Tribomechanical properties of the tool steels surface after laser modification

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Abstract. The influence of pulsed laser hardening treatment of tool steels on the adhesion component of the friction coefficient at movable contact with structural steel is considered. The description of the diagnostic complex with a computer data collection system intended for measuring the adhesion component of the friction coefficient is given. By the example of friction contact in the bushing-cone system at the axial motion of a cone with a hardened lateral surface, it is shown that laser hardening leads to a decrease of the friction coefficient by 20-50 % when the contact normal stresses are 120-180 MPa.

1. Introduction

Reducing wear of machine parts and metalworking tools is an important engineering problem. One of the main reasons for wear of machine parts and cutting tools is the friction that occurs during the interaction of the contacting surfaces. The adhesion phenomena, caused by the forces of intermolecular interaction plays the decisive role in this process. The degree of interaction between contacting surfaces during friction is characterized by an adhesive (molecular) component of the friction coefficient. Many studies have been devoted to the search for effective ways to reduce adhesion. The hardening laser treatment (LT) in air can be considered as one of the methods which able to provide a decrease in the wear rate of the contacting surfaces. Reduction of parts wear after hardening is caused by high hardness of the surface, high dispersity of the structure, increase in bearing properties of the surface, decrease in the friction coefficient, etc. The oxide film is formed on the laser exposure zone surface after laser treatment on the air. The properties of oxide films of the laser treatment zone have a significant effect on the friction process. The presence of a hardened layer and oxide film in the contact area of the parts reduces the adhesion of the contacting surfaces, preventing them from grasping, reduces wear, and increases the durability of machine parts.

As a rule, the effect of laser treatment on tribomechanical properties of the surface of the hardened material is considered at pressures in the contact zone, not exceeding 10 MPa. At higher contact pressure equal to 300 MPa at loading under the "plane-roller" scheme a positive effect of hardening laser treatment was achieved also [1]. However, due to the chosen loading scheme, the contact pressure did not exceed 50 MPa at the end of the test, which is not commensurate with the stresses during cutting.

The aim of this work was the experimental evaluation of the adhesion component of the friction coefficient at contact of tool and structural steels after laser hardening of the contact surface at high
values of normal contact stresses.

2. Experimental technique
The study of adhesion characteristics of the contact surface was carried out on the diagnostic complex described in [2], the principle of which is based on the method of I. Kragelsky [3]. The basis of this method is following: adhesive bonds, which are the result of the action of Van der Waals’ forces arise between the contacting surfaces on the contact spots under the compressive load. These forces arise when two solid bodies are contacted under a compressive load and are accounted by the molecular component of the friction coefficient. The mechanical component of the friction coefficient is determined by the deformation properties of the frictional bond. Since the adhesion interaction involves the thinnest surface layers, and the deformation processes take place in deeper layers (2-3 orders of magnitude), then both of these interactions can be considered independently, and the integral component of the friction force can be represented as a sum of these components.

In a zone of dynamic contact of the tool with the work material the complex system is formed, which possesses specific properties different from properties of the tool and work materials, considered separately out of contact. For a number of reasons it is practically impossible to determine the shear strength of adhesive bonds (τn) from data on contact processes, obtained directly in the working of metals. Among them, the main ones are: irregular distribution of pressure and temperature at the contact area, different chemical purity and discreteness of contact of the contacting surfaces, which makes difficult to determine the actual contact loads. Taking into account all these factors, it is not possible to calculate the value of τn on the basis of theoretical analysis alone. Therefore, the only way to obtain reliable data on the adhesive interaction between the tool and the workpiece is a direct experiment performed under conditions as close as possible to the processing conditions, namely under high contact pressures and temperatures. Under the experimental procedure, such conditions must be created when the shear strength of the adhesion bonds plays a decisive role in the wear process.

The physical model, which in the first approximation reflects the real conditions of friction and wear in the cutting zone, was used to estimate the friction characteristics of the shiftable contact. According to this model, the sample-indenter (made of tool steel) in the form of a truncated cone is inserted into a cylindrical sample (structural steel). Then the normal load (N) is applied to the cone, and the cylinder rotates around its own axis, while the cone sample remains stationary (figure 1). Three main stages characterize the dynamics of the experiment: I – the system is in an unloaded state; II – the stage of the active experiment, including the stage of application of the normal load and the stage of moving of the cylinder with respect to the cone; III – the stage of analysis and diagnosis of the contact area.

![Figure 1. Stages of the full-scale experiment.](image_url)

The diagnostic complex for the investigation of adhesion interaction, based on the model described above, is shown in figure 2. It consists of two parts: a loading device with a normal load sensor and a
device that provides a relative movement of the contact pair, which is under the influence of a compressive normal load with a breakaway force sensor.

