Features of Increasing the Wear Resistance of Steels under Implantation by Al Atoms

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Abstract – The study results of the endurance and acoustic emission of steel samples after annealing, quenching, irradiation by an Ar^+ ion beam with a wide energy range and doped by Al atoms by the ion mixing method are presented.

The comparison of changing the frictional force, relief and surface of a frictional path of samples (annealing, quenching, irradiation by Ar^+ ions and doping by Al atoms) testifies that in case of irradiation and doping of the surface, the abrasive wear is considerably reduced at the expense of the absence of microparticles on the irradiated and doped surface of steel samples.

1. Introduction

One of the prospective ways of increasing the operational properties of materials (for example, wear resistance) and products on their base is modification of the surface of materials by beams of charged particles. This work shows the results of changing the wear resistance of a number of steels under irradiation by beams of Ar^+ ions with a wide energy spectrum and doping of their surface by the ion mixing method, for example by Al atoms.

2. Experimental Procedure

Steel samples (Steel 20, Steel 45, ШХ15) in their initial state Hμ = 230 ± 20 kg/mm^2 and quenched Hμ = = 450 ± 30 kg/mm^2 were investigated. The surface of a part of the annealed samples was irradiated by a wide energy beam of Ar^+ ions (with a mean energy of 10 keV and an irradiation dose of $0.7 \cdot 10^{18}$ ion/cm^2) [1] and doped by Al atoms. For this purpose, thin aluminum films 50 nm in thickness were applied on the surface of a part of annealed samples by thermal evaporation in vacuum ($p < 1 \cdot 10^{-5}$ Pa) before irradiation. During the irradiation with a doze of $D =$ $= 1 \cdot 10^{18}$ ion/cm^2, a part of the film atoms was implanted into the surface layer of a material, i.e. ion mixing was carried out [2]. The wear resistance of samples was investigated on the installation "Friction-1MA" [3] under the following regimes: the rotation number was 33 ± 1 min^{-1}, the friction pair was "plane – sphere", the sphere radius was equal to 3.12 mm, the indenter load was 110 and 55 g, and the type of friction was dry. The installation's scheme is shown in Fig. 1, which has the following basic assemblies: a stabilized mechanism of rotation (an electric motor, a muff); a scheme to measure the friction force (a piezosensor, strain gauges, a strain-gauge multiplier, an input of the COMPUTER-based analyzer); a circuit to register an acoustic signal (a strain gauge, a broadband amplifier, an analyzer of pulses, an input the COMPUTER-based analyzer). The wear resistance of a material was estimated on a change of the friction force value from the time and the track depth for an indentor load of 55 and 110 g. The ultrasonic emission characteristics of friction pairs were investigated by an amplitude analysis. For this purpose, the acoustic signal was transformed to an electric signal by a piezosensor with a resonant frequency $f_r \approx 1.250$ MHz. Then the electric signal was amplified by a broadband amplifier and its peak value was registered by a pulse analyzer (AI-1024).

The «number of pulses – amplitude» spectrum was accumulated during the wear and then the spectrum obtained was processed on a COMPUTER using the program AKUSTIK. To study the friction track structure, an optical microscopy was used.

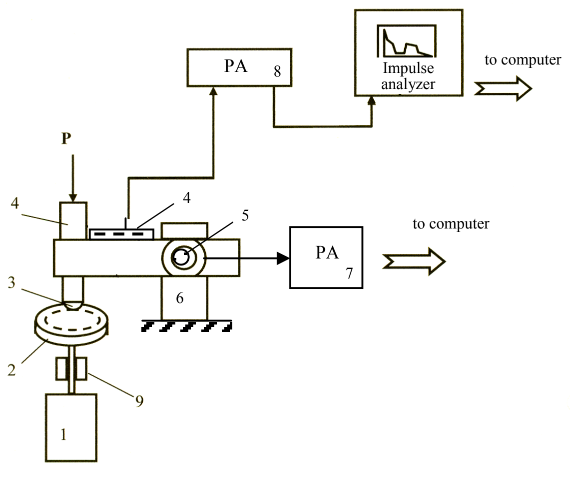

Fig. 1. A scheme of the installation "Friction-1MA": 1 – electric motor; 2 – sample; 3 – spherical indentor; 4 – strain gauge; 5 – piezosensor to measure the frictional force; 6 – holder; 7 – piezosensor amplifier; 8 – tensometric amplifier; 9 – muff

