Experimental definition of rational modes of shock-acoustic treatment

S B Skobelev[1], V F Kovalevsky[1], E G Bezzateeva[1], G G Bury[2], I K Poteryaev[2]

[1]Omsk State Technical University, 11 Mira ave., Omsk, 644050, Russia
[2]Siberian State Automobile and Highway University (SIBADI), Omsk, Russia

Abstract. The paper presents the results of experimental studies to determine the rational technological parameters of shock-acoustic treatment (SAT) in order to provide the best antifriction properties for the outer surfaces of parts made of Steel 45. On the basis of experimentally selected processing modes, the specified values of overlap coefficients for the ultrasonic instrument and workpiece contact areas are determined. The use of shock-acoustic treatment with simultaneous application of a solid lubricant coating allows the surface microhardness to be increased almost by the factor of two and the roughness to be reduced to *Ra 0.2*.

Keywords: shock-acoustic treatment, contact area, overlap coefficient, microhardness, wear resistance.

1. Introduction

Steel 45 is widely used in mechanical engineering in the manufacture of parts such as stepped shafts, spindles and cams, gears, fasteners, and sheet material, that is, parts operating at high specific loads and being used in friction pairs. According to statistics, in 80% of cases, the cause of components and assemblies failure is the wear of working surfaces of friction pairs [1]. Therefore, providing the necessary anti-friction properties of parts made of this material is a relevant task for mechanical engineering technology.

Introduction of such operations as heat treatment (quenching, tempering, and normalization) is provided to improve anti-friction properties in the processes of parts manufacturing. For example, the use of carbon normalized steel 45 with plasma quenching instead of improved structural steel 40X not only reduces the wear of parts and costs of materials, but also reduces the process [2, 3].

In addition, methods of chemical-heat treatment in powder mixtures of a certain composition are used in order to increase corrosion resistance. These methods strongly improve the corrosion resistance of diffusion-chrome carbon steels [4, 5]. For instance, the use of ion-beam nitriding for gear teeth allows the increase of the surface layer microhardness to the values of HV 1200...1800 with a multiple increase in wear resistance [6].

Methods of applying protective antifriction coatings by creating a film on the surface of the product are also used. The use of coatings by self-propagating high-temperature synthesis (SHS) with chromium and boron compounds as the main ingredients of the charge allows one to obtain antifriction coatings with a thickness of 35...40 μm due to changes in the content of boron in the charge and the process time, namely the exposure in the reactor [7].

Production of thin antifriction films applies the technology of magnetron sputtering. The advantages of this technology are as follows. The first is versatility (i.e. the ability to apply coatings from almost any material), the second is high process control, the other one the possibility to obtain a uniform coating, and the ability of applying multi-layer coatings. The use of this technology allows one to increase the nano-hardness of the surface layer by more than three times and significantly increase the wear resistance [8].

The above methods serve in modifying the surface layer, improving its physical and mechanical properties, but such methods do not allow obtaining a regular micro-relief with large radii of projections and cavities on the surface, this micro-relief being necessary for the normal operation of heavily loaded parts of friction pairs. This technological problem is solved by applying the methods of surface plastic deformation, such as deep rolling and unrolling, shot blasting, centrifugal treatment, ultrasonic hardening, vibration rolling [9].

One of the most effective technological methods is a shock-acoustic treatment (SAT), developed and put into operation by Doctor of Engineering, Professor A. V. Televnoy. By means of this technology the introduction of a solid lubricant based on molybdenum disulfide MoS_2 is performed by ultrasonic instrument oscillating at a frequency of 18...22 kHz and having an oscillation amplitude of about 40μm, this resulting in a modification of the surface layer of the workpiece and increasing the compatibility of the friction pair [10].

2. Theory

Currently assignment of the main technological parameters of processing, such as tool feed and workpiece rotation speed, is performed experimentally.

Paper [1] provides formulas to assign feed and rotation speed of the workpiece:

$$S = 2\sqrt{2 \cdot R_1 \cdot h} \cdot (1 - K_n^S) \tag{1}$$

$$n = \frac{60 f \cdot \sqrt{D \cdot h}}{\pi R_2} \cdot (1 - K_n^n), \tag{2}$$

where R_1 is the radius of the ultrasonic instrument indenter, mm; h is the depth of indenter penetration into the workpiece surface, mm; R_2 is the radius of the workpiece surface, mm.; f is the frequency of the magnetostriction transducer, Hz; D is the diameter of the workpiece surface, mm.; K_n^s is the overlap factor of the instrument and workpiece contact areas in the feed direction; K_n^n is the overlap factor of the instrument and workpiece contact areas in the direction of the primary motion.