Figure 2. The diagnostic complex scheme for measuring the adhesion component of the friction coefficient: 1 – base; 2 – racks; 3 – bearing support; 4 – bearing; 5 – cylinder holder; 6 – cylinder; 7 – cone; 8 – pusher; 9 – normal load cell; 10 – screw-pusher; 11 – thrust; 12 – guides; 13 – thrust support; 14 – screw-draft; 15 – support of breakaway force sensor; 16 – breakaway force sensor.

The principle of operation of this diagnostic complex is as follows. The normal load \( N \) is created by the movement of the pusher screw 10, passing through the normal load cell 9 and the pusher 8 the loading force on the contact pair "cylinder-cone" 6, 7. The rotational motion of the cylindrical sample 6, which is hard fixed in the holder 5, located on the bearing 4, is provided by a thrust 11. The system consisting of ways 12, on which the thrust support 13 and support of breakaway force sensor 15 move with the help of the screw-draft 14, which transmits the movement to the thrust 11, rotates the cylindrical sample 6. Signals from the load cells are fed to the data acquisition board and signal booster, and then saved to the personal computer. Load cells of normal load 9 and breakaway force (tangential force) 16 consist of elastic elements made from spring steel with resistive-strain sensor attached to them, connected by a half-bridge circuit. The half-bridges formed by load cells were supplemented to a full measuring bridge using precision resistors. When the elastic element is loaded, on the arms of the measuring bridge a potential difference occurs, proportional to the deformation of the sensor arises, which is fed to the inputs of the differential amplifier. Amplifier output signal hits the divider, by means of which the sensors were calibrated. The sensors were calibrated using a standard portable reference dynamometer of a compression on loading of 5000 N (for measuring the normal load) and 300 N (for measuring the force of breakaway).

Figure 3 shows a scheme for determination the tangential strength of adhesive bonds under friction. In this scheme, \( \phi_0 \) is the angle of the cone vertex; \( r_1 \) and \( r_0 \) are the radii of the inner hole of the cylindrical sample before and after loading, respectively. The force expended on the rotation of the cylindrical specimen \( (F) \) is mainly due to the shear strength of the adhesive bonds, since the deformation component of the tangential forces is negligibly small. The adhesion component of the friction coefficient \( (f_a) \) is
defined as $f_M = \tau_n / p_n$, where $\tau_n$ is average shear stress, $p_n$ is the normal contact stress acting on the surface of the cylindrical sample in the entire imprint area ($S$). It follows from figure 4 that the projection of the force $N$ on the normal to the surface is: $N_n = N \cdot \sin(\varphi_0 / 2)$.

Considering that $p_n = N_n / S$, where area of contacting surface is

$$S = \int_0^{2\pi} \int_{r_1}^{r_0} dS = 2\pi \int_{r_1}^{r_0} r dr = \frac{\pi \cdot (r_0^2 - r_1^2)}{\sin(\varphi_0 / 2)},$$

we receive

$$p_n = \frac{N \cdot \sin(\varphi_0 / 2)}{S} = \frac{N \cdot \sin^2(\varphi_0 / 2)}{\pi \cdot (r_0^2 - r_1^2)}. \tag{1}$$

To rotate a cylindrical specimen about a geometric axis, it is necessary to attach a moment:

$$M = \int \tau_n r dS = \tau_n \int_0^{2\pi} \int_{r_1}^{r_0} r dr d\varphi = \frac{\tau_n}{\sin(\varphi_0 / 2)} \int_{r_1}^{r_0} r^2 dr \int_0^{2\pi} d\varphi.$$

After integration:

$$M = \frac{2\pi}{3} \cdot \frac{\tau_n}{\sin(\varphi_0 / 2)} \cdot (r_0^3 - r_1^3). \tag{2}$$

On the other hand

$$M = F_{\text{exp}} \cdot R, \tag{3}$$

where $F_{\text{exp}}$ is the breakaway force recorded during the experiment; $R$ is the radius of the cylinder holder 5 (figure 2) in which the sample is fixed, $R=30$ mm.

Equating (2) and (3), we obtain an expression for determining the value of the average shear stress $\tau_n$:

$$\tau_n = \frac{3}{2\pi} \cdot \frac{F_{\text{exp}} \cdot R \cdot \sin(\varphi_0 / 2)}{(r_0^3 - r_1^3)}. \tag{4}$$
Then the final formula for determination of the adhesion component of the friction coefficient is:

$$f_\text{M} = \frac{\tau_\text{n}}{p_\text{n}} = \frac{3}{2\pi} \frac{F_\text{exp} \cdot R \cdot \sin(\phi_0/2)}{(r_0^3 - r_1^3)} \cdot \frac{\pi \cdot (r_0^2 - r_1^2)}{N \cdot \sin^2(\phi_0/2)} \cdot \frac{2}{2} \frac{R \cdot (r_0^2 - r_1^2)}{(r_0^3 - r_1^3) \cdot \sin(\phi_0/2)} \cdot \frac{F_\text{exp}}{N}. \quad (4)$$

Here $r_1=6\text{mm}$, $\phi_0=45^\circ$, and the value of $r_0$ and the values of the forces $F_\text{exp}$ and $N$ are determined from the experiment.

3. Experimental result

In experiments under conditions of dry friction a contact interaction was simulated between a cylindrical specimen of structural steel 20 (USA, ASTM analog – steel 1020) and a cone made of steels: high-speed steel P18 (USA analog – T1, Germany DIN standard – HS18-0-1), alloy tool steel 9XC (Germany DIN standard – 150Cr14), blanking steel X12M (USA analog – D2, Germany DIN standard – X165CrMoV12) and carbon tool steel U7 (USA analog – W1-7, Germany DIN standard – C70W2), with and without preliminary laser treatment of the cone forming surface. Laser treatment was carried out in a pulsed mode on air with a fluence equal to 2.2-2.4 J/mm$^2$. These modes of laser treatment provided the formation of a stable oxide film on the surface of the laser exposure zone. Under this treatment regime, the depth of the laser exposure zone for high-speed tool steel was 65-70 $\mu$m, and the microhardness increased up to 9 GPa, in comparison with 6.5-7.0 GPa for the basic material [2]. Formed on the surface of the laser exposure zone the multilayer oxide film mainly consists from Fe$_3$O$_4$, and its thickness does not exceed 0.2 $\mu$m [4].

The load N in the experiments was selected in such way that the contact zone provides an average contact stress equal to the stresses during metal cutting. Taking into account the geometry of the model samples, the actual value of the normal load was about 3000 N and potentially could be increased to 5000 N. The calculated value of the normal stresses at the contact was in the range of 120-180 MPa (table 1).

| Contact pair                  | $N$, N    | $F_\text{exp}$, N | $p_\text{n}$, MPa | $\Delta l$, $\mu$m | $f_\text{M}$ |
|------------------------------|-----------|-------------------|-------------------|---------------------|-------------|
| 1020-150Cr14 without LT      | 2934.07±10.66  | 138.22         | 122.73           | 226.5±28.3         | 0.658       |
| 1020-150Cr14 with LT         | 2959.13±6.69   | 82.69          | 136.02           | 218.2±32.4         | 0.365       |
| 1020- D2 without LT          | 2901.09±7.89   | 113.42         | 131.78           | 215.5±17.4         | 0.519       |
| 1020- D2 with LT             | 2913.29±8.87   | 57.66          | 119.69           | 244.6±46.5         | 0.259       |
| 1020- W1-7 without LT        | 2947.65±10.16  | 90.40          | 181.81           | 217.3±17.8         | 0.823       |
| 1020- W1-7 with LT           | 2951.25±6.90   | 97.22          | 125.64           | 236.2±36.7         | 0.436       |
| 1020- T1 without LT          | 2886.0±92.0  | 132.90          | 135.56           | 215.0±21.0         | 0.596       |
| 1020-T1 with LT              | 3125.0±72.0   | 115.31         | 135.68           | 232.5±20.6         | 0.478       |

The results of the experiments are presented in table 1. Here it is also presented the data on the magnitude of normal contact stresses $p_\text{n}$, calculated by the formula (1), and the average values of the width $\Delta l$ of the contact islands on the inner surface of the hole of the cylinder after loading, according to the results of 10 measurements in randomly chosen directions. Figure 5 shows typical dependences of the normal load N and the breakaway force $F_\text{exp}$ during the contact of steel 1020 and steel 150Cr14 after laser treatment (figure 5a) and without the laser treatment of the cone surface (figure 5b). Figure 6 shows a typical view of the contact area on the inner surface of a cylindrical specimen after unloading for contact pair steel 1020 and steel W1-7.
Analysis of experimental results shows that hardening laser treatment leads to a decrease in the friction coefficient, or rather its adhesion component by 20-50% regardless of the materials of the contact pair.

Figure 5. Change of normal load $N$ (curve 1) and tangential force of breakaway $F_{exp}$ (curve 2) during the time of the experiment.

Figure 6. The appearance of the contact area on the inner surface of the hole of a cylindrical specimen, $\times 20$.

4. Conclusion
The results of the experiments showed that hardening laser treatment of the contact surface leads to a decrease in the friction coefficient at the contact “tool-work material” by 20-50% with normal contact stresses of 120-180 MPa. The established reduction in the friction coefficient is an important factor ensuring high performance characteristics of hardened parts of machines and metalworking tools operating in conditions of increased pressures at the contact.

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