3. Experimental Results and Discussion

The experimental results on measuring the friction force on steel samples for a load of 110 g after annealing, quenching, irradiation by a wide energy beam of Ar^+ ions, and doping by Al atoms have shown that there is an essential increase in the wear resistance of samples after irradiation and doping (Fig. 2). At that, the most effect is observed for samples doped by Al. A similar picture is observed for tests of samples at a load of 55 g (Fig. 3).

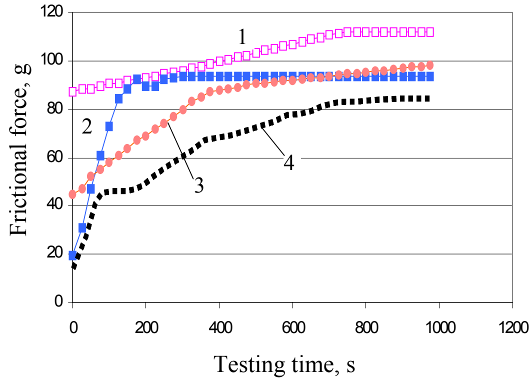

Fig. 2. The dependence of the frictional force from the time for tests of Steel 45 at a load of 110 g: 1 – initial state; 2 – quenched sample; 3 – sample irradiated by Ar^+; 4 – sample doped by Al

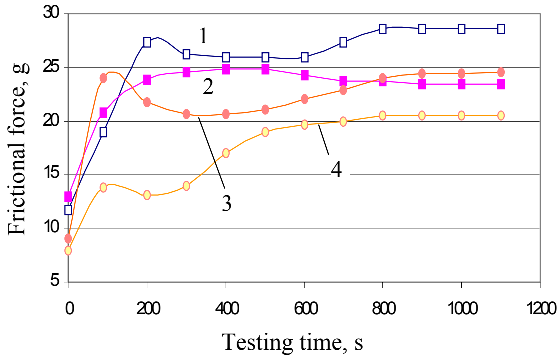

Fig. 3. The dependence of the frictional force from the time for tests of Steel 45 at a load of 55 g: 1 – initial state; 2 – quenched sample; 3 – sample irradiated by Ar^+; 4 – sample doped by Al

An analysis of the "friction track" structure of samples in their initial and quenched states shows the following: (1) an alignment of the friction surface with a deformation forming occurs at the initial wear stage for the time of 0–200 s (Fig. 4, *a*); (2) a wear with separation of fragments from the friction surface and their transfer takes place for the time of 200–600 s (Fig. 4, *b*); (3) when the time is higher than 600–800 s (Fig. 4, *c*), there is formation of an advanced relief of the surface and a layer of fine-dispersed particles promoting the prevalence of the abrasive character of wear [4].

Study of the surface structure change of samples irradiated by argon ions and doped by aluminum makes it possible to assume that the increase in their wear resistance is related to an increase in the surface hardness and a decrease in the adhesive ability of the rubbing surfaces. Thus, the friction force decreases (for example, for samples of Steel 45 at a load of 55 g $F_{initial}$ = 28 g, F_{Al} = 20.3 g) as a result of ion mixing, and the contribution to deterioration of an abrasive component of friction is reduced.