Having determined the values of the overlap coefficients for different materials of friction pairs and for different friction schemes, it will be possible to use the formulas (1) and (2) for assigning rational technological parameters of shock-acoustic treatment. So, the objectives of this experimental study are as follows. The first one is to determine processing modes, in which the best wear resistance of samples of steel 45 is achieved. Then it is necessary to determine from formulas (1) and (2) the values of the coefficients of K_n^s and K_n^n, which can later be implemented in the design of the technological operation of shock-acoustic treatment for assigning technological modes of feed and rotation speed, this being done on the basis of rational processing modes.

Let us transform formulas (1) and (2). The indenter h depth is determined by the formula presented in [10, 11]:

$$h = \frac{P_{st}}{2\pi R_r \cdot HD}, \tag{3}$$

where R_r is the relative radius for the surfaces of the contacting bodies, mm; *HD* is the plastic hardness of the workpiece material (HD=1.22·HV [11]), P_{st} is the static clamping force of the ultrasonic instrument to the surface of the workpiece, *N*. Also, according to [11], R_r is taken to be equal to 4.92 mm for the contact scheme of two cylindrical samples.

Let us substitute the formula (3) in the formulas (1) and (2), and we obtain the refined formulas to determine the feed and rotation speed:

$$S = \sqrt{\frac{R_1 \cdot P_{st}}{R_r \cdot HV}} \cdot (1 - K_n^S) \tag{4}$$

$$n = 13{,}8 \cdot f \cdot \sqrt{\frac{P_{st}}{D \cdot R_r \cdot HV}} \cdot (1 - K_n^n) \tag{5}$$

Using formulas (4) and (5), the coefficients of K_n^s and K_n^n will be found on the feed and rotation speed values determined in experimental studies.

An ФТ-11 universal lathe unit with the ultrasonic generator УЗГ-3-4, a dynamic technological module ДТМ-7 developed on the basis of magnetostriction transducer ПМС 15-А-18 was used to produce impacts on the treated surface with a frequency of 18±1.35 kHz [1]. As a solid lubricant coating, a suspension of molybdenum disulfide MoS_2 and kerosene in a ratio of 1:7 was used.

As samples, rollers made of steel 45 with an outer diameter of 40 mm and an initial roughness of the outer surface R_a of 0.63 µm were prepared. Rollers made of material CuAl9Fe4 with the same dimensions were used as the counter bodies.

Test modes are given in the experiment planning matrix (**Table 1**).

Table 1. Experimental study results

Experiment number (the number of the pattern)	Rotation frequency *n* (rpm)	Longitudinal feed *S* (mm/r)	Static clamping force P_{st} (N)	Micro hardness HV_{100} (MPa)	Roughness R_a (µm)	Friction torque, M_{fr} (N·m)	Overlap coefficients $K_п^S$	Overlap coefficients $K_п^n$
1 (7)	80	0.10	40	226	0.28	1.1	0.71	0.990
2 (9)	20	0.17	40	483	0.25	0.75	0.51	0.997
3 (5)	20	0.10	100	271	0.25	1.16	0.82	0.998
4 (3)	40	0.14	40	210	0.29	0.9	0.60	0.995
5 (2)	40	0.10	80	454	0.29	0.7	0.80	0.996
6 (1)	20	0.12	80	328	0.20	1.1	0.76	0.998
7 (14)	63	0.12	40	473	0.28	1	0.65	0.991
8 (13)	63	0.10	60	345	0.22	1	0.76	0.993
9 (4)	20	0.14	60	488	0.29	0.8	0.67	0.999
10 (6)	40	0.12	60	405	0.29	0.85	0.72	0.996
11 (8)	Sample without SAT		-	203	0.63	1.65	-	-
12 (15)	Heat-treated sample, without SAT		-	428	0.63	1.45	-	-

The table also shows the values of the overlap coefficients in the feed direction K_n^S and in the direction of the primary motion K_n^n calculated from formulas (4) and (5).

3. Experimental results

Wear resistance tests were performed on the friction machine ИИ-5018 at a sample rotation speed of 200 rpm and a loading force of 100 N within the period of 21 minutes. During the friction test, the friction torque readings were taken. The calculation results are shown in table 1.

