower resistance to thermal fatigue, as well as additionally there can be state a partially deformation of the produced surface layer, even by 1.2 kW laser power (Fig. 11).
Fig. 10. Cracks in the surface layer after thermal fatigue test on the cross section of the 32CrMoV12-28 steel sample remelted with laser power:
   a) 1.6 kW, b) 2.0 kW

Fig. 11. Defoliation of the alloyed surface layer of the 32CrMoV12-28 steel alloyed with TaC powder, laser power 2.3 kW, laser power 1.2 kW, obtained during the thermal fatigue investigations

Fig. 12. Defoliation of the alloyed surface layer of the X38CrMoV5-3 steel alloyed with TaC powder, laser power 1.2 kW, obtained during the thermal fatigue investigations

Fig. 13. Cracks in the surface layer after thermal fatigue test on the cross section of the NbC alloyed: a) 32CrMoV12-28 steel, laser power 1.6 kW, b) X38CrMoV5-3 steel, laser power 1.6 kW
The average crack deep as a measure of the thermal fatigue increase according to the laser power used for laser alloying and achieves its maximum for 2.0 kW for both 32CrMoV12-28 and X38CrMoV5-3 steels alloyed with titanium carbide powder (Figs. 14, 15). Smaller maximal crack depth was achieved in case of the 32CrMoV12-28 hot work tool steel, it is supposed that the reason for this is a slightly higher amount of carbon - 0.372%, vs 0.308% for the 32CrMoV12-28 steel - as a chemical composition compound, where higher carbon content leads to increasing of the martensitic cell structure enabling, during higher stress potential, a destructive impact in form of crack propagation. Compared both types of the investigated steels only a small difference can be found, concerning mainly the maximal crack depth.

Assuming the carried out investigations it can be state, that the highest possible thermal fatigue resistance in relation optimal hardness can be obtained for TiC alloyed 32CrMoV12-28 steel, with a laser power of 1.6 kW. This value is optimal because for lower laser power the average crack depth grows, whereas for higher laser power the surface layer hardness decreases even to 39.7 HRC.

The resistance to the thermal fatigue measured with the average crack deep subjected to steel alloyed with TiC powder is few times smaller compared to the steel after a conventional heat treatment, which was used as the reference material for both types of steels.

Fig. 14. Cracks in the surface layer after thermal fatigue test on the cross section of the TiC alloyed X38CrMoV5-3 steel, laser power: a) 1.6 kW, b) 2.0 kW

Fig. 15. Cracks in the surface layer after thermal fatigue test on the cross section of the TiC alloyed 32CrMoV12-28 steel, laser power: a) 1.6 kW, b) 2.0 kW
Comparing the TiC and NbC ceramic powders, on the basis of the average, and maximal crack depth it was found, that alloying with TiC reveals ca 70% smaller cracks (Fig. 16, 17) compared to NbC.

In general as a result of the performed thermal fatigue test it can be seen that the resistance increases with increasing laser power and the highest resistance occurs in case of samples alloyed with 2.3 kW power. Compared to the steel remelted only - without any ceramic powder used – can be also clearly state an improvement of the thermal fatigue resistance.

It can also be state, that in case of the titanium carbide powder the difference of the remelted area thickness among the power of 1.2 kW and 2.3 kW is about 15 % larger for the 2.3 kW power. Fig. 18 shows the hardness measurements results of the remelted surface for 1.2, 1.6, 2.0 and 2.3 kW laser power. The highest hardness value is achieved for the 2.3 kW laser power Fig. 19. On Fig. 20 there is showed the microhardness measurement result of the remelted surface for 2.0, kW laser power for each for the investigated ceramic powder. The highest value is achieved for alloyed top surface and decreases with the remelting depth until the hardness value of the steel matrix is achieved of ca 800 HV, except the TiC surface layer where unfortunately the microhardness of the laser treated surface is lover compared to the value of the steel substrate.

Finally the hardness for the TiC alloyed 32CrMoV12-28 steel was measured (Fig. 18), where the optimal laser power was 1.2 kW, where a HRC value of 53.4 was obtained.

![Fig. 16. Average crack depth in relation to the laser power and applied ceramic powder for both types of steels](image1)

![Fig. 17. Maximal crack depth in relation to the laser power and applied ceramic powder for both types of steels](image2)

![Fig. 18. Hardness measurements results of the remelted surface layer after TiC alloying](image3)
5. Conclusions

The laser remelting and alloying show a huge dependence of used diode laser parameters on the structure and properties of the applied hot work tool steels 32CrMoV12-28 and X38CrMoV5-3. On the basis of the performed investigations it is possible to conclude, that as a result of heat-treatment as well as remelting of the hot work steels with the ceramic TiC, NbC and TaC powders there is possible to obtain high-quality surface layer which contain no
cracks - except the TaC powder - and defects as well as of much more higher hardness and microhardness value compared to the material which was not remelted. In case of TiC powder the increasing laser power depth of remelting material is higher and the surface is more regular. Allo ying with NbC powders, reveals a compact structure of the obtained surface layer, but the resistance to thermal fatigue is much more lower the in case of the TiC ceramic powder. The hardness value decreases generally according to the laser power used, so that the highest power applied gives to lowest hardness value in the remelted layer, and decreases in case of the titanium carbide powder. Also the surface of the remelted area is more regular less rough and more flat with increasing laser power. The metallographic investigations on the scanning microscope using the EDS analysis confirm the occurrence of titanium carbide TiC, which is present in the matrix mostly in form of clusters, a small amount of titanium is dissolved in the steel matrix. The performed investigations allow to conclude, that the surface of the remelted area is more regular, less rough and more flat with increasing laser power. The metallographic investigations on scanning and light microscope reveal a dendritic structure which is present in the heat influence zone in samples alloyed with every applied laser power. In can be stat that the dendrite size increases with the increased laser power.

Laser power increase influence can be state in case of the fatigue resistance test, where the highest combination of hardness and thermal fatigue resistance is achieve for the laser power of 2.0 kW. As a result of this investigation can be hold that with increased laser power increase also the wear resistance of the alloyed surface layer of the worked steel. The resistance increases also compared to the steel remelted only without any ceramic powder used, that confirms the application of ceramic powder for appliance of the titanium carbide ceramic powder as a material for improvement of mechanical properties.

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