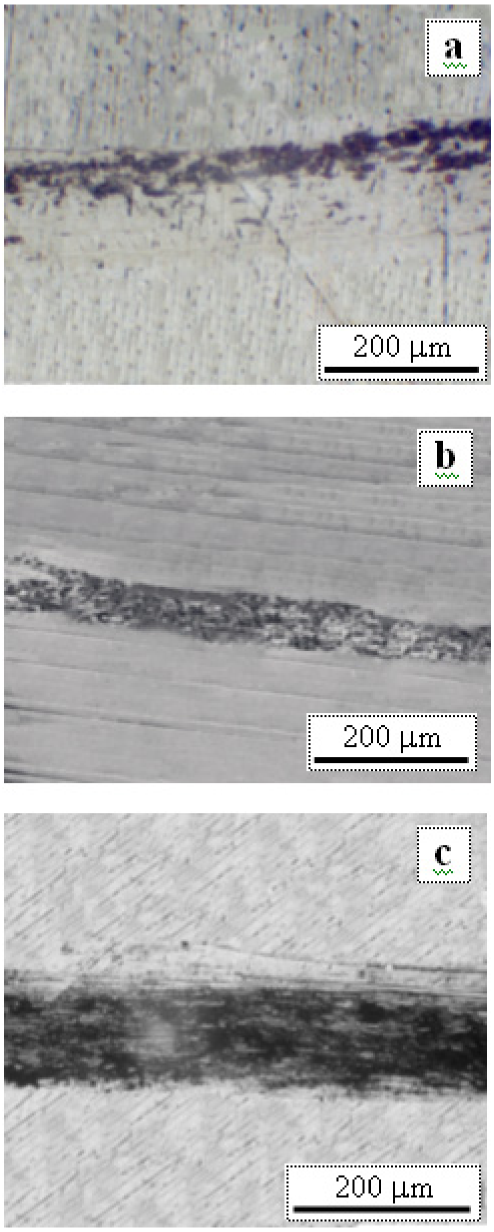

Fig. 4. The "friction track" structure of a Steel 45 sample for various testing times: 200 (a); 500 (b); 1000 s (c)

Figure 5 shows the typical spectrum of acoustic emission obtained during the wear-resistance test of ШХ15 steel samples at a load of 55 g. It is seen from the figure that the spectrum is characterized by an intensive signal emission with amplitudes of 1–3 (10–45 rel. un.) and 6–9 V (138–170 rel. un.) and a weaker emission in the 4–6 V range (70–120 rel. un.) at the initial stage of tests ($t < 200$ s). With an increase of the testing time (200–600 s), the acoustic signal amplitude distribution changes: the spectrum is shifted both to the area of smaller values (up to 0.3 V) of the amplitude signal, and to the area of higher values of amplitudes up to 12 V (190 rel. un.). At the same time the output of a signal for the average part of the spectrum simultaneously decreases. A significant decrease of the signal emission is observed for the testing time higher than 600–800 s at the average part of the peak distribution, which is obviously related to the formation of a uniform crystal structure in the contact area of friction pairs, the grains making smaller up to sizes of 5–10 μm [5].

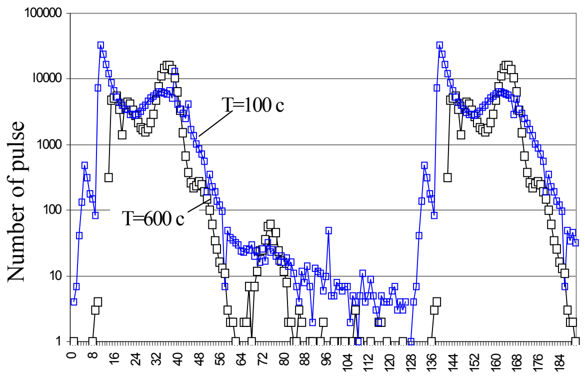

Fig. 5. Peak distribution of a acoustic spectrum at various times of tests (100 and 600 s)

The comparison of a change in the radiation intensity of acoustic signals ***N*** (Fig. 5) and friction forces (Figs. 2 and 3) at various testing times testifies that acoustic emission is connected to a change in the friction force, as well as formation of the typical structure of the surface of friction.

It follows from the data of work [6] that the intensity of the acoustic signal can be related to the value of the internal mechanical stress in the area of friction by the following equation:

$$N = N_0 K^m,$$

where N_0 – a constant describing the material and efficiency of registration of an acoustic signal, K – a coefficient of the internal mechanical stress, m – an exponent of power, $m = 4$–10 (at $m = 4$).

