The laser-plasma cementation as a method of increasing the abrasive resistance of medium-alloy tool steels

Evgeny Marinin1,*, Gennady Gavrilov2 and Irina Belashova3

1Vyatka State University, 36, Moskovskaya street, Kirov city, Kirov region, Russia.
2R.E. Alekseev Nizhny Novgorod State Technical University, 24, Minina street, Nizhny Novgorod, Russia.
3Moscow Aviation Institute (MAI), 4 Volokolamskoe shosse, Moscow, Russia.

*e.marrini@gmail.com

Abstract. The paper is devoted to the study of resistance of medium alloy tool steels after laser-plasma cementation. The authors propose a method of increasing abrasive resistance by means of the combined effect of DC electric arc of reverse polarity and laser radiation. The increased concentration of carbon in the near-surface layer is provided by the erosion of the carbon electrode and melting due to the combined energy effect of laser radiation and electric arc. The formation regularities of the diffusion hardened layer are established. The modes of laser-plasma cementation and test results of the studied materials are presented. The reasons of resistance increase are revealed. The mechanical characteristics of the hardened surface layer are shown. The influence of the energy regimes of the technological process on the depth of the diffusion hardened layer is given.

1. Work actuality
Improving the service life and reliability of machines, mechanisms and tools is one of the main issues in the output competitiveness. As practice shows the destruction of 90% of machine parts and tools begins with the surface [1]. Therefore surface hardening is one of the main factors improving service life and reliability. Efficiency and resistance are determined by the rational choice of material grade and surface hardening technology.

Medium-alloyed tool steels with increased resistance (Cr6WV, 8Cr6NiWTi) are used for the manufacturing of the blade woodworking tools with a long cutting edge. In many cases the use of these materials is economically feasible and sound as well as tools made of hard alloys.

The wear while the woodcutting is rather complex process which in general can be explained with chemical reactions in the contact area and wear mechanical action [2]. So one of the main criteria when choosing a surface hardening technology is abrasive resistance.

At present a lot of surface hardening technologies have been developed: thermomechanical, chemical-thermal, local thermal (gas-plasma, light-beam, plasma, induction, electron-beam, laser), electrospark, ultrasonic.

Chemical and thermal treatment is aimed at solving the problems of reducing such wear. It combines thermal and chemical action to change the chemical composition, structure and properties of the surface layer of metal or alloy. Chemical and thermal treatment is performed as a result of diffusion saturation.
of metal or alloy with non-metals (C, N, B, etc.) or metals (Al, Cr, Zn, etc.) at a certain temperature and an active saturating medium.

The cementation processes including tool steels cementation are most widely used processes to increase the durability of the most important parts [3].

Problem solution of the abrasive resistance increasing of the experimental tool steels made of non-heat resistant tool steels without a multiple cost increase will reduce the metal content of the process. Also it will improve the environmental performance of the process and increase the competitiveness of the equipment by reducing operating costs.

2. Theoretical part
The literature analysis of different methods of hardening with the help of cementation of the surface layer as well as the study of production experience showed that nowadays the most promising technological processes of cementation of the surface are:

- ion-plasma cementation in vacuum;
- cementation in arc and glow discharge under atmospheric conditions;
- laser cementation under atmospheric conditions.

The laser treatment has the greatest potential which helps to form resistant layer on the surface for one operation. This is possible due to the high rates of heating and cooling of laser action. The laser forms an ultra-fine structure on the surface characterized by increased mechanical characteristics.

There are several methods of laser cementation:
1. cementation from carbon-containing coatings [4],
2. cementation in a pressurized gas chamber with an alloying component [5],
3. cementation under atmospheric conditions with the gas current of an alloying component to the treatment area [6],
4. cementation with the use of the eroding carbon electrode [7].

The optimal scheme of laser cementation in terms of technological reproducibility and properties stability of the treated surface is shown in the paper [8]. The source of carbon is the erosion of the carbon electrode under the action of an electric arc of reverse polarity DC. Direct saturation of the surface is due to convection mixing and diffusion in the melt bath. The melt bath is formed due to the thermal effect of laser radiation. This scheme was chosen to increase the abrasive resistance of the experimental materials with laser cementation method.