On the basis of the experimental results the equations, describing the influence of the key processing parameters, that is rotation speed, feed and static clamping force on the roughness and microhardness of the treated surface, as well as on friction torque during the run-in period, are developed:

$$y_{Ra} = 0.28 \cdot x_1 + 0.25 \cdot x_2 + 0.25 \cdot x_3 + 0.09 \cdot x_1 \cdot x_2 - 0.045 \cdot x_1 \cdot x_3 - 0.0225 \cdot x_2 \cdot x_3 \\ - 0.135 \cdot x_1 \cdot x_2 \cdot (x_1 - x_2) - 0.54 \cdot x_1 \cdot x_3 \cdot (x_1 - x_3) + 0.6075 \cdot x_2 \cdot x_3 \cdot (x_2 - x_3) + 0.7425 \cdot x_1 \cdot x_2 \cdot x_3 \quad (6)$$

$$y_{HV} = 226.29 \cdot x_1 + 483.33 \cdot x_2 + 271.17 \cdot x_3 + 61.02 \cdot x_1 \cdot x_2 - 679.185 \cdot x_1 \cdot x_3 - 128.15 \cdot x_2 \cdot x_3 \\ - 2350.215 \cdot x_1 \cdot x_2 \cdot (x_1 - x_2) - 634.635 \cdot x_1 \cdot x_3 \cdot (x_1 - x_3) + 570.2738 \cdot x_2 \cdot x_3 \cdot (x_2 - x_3) + \\ + 128.351 x_1 \cdot x_2 \cdot x_3 \quad (7)$$

$$y_{M_{fr}} = 1.1 \cdot x_1 + 0.75 \cdot x_2 + 1.16 \cdot x_3 + 0.11 \cdot x_1 \cdot x_2 - 0.25 \cdot x_1 \cdot x_3 - 1.26 \cdot x_2 \cdot x_3 \\ - 2.16 \cdot x_1 \cdot x_2 \cdot (x_1 - x_2) - 1.1 \cdot x_1 \cdot x_3 \cdot (x_1 - x_3) + 0.11 \cdot x_2 \cdot x_3 \cdot (x_2 - x_3) + 0.63 \cdot x_1 \cdot x_2 \cdot x_3 \quad (8)$$

where x_1=(n-20)/60; x_2=(S-0,10)/0,07; x_3=(P-40)/60.

According to the results of experiments, the minimum value of the friction torque 0.7 N m in the run-in period is at a longitudinal feed of 0.1 mm / rev, spindle rotation speed of 40 rpm, and static clamping force of the instrument of 80 N.

4. Results discussion

Experimental studies determined rational technological parameters of processing. They provide the best anti-friction properties for the surfaces of parts made of steel 45.

The key quality indicators of the surface layer, affecting its wear resistance, are microhardness and roughness. In accordance with the results of experimental studies, the microhardness of the surface after shock-acoustic treatment is found to be increased by a factor of 2.5 compared to the untreated sample (HV 488 vs. HV 203), and it even exceeds the indicator of the heat-treated sample (HV 428) (**Figure 1**).

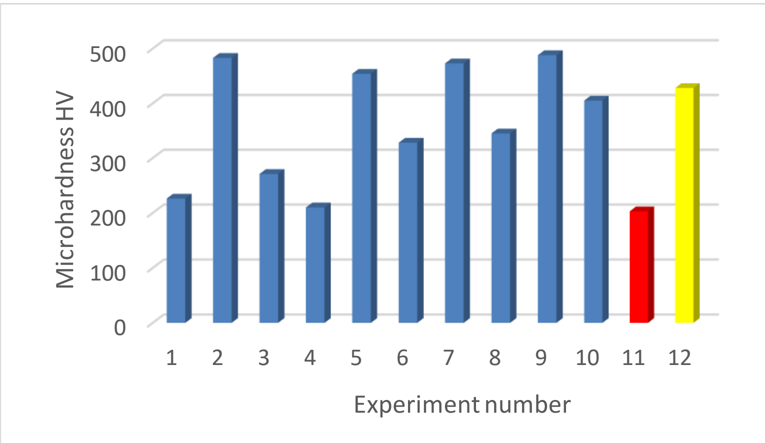

Figure 1. Comparison of samples microhardness

The roughness of the surface treated with shock-acoustic treatment decreased to Ra 0.3 compared to the initial value of Ra 0.63 (**Figure 2**).