Figure 6 shows the K-value ($m = 4$) dependence from the testing time that has a linear area ($t = 0$–600 s). The K-value attains its peak at the testing time of 600–700 s and then it decrease for $t > 700$–900 s.

The concentration of mechanical stresses K at various testing times for steel samples doped by Al-atoms is presented in Table 1. The presented results make it possible to point out the following general tendency. With increasing the contents of Al-atoms in the modified layer, the interval of changing the K-value is shifted to the area of smaller values: from 1.2–1.4 $C_{Al} = 0$ at% to 0.7–0.9 $C_{Al} = 5$ at%. Thus, the maximal change of K is observed for the ШХ15 steel, $\Delta K = 0.3 \pm 0.05$. It is of interest to compare K-values for steel samples and Fe (АРМКО) samples. These data show that the increased Al-content in Fe results in an increase of the K-change during the tests. At that, the maximal K-value approaches the values obtained for steel samples.

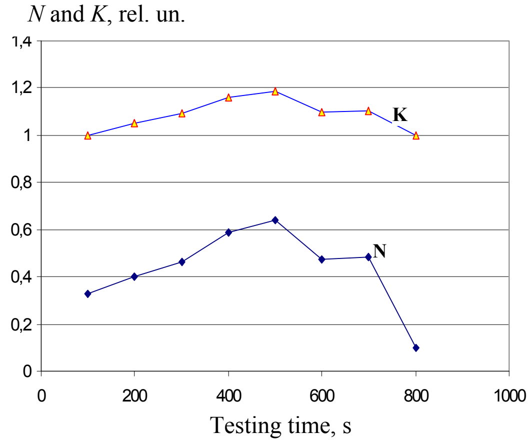

Fig. 6. The change of the intensity of acoustic emission N and the concentration coefficient of the internal stress K from the time of tests for a ШХ15 sample doped by Al atoms ($C_{Al} = 2$ at%)

Table 1. The K-value change (at $m = 4$) for steel samples doped by Al atoms

Content of Al atoms in near layer of steel samples, at%	Fe	Steel 20
0	0.8 – 1.1	0.9 – 1.2
2	0.7 – 1.0	0.9 – 1.2
5	0.7 – 1.2	0.8 – 1.2
	Steel 45	ШХ15
0	1 – 1.2	1.1 – 1.4
2	0.9 – 1.1	0.9 – 1.2
5	0.7 – 1.1	0.7 – 1.1

4. Conclusion

The data of changing the friction force, acoustic spectrum, and metallographic researches of steel samples show that three wear stages are observed during the tests.

The first stage – the alignment (at the testing time of 0–200 s). For this stage, a linear growth of the friction force and an increase in the value of peaks and intensity of the acoustic signal are characteristic. The alignment of friction surfaces occurs and the structure of a friction track with formation of the ring zones of deformation is formed. The concentration values of the internal voltage have a linear dependence on the time of tests.

The sond stage – (for the 200–600 s time range). It is characterized by stabilization of the friction force. Formations of a friction track up to 1 μm in depth with generation of welding zones and their peeling continue. The features of friction at this stage are stabilization of the crystal structure, physico-mechanical properties of the surface layer of a material, stabilization of the friction force and the wear intensity. The *K*-value linearly increases with the testing time *t*.

The third stage – (for testing time > 600–800 s). It is characterized by the fact that the output value of a frictional force attains its constant value. The "friction track" structure formation (the depth $h = 2$–7 μm) comes to the end. Deformation changes cover all the body of a grain. The features of this stage are:

– the formation of a uniform structure of a material along the friction track,

– the presence of fine-dispersed particles – products of abrasion,

– a partial relaxation of mechanical stresses in the friction area.

In case of irradiation by Ar^+ ions and the surface doping of samples by Al atoms, abrasion significantly decreases as there is a slight formation of microparticles in the "friction track" area.

As to doping the steel samples by Al atoms, the *K*-value (a coefficient of the internal mechanical stress) reduces