3. The methodology of the experiment
Laser cementation of samples was performed at a special disc laser stand of maximum power 1 kW. The schematic diagram of the treatment is shown in Figure 1. The treatment area was protected with argon. A carbon electrode (SK d=10 mm according to the Technical Conditions 16-757.034-86) was used as a source of ions and carbon atoms. For a more accurate focusing of the carbon flux the contact tip of the electrode was sharpened to d=3 mm. The carbon electrode was fixed at 5 mm distance from the treated surface.

Figure 1. The schematic diagram of the laser cementation
The samples were fixed on the machine table to perform laser cementation, a carbon electrode (gas burner option) and a protective gas supply nozzle (argon) were installed on the scanning device with grippers. The cementation process was performed according to the developed control program with simultaneous supply of electric current to the electrode and focused laser radiation to the treated surface. The movement was transmitted directly to the scanning device.

The parameters of laser radiation and technological modes of the process are given in the Table 1. The power density of laser radiation, the movement speed of the laser spot and the initial structure of the materials were chosen as the parameters that affect the abrasive resistance and the process of surface saturation with carbon.

**Table 1. The modes of laser cementation.**

| Parameter                                      | Unit of Measure | Value          |
|-----------------------------------------------|-----------------|----------------|
| Wave length of laser radiation                | μm              | 1.03           |
| The power density of laser beam q             | 10⁴ W/cm²       | 3.8 – 11.5     |
| The diameter of the focused laser beam on the treated surface | mm              | 1.0            |
| The speed of the laser beam                   | mm/s            | 20; 30         |
| The focal length of the optical system        | mm              | 450            |
| Protective gas consumption (Ar)               | L/min           | 6-8            |
| Current strength                              | Ampere          | 50             |

The laser cementation was performed for the flat samples of steel Cr6WV and 8Cr6NiWTi of 150×50×10 mm. The initial structure and mechanical properties of the experimental materials are given in Table 2.

**Table 2. The modes of pre-heat treatment and the initial structure of the experimental steels.**

| Steel Grade      | The modes of thermal treatment | Hardness | Microstructure              |
|------------------|--------------------------------|----------|-----------------------------|
|                  | normaliz., t, °C    | hardening, t, °C | cooling medium | tempering, t, °C | HB | HRC |                      |
| Cr6WV            | 820                | 970      | air                        | oil | 200 | -    | 240 | 60-62 | perlite + carbides martensite + carbides |
| 8Cr6NiWTi        | 840                | 1000     | air                        | oil | 200 | -    | 244 | -     | perlite + carbides martensite + carbides |

Microhardness measurement was performed inward from the treated surface at the Microhardness Testing Machine PMT-3. Metallographic studies were performed at the optical microscope Neophot 21 and the scanning electron microscope JeoL JSM. Abrasive resistance was estimated by the relative units of mass loss while friction against loose particles according to State Standard 23.208-79. The samples without laser cementation were used as standard.

4. Experimental results and discussion
As a result of experimental work the hardened area with a carbon content of 1.8 – 2.1% is formed in the steel surface layer. The effect of power density on the thickness of carbon saturation is shown in Figure 2. The experimental data show that an increase of the power density of laser radiation increases the diffusion area with a marked power dependence (an increase of the power density of laser radiation decreases the rate growth of the saturated area). To a greater extent the thickness depends on the thickness of the melt bath and the waves formed on its surface causing convective mixing and the lifetime of the melt bath. These parameters ceteris paribus depend on the thermophysical constants of
steel (heat capacity, thermal conductivity and density). Therefore, there is an increase in the diffusion area with an increase of the power density of the laser radiation.

Figure 2. The effect of the laser radiation power density on the size of the diffusion layer

During the laser cementation process in addition to saturation of the surface layer with carbon due to high cooling rates hardening processes take place both in the saturated area and in the area with the initial chemical composition. The maximum microhardness for steel 8Cr6NiWTi is 8700 MPa, for Cr6WV is 7700 MPa. The microhardness of samples from the same tool steels but with different initial structure does not exceed the systematic measurement error. The thickness of hardening and the maximum microhardness are determined by the chemical composition of the hardened samples (including the result of saturation of the surface with carbon) and the mode of pre-heat treatment of the experimental steels. The results of the microhardness distribution deep into the treatment surface, the power density effect of laser radiation, pre-heat treatment into the thickness of carbon saturation for the experimental steels are shown in Figure 3, 4.

Figure 3. The effect of laser radiation power density on the microhardness of steel Cr6WV during laser cementation process:
1 – $q=3,8\times10^4$ W/cm², normalization; 2 - $q=3,8\times10^4$ W/cm², hardening+tempering; 3 – $q=7,6\times10^4$ W/cm², normalization; 4 - $q=7,6\times10^4$ W/cm², hardening + tempering

The Figures of hardness distribution show that the formed hardened area is larger in the hardened initial state than in the normalized one. For the hardened state the mechanical properties of the so-called tempering area are worse than the properties of the original structure. It happens due to the low heating temperature of the material not exceeding the hardening temperature.
Dendritic cast structure was found on the surface of the experimental steels (Figure 5). The dimension of the dendrites increases deep into the treated material; the phase composition of the surface layer is represented by a composition of martensite, austenite residual and carbides. A fine structure consisting of martensite, austenite and carbides is likely to be formed due to the volumetric absorption of laser radiation by the metal and a higher temperature gradient deep into the material than on the surface.

It was found that after laser cementation the amount of residual austenite increases in the surface. As a result of laser cementation there is an increase in the lattice period $\gamma$-Fe (austenite residual); indirectly it indicates that austenite is saturated with carbon to a greater extent.

The main reasons of residual austenite increase in the surface layer are:
1. Enrichment of the surface layer with carbon and the reduction of the martensitic point;
2. The carbides are dissolved in a greater extend than during furnace hardening with standard modes due to high temperatures and high power density of laser radiation energy.

As a result of laser cementation such structural defects as internal and external pores and cracks can be formed in the experimental steels. The main reasons of defects are the stresses in the surface layer due to the temperature gradient and the carbon concentration (cracks), accelerated ablation of the metal due to the high heating and low thermal conductivity oh 8Cr6NiWTi and Cr6WV steels. It is shown that the initial normalized structure has a tendency to the formation of defects. As a result of the full factorial experiment $2^3$ degrees the optimal modes were determined to ensure maximum performance and to exclude the formation of a defective structure (Table 3).

The tests with non-rigidly fixed particles were carried out to confirm the hypothesis of the effectiveness of laser cementation for improving abrasive resistance friction in accordance with State Standards 23.208-79. The resistance was estimated by the relative weight loss. A standard for each tool
steel grade was the samples of the same steel grade subjected to volumetric hardening and low tempering. The loss of mass was determined with accuracy up to 0.0001 g.

Table 3. Recommended modes of laser cementation.

| Steel Grade   | The power density of laser beam q, \(10^4\) W/cm² | Movement Rate, mm/sec. | Pre-heating | Current Strength, Ampere |
|---------------|---------------------------------|------------------------|-------------|--------------------------|
| 8Cr6NiWTi     | 8.9                             | 30                     | hardening+  | 50                       |
| Cr6WV         | 8.9                             | 30                     | tempering   |                          |

The number of turns for testing of all samples – 3600, rotation speed - 60 turns/min. The results of calculation of the coefficient of relative resistance is shown in Figure 6.

Figure 6. The relative resistance of the experimental steels

As a result of laser cementation there is an resistance increase of all experimental tool steels grades. There can be several explanations for this.

First, microhardness of the surface after laser cementation is not the maximum compared with the results of laser hardening of the experimental steels. [9]. It is obvious that the microhardness decrease is connected with the residual austenite increase, which is a "softer" phase. Residual austenite has a higher thermal conductivity (\(\lambda=0.1\) cal/(cm·s·°C)) compared to other structural components (e.g. carbides \(\lambda=0.017\) cal/(cm·s·°C)) [10]. Local heating at the contact point releases excess heat preventing overheating and strength loss due to tempering.

Secondly, it is possible that the residual austenite has deformation martensitic transformation during the material operation strengthening its surface [11].

Thirdly, there is a grinding of carbides [12]. The dispersion of carbides is significantly increased. It should be said that some carbides do not have time to be dissolved and present in the structure almost unchanged being additional crystallization centers.

5. Conclusions

The modes of laser cementation improving abrasive resistance of the experimental tool steels are shown in the paper.

The influence of the energy parameters of laser cementation, the initial structural state for the formation of the hardened area, the thickness of diffusion carbon saturation, the probability of surface defects are determined in the paper. It is shown that the most hardened layer is formed by laser cementation of samples after hardening and low tempering.

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