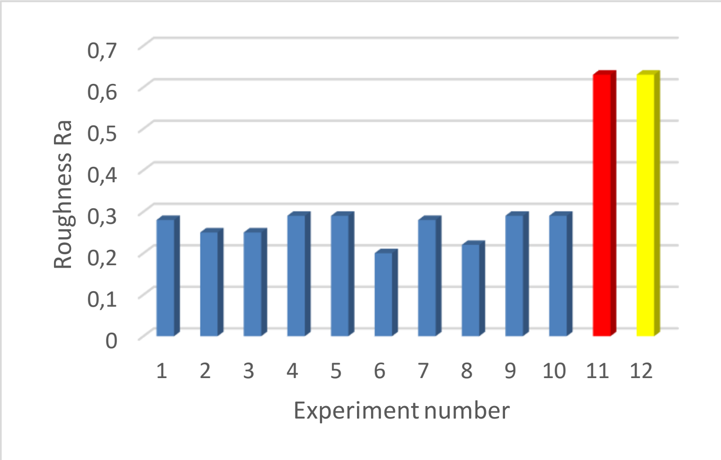

Figure 2. Comparison of samples roughness

In this paper, the dependence of the surface layer microhardness on the friction torque during the run-in period is also investigated. Analyzing the dependence in **Figure 3**, a conclusion is made that the friction torque of the samples subjected to shock-acoustic treatment with the introduction of solid lubricant is much lower than that of the sample after machining and hardened sample without shock-acoustic treatment.

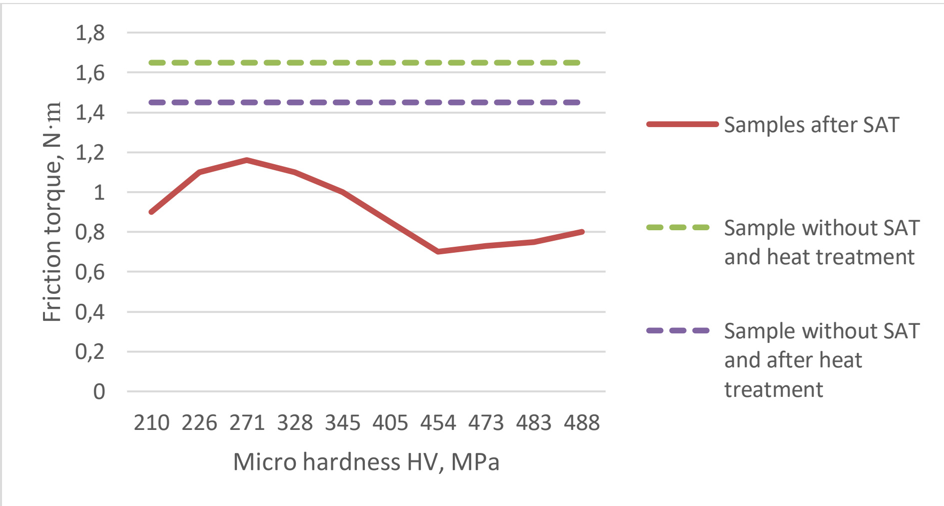

Figure 3. Dependence of the friction torque on the microhardness of the sample surface in the run-in period

The lowest values of friction torque were observed in samples with microhardness of HV 405...488. The minimum friction torque value of 0.7 N·m is obtained at the microhardness value of HV 454, which is achieved with a longitudinal feed of 0.1 mm/rev, spindle rotation speed of 40 rpm, static clamping force of the instrument of 80 N.

Thus, based on the dependencies in **Figure 3** we conclude that to ensure high anti-friction properties for the surface of the parts made of steel 45, it is necessary to ensure the microhardness of the surface layer of HV 405...488.

The next stage of research was to determine the values of the overlap coefficients. At these coefficients we achieve the obtained processing modes. According to formulas (4) and (5) the values of the overlap coefficients K_n^S=0.8 and K_n^n=0.996 correspond to these modes.

5. Conclusion

The findings of the experimental studies are as follows:

1. Application of shock-acoustic treatment technology with the use of solid lubricant based on MoS2 can increase the microhardness of the surface more than twice and reduce the surface roughness to R_a 0.2.
2. The friction torque during the run-in period of the samples after shock-acoustic treatment is less than half compared with the samples without treatment and with heat treatment.
3. To ensure high anti-friction properties for the parts surface made of steel 45, it is appropriate to ensure the microhardness of the surface layer HV 405...488.
4. Rational processing modes are defined for the friction couple steel 45 – CuAl9Fe4. These modes are: n=40 rpm, S=0.1 mm/rev, P=80 N.
5. The values of the overlap coefficients K_n^S=0,8 and K_n^n=0,996 are defined, at which rational processing modes are achieved for a friction pair steel 45 — CuAl9Fe4 of the contact scheme "roller on roller".

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