AVALIAÇÃO DA EFICIÊNCIA DE ENDURECIMENTO COM O MECANISMO DE TRANSFERÊNCIA DE CALOR MASSA CONVECTIVO DURANTE A LIGA SUPERFICIAL A LASER NO MODO DE REFUXO

EVALUATION OF HARDENING EFFICIENCY WITH CONVECTIVE HEAT AND MASS TRANSFER MECHANISM DURING LASER SURFACE ALLOYING IN REFLOW MODE

ОЦЕНКА ЭФФЕКТИВНОСТИ УПРОЧНЕНИЯ ПРИ КОНВЕКТИВНОМ МЕХАНИЗМЕ ТЕПЛОМАССОПЕРЕНОСА ВО ВРЕМЯ ЛАЗЕРНОГО ПОВЕРХНОСТНОГО ЛЕГИРОВАНИЯ В РЕЖИМЕ ОПЛАВЛЕНИЯ

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RESUMO

O estágio atual de desenvolvimento de tecnologia exige muito das características operacionais das peças. Vários componentes e peças de máquinas, ferramentas de corte de metal, elementos estruturais metálicos trabalham sob condições de maior atrito, altas cargas específicas, altas temperaturas, uma ampla gama de velocidades e exposição a ambientes agressivos, por exemplo. Portanto, a melhoria da qualidade, confiabilidade, eficiência e produtividade de máquinas, ferramentas, equipamentos e outros produtos de engenharia mecânica, reduzindo seu consumo específico de material e consumo de energia, é alcançada principalmente pelo uso de materiais e tecnologias de endurecimento progressivo para aumentar a força, a resistência ao desgaste, à resistência, à corrosão e outras propriedades físicas e mecânicas das peças de máquinas e ferramentas. Portanto, o principal objetivo do trabalho foi avaliar a transferência de massa durante a adição superficial a laser no modo fusão. Para avaliar a eficácia das tecnologias de endurecimento de superfície, propõe-se o uso de dois novos parâmetros – desgaste reduzido e microdureza integrada reduzida da camada superficial modificada. Com base na análise dos dados experimentais sobre o desgaste de uma fresa de aço de cromo-tungstênio-zircônio e U10, processada pelo laser com manchas no modo de fusão, se mostra a existência de uma correlação entre os parâmetros inseridos e a equação de regressão foi obtida. A abordagem proposta para avaliar a eficácia do endurecimento da superfície pode ser usada não apenas no caso particular de modificação a laser, mas também para qualquer outra tecnologia para criar revestimentos funcionais com gradiente.

Palavras-chave: *endurecimento superficial, resistência ao desgaste, desgaste reduzido, microdureza integral reduzida, liga a laser.*

ABSTRACT

The modern stage of equipment development imposes increased requirements for the performance characteristics of parts. Different components and parts of machines, metal-cutting tools and metal structural elements work in the conditions of high friction, high specific loads, high temperatures, a wide range of speeds and impact of aggressive media, for instance. Therefore, improvement the quality, reliability, economical efficiency and productivity of machines, tools, equipment and other engineering products as well as reduction of their specific material consumption and energy consumption is achieved primarily by the use of materials and progressive strengthening technology that improve the hardening, wear resistance, corrosion resistance and other physical and mechanical properties of machine parts and tool. Therefore, the main objective of the paper was to evaluate the mass-transfer during laser surface alloying in the reflow mode. To evaluate the effectiveness of surface hardening technology, it was proposed to use two new parameters – reduced wear and reduced integrated micro hardness of the modified surface layer. Based on an analysis of the experimental data

on the wear of a cutter made of HVG and U10 steel, processed by a laser with smears in the reflow mode, the existence of a correlation between the entered parameters is demonstrate and the regression equation is obtained. The proposed approach to evaluating the effectiveness of surface hardening can be used not only in the special case of laser modification but also for any other technology for creating gradient and functional coatings.

Keywords: *surface hardening, wear resistance, reduced wear, reduced integral micro hardness, laser alloying.*

АННОТАЦИЯ

Современный этап развития техники предъявляет повышенные требования к эксплуатационным характеристикам деталей. Различные узлы и детали машин, металлорежущие инструменты, металлические элементы конструкций работают в условиях повышенного трения, больших удельных нагрузок, высоких температур, широкого диапазона скоростей, воздействия агрессивных сред и т. д. Поэтому повышение качества, надежности, экономичности и производительности машин, инструмента, оборудования и других изделий машиностроения, снижение их удельной материалоемкости и энергопотребления достигается прежде всего применением материалов и прогрессивных упрочняющих технологий, позволяющих повысить прочность, износостойкость, коррозионную стойкость и другие физико-механические свойства деталей машин и инструмента. Поэтому основная цель работы заключается в оценке массопереноса во время лазерного поверхностного легирования в режиме оплавления. Для оценки эффективности технологий поверхностного упрочнения предложено использовать два новых параметра – приведенный износ и приведенную интегральную микротвердость модифицированного поверхностного слоя. На основе анализа экспериментальных данных износа резца из стали ХВГ и У10, обработанного лазером с обмазками в режиме оплавления, показано существование корреляционной связи между введенными параметрами и получено уравнение регрессии. Предложенный подход к оценке эффективности поверхностного упрочнения может быть использован не только в частном случае лазерного модифицирования, но и для любой другой технологии создания градиентно-функциональных покрытий.

Ключевые слова: *поверхностное упрочнение, износостойкость, приведенный износ, приведенная интегральная микротвердость, лазерное легирование.*

1. INTRODUCTION

Obvious advantages of laser technologies of surface hardening are high heating and cooling rates, lack of contact during processing, locality and the ability to process hard-to-reach areas, absence of deformation of the work pieces and the relative simplicity of technology, as well as possibility to modify the surface of materials to obtain new physical, mechanical and operational characteristics (Moldagozhieva *et al.*, 2017; Burkov *et al.*, 2018). The modification method is especially effective for parts that operate under sliding friction, abrasive and erosive wear and for tool hardening, namely, for cutting tools of simple shape and small dimensions of the cutting edge. Thus, it makes, inexpensive low-alloy tool steels, modified layers of high hardness, strength, wear resistance, heat resistance, similar in properties to high-alloy high-speed steels (Orlov *et al.*, 2003; Skvortsov *et al.*, 2009; Skvortsov and Karizin, 2012; Skvortsov *et al.*, 2016; Skvortsov and Karizin, 2017). Therefore, alloying the surface of such steels is done according to the regimes providing possibility of modification, i.e. with surface melting. When the surface is melted as a

result of laser exposure, the alloying elements of coating are mixed with the base material and they interact.

The mechanism of mass transfer during laser alloying is quite complex and does not have common interpretation. In number of works (Borovsky *et al.*, 1982; Arutyunyan *et al.*, 1988) it was shown that the circulation process and movement of the melt due to *thermocapillary effect* are the basis of transfer process. On the surface of melt, the temperature decreases from the center of irradiation to the edge of liquid bath. As the melt temperature changes, the surface tension force also changes, increasing toward the edges of liquid bath. Due to a change in the surface tension force, melt moves from the center of liquid bath to its edge; this movement of the melt on surface is transmitted inward due to the forces of viscous friction. An approximate calculation of the motion of melt and the shape of its surface suggests evaluating velocities of the motion of molten metal and the role of surface tension forces.

The calculations shown by the authors of (Borovsky *et al.*, 1982) for iron, with width and depth of melting zone of 2.0 and 0.2 mm,

respectively, and temperature difference in the central and regional parts of 500° C, showed that the mass of the melt in the surface layer can move at a speed of the order of 1-3 m / c, and its internal areas – with a speed of 3-4 times less. The mass transfer model based on thermocapillary effect accounts for the observed high rates of mass transfer and melt mixing. In the work (Arutyunyan *et al.*, 1988), the authors, exploring the possibility of alloying 10X18H9T tantalum steel under the action of monochromatic radiation, explain the characteristic depths of tantalum penetration (to a depth of about 100 nm) by *diffusion in liquid phase*. The nature of concentration profiles of tantalum and calculation of diffusion coefficient, which is estimated to be of the order of $10^{-8} \text{ m}^2 / \text{s}$, which is characteristic of diffusion in liquid phase, are presented.

In the works (Belashova, 2004; Belashova and Tarasova, 2008; Belashova *et al.*, 2009), the fact of the ***parallel action of convective and thermal diffusion mass transfer*** during laser irradiation is established, which is some obstacle to obtaining a stably uniform doped layer: the action of the first mechanism leads to significant inhomogeneity of melting bath, and due to the second, the convective flows of alloying are continuously dissolving elements. Despite the fact that action of the second mechanism leads to a more uniform distribution of alloying elements over melting bath, the microstructure of the layer remains extremely uneven, areas with different etchability are observed, which are located in different parts of melting bath (Figure 1). It was also established: that both various etchability and abrupt changes in micro hardness are associated with changes in the concentration of alloying elements in the volume of melting both. These micro hardness jumps are characteristic of the mixing mechanism during laser alloying and they do not depend on the type of alloying element.

Laser technologies of surface hardening differ both in the depth of the modified layer and in the nature of change of its properties along depth. Thus, the problem arises of choosing the optimal technology parameters, in particular, the compositions of alloying ingredients that provide the greatest wear resistance of the modified surface layer. To get a theoretical solution to this problem by methods of mathematical modeling is currently quite difficult, based on the above alloying mechanism, and the fact that experimental studies of wear processes are very time-consuming and lengthy. So, it seems appropriate to use other criteria for quantifying

the effectiveness of laser technologies of surface hardening, which have correlation with wear resistance and allow experimental determination at smaller cost.

In this work, for the criterion, it is proposed to use a new characteristic – ***reduced integral micro hardness***. The definition of the introduced parameter is given below and, based on the processing of experimental data, it was demonstrated that there is a significant correlation between it and the wear resistance of the modified surface layer.

2. MATERIALS AND METHODS

As the studied materials, low alloyed and carbon tool steels HVG and U8-U10 were selected. Samples were pre-heated by the standard treatment for each type of steel in a tempering temperature from 780-800 °C and low temperature tempering, 180-220 °C. The powders were deposited in form of coating with an organic binder. Hardening was performed on a "Quantum-16" laser machine of pulsed action with a telescopic nozzle that improves collimation of radiation. The samples were processed after laser had reached stable operation. The radiation power density was varied both by changing the pulse energy and focal length, i.e. position of the surface of sample relative to the focal plane of output lens of the laser optical system (ΔF). Depending on power density and thickness of saturating coating (δ), various structures of hardened zones were obtained that have specific for this mechanism and difficult to predict micro hardness distribution over cross section of melt pool. Micro hardness was measured on PMT-3 instrument with load of 0.98 N.

The geometric dimensions of the spot were calculated from the diameter and thickness of laser irradiation area. The diameter of laser exposure area is the distance between boundaries of structural transformations on the metal surface; the thickness of laser exposure area is the maximum distance in the center of phase transformations to the initial structure.

The wear resistance was determined during wear of the sample after laser alloying by friction paired with a counter body on SMT-1 friction machine. The counter body was made of 30 HGS steel after heat treatment with hardness of 50 ... 56 HRC. The disk rotation frequency was 300 rpm, the force of pressure of the test sample to the disk was 240 N. The specific pressure was 1.2 MPa. As coolant (cutting fluid) AKVOL-3 was used, which filled the

test chamber. Then, the samples were ground until reaching the contact surface of 95% using diamond paste AFM 40/28. Prior to the test, the samples were washed, dried and weighed on analytical balance with an accuracy of 0.05 mg. Given the number of revolutions of disk and the load on the sample, after 30 minutes, weighing of frayed samples was repeated.

During the tests, the moment of friction was registered and the coefficient of friction was determined; The temperature of samples was measured using a thermocouple and a potentiometer.

In order to study kinetics of laser alloying and the phenomenon of mass transfer, distribution of elements in the alloying areas was studied by X-ray spectral and radiographic analyzes.

When alloying, heating was done to temperatures exceeding the melting temperature. Thus, the laser exposure area consists of a melting area and a thermal influence area. These characteristics were measured using a metallographic microscope with an accuracy of 0.01 mm.

3. RESULTS AND DISCUSSION:

To quantify the effectiveness of surface hardening technologies, authors proposed to use a new parameter – reduced wear Y equal to the ratio of wear of modified surface layer to tool wear in the absence of hardening in the same operating conditions (tests). Reduced wear Y is a dimensionless quantity that characterizes the decrease in wear (increase wear resistance) of modified surface layer. In absence of hardening, specified wear Y the base metal is assumed to be 1. Nonetheless, the experimental determination of reduced wear Y is very laborious and time consuming. Thus, it seems appropriate to try using other criteria for quantifying the effectiveness of surface hardening technologies, which have correlation with the wear Y and allowing experimental determination with less cost.

As it was noted above, one of the parameters of modified surface layer, which is not difficult to determine experimentally, is its micro hardness. Figure 2 displays the distribution of micro hardness of depth of hardened layer by doping with various coating saturating. It is easy to see that the nature of change in micro hardness in depth for different compositions of

alloying composition is significantly different. For example, when doping from coating, where titanium is the saturating medium, a layer with depth of up to 50 μm with high micro hardness (up to 18000 MPa) is obtained on the surface of sample, then it drops to 10300 MPa, and evens out at depth of 100 to 150 μm at hardness values of 11700-13000 MPa. For the coatings in which niobium is the main alloying component, the graphs have a completely different look: on the surface of sample, the hardness values do not exceed 13000 MPa, then at depth of about 50 μm the micro hardness of layer sharply increases to 16000-18000 MPa and then decreases to 13000 MPa by depth of 100-150 μm .

It brings a question: is it possible to use any characteristic of the micro hardness distribution non-uniform in depth as a criterion for quantifying the effectiveness of laser technologies of surface hardening, i.e., is there a correlation between such a characteristic and reduced wear. To make it easy, peak (maximum) micro hardness values could be used for this purpose. Nonetheless, this approach was not successful: it was not experimentally possible to establish a correlation between this parameter and wear resistance (Belashova, 1998). This is because of the fact that under conditions of operation of products from tool steels, the work of the entire layer as a whole is important, i.e. its integral characteristic. Thus, as a desired criterion, it is proposed to use a new characteristic – the reduced integral micro hardness of modified surface layer Y' , which is calculated by the Equation 1.

Where h - is depth of the modified layer;
 H_{μ}^0 - is micro hardness of the base metal;
 $H_{\mu}(x)$ - is micro hardness of the modified layer at a point at a depth x , $0 \leq x \leq h$.

From the formula (1) it follows that the reduced integrated micro hardness of the modified surface layer Y' is dimensionless quantity and characterizes the change in micro hardness of the entire modified layer with respect to the micro hardness of homogeneous layer of base metal of the same thickness. In the absence of hardened layer, the parameter Y' should be assumed equal to 1. Let us note that, in contrast to the peak values of micro hardness, the reduced integral micro hardness of modified surface layer Y' characterizes properties of the entire modified layer.

The advantage of introduced parameter is

the simplicity of its calculation directly from experimental data: the value of reduced integral micro hardness is proportional to the area of curved trapezoid, limited from above by the graph of micro hardness of modified layer in depth. When tabulating the dependence of micro hardness over depth of modified layer, the area of curved trapezoid can be calculated using simple quadrature formulas, for example, the trapezoid formula.

To confirm the existence of correlation between reduced wear $\bar{Y}$ and reduced integral micro hardness $\bar{Y}'$ of modified surface layer, results of experimental studies of the wear of a cutter made of HVG and U10 steel, treated with laser with smears in flash mode, were used (Belashova, 1998). Titanium, niobium and carbon (graphite) were chosen as alloying elements for the surface modification and hardening of the studied instrumental steels.

During experiments, chemical composition of saturating coating was varied. The elements that participate in compounds form a triple system, therefore, to select the content of components in compounds, the simplex lattice method proposed by Scheffe (Scheffe, 1963) for constructing "composition-property" diagrams were used.

As we know, a measure of tightness of functional relationship between two random variables is the pair correlation coefficient. The value can vary from 0 to ± 1 . If it comes close to zero, then the connection is either completely absent or is substantially nonlinear. If it comes close to ± 1 , then the connection is linear. At the range of intermediate values, the relationship is stronger, the closer the correlation coefficient to unity. For processing experimental results provided in (Belashova, 1998), the method for calculating the correlation coefficients proposed in (Novik and Arsov, 1980) was used. As a result of calculations, the pair correlation coefficient for reduced wear $\bar{Y}$ and reduced integral micro hardness $\bar{Y}'$ modified surface layer was equal to $-0,73$, which allows us to conclude that there is a significant linear relationship between these two parameters. The corresponding linear regression model has the following look Equation 2.

Therefore, when conducting experiments on selecting the optimal parameters of hardening technologies that provide the greatest wear resistance of modified surface layer, it is possible to exclude laborious tests of wear resistance and use reduced integral micro hardness as an

optimization criterion $\bar{Y}'$ of modified surface layer, the finding of which requires less time (Rabinsky and Tushavina, 2019; Formalev *et al.*, 2018a; Kakhramanov *et al.*, 2017; Lomakin *et al.*, 2018; Lomakin *et al.*, 2017; Formalev *et al.*, 2018b; Formalev and Kolesnik, 2019; Babaytsev *et al.*, 2017; Formalev *et al.*, 2017; Bulychev *et al.*, 2018; Rabinskiy and Tushavina, 2019a; Nikitin *et al.*, 2019; Rabinskiy and Tushavina, 2019b).

4. CONCLUSIONS:

To assess the effectiveness of laser technologies of surface hardening, it was proposed to use two new parameters – reduced wear and reduced *integrated micro hardness* of modified surface layer. Based on analysis of experimental data on the wear of cutter made of HVG and U10 steel, processed by laser with smears in reflow mode, the existence of correlation relationship between the introduced parameters was demonstrated. Considering that the experimental studies of wear processes are very laborious and lengthy, the presence of correlation between the entered parameters can significantly reduce the complexity of research when assessing the effect of a particular type of alloying coating on cutting properties of instrumental materials.

The proposed approach to assessing the effectiveness of surface hardening can be used not only for the particular case of laser modification, but also for any other technology of creating gradient-functional coatings.

The possibility of evaluating hardening efficiency under various thermal conditions is outlined in.

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$$Y' = \frac{1}{hH_{\mu 0}} \int_0^h H_{\mu}(x) dx \quad (\text{Eq. 1})$$

$$Y = 1,29 - 4,55 \times Y' \quad (\text{Eq. 2})$$

Figure 1. Microstructures of laser exposure zones: a) – is steel U10, pulse energy $E_{imp} = 20 \text{ J}$, coating density $\delta = 5 \text{ mg/cm}^2$, coating composition: titanium-niobium-carbon; b) – is steel 12X13, $E_{imp} = 15 \text{ J}$, $\delta = 4 \text{ mg/cm}^2$, laser cementation, (x250)

Figure 2. Micro hardness distribution over the depth of hardened layer upon alloying with various saturating coatings (the choice of compositions according to Scheffe method [5]):

- 1 – Ti: Nb: C = 1: 1: 1; 2 – Nb: C = 2: 1; 3 – Ti: C = 2: 1; 4 – Nb: C = 1: 1;
 5 – Ti: Nb = 1: 1; 6 – Nb: C = 5: 1; 7 – Ti: C = 5: 1; 8 – Ti: Nb: C = 1: 1: 2;
 9 – Ti: Nb: C = 2: 4: 1; 10 – Ti: Nb: C = 4: 2: 1; 11 – Nb (100%); 12 – Ti (100%);
 13 – Ti: Nb = 1: 1; 14 – Ti: Nb = 1: 3; 15 – Ti: Nb = 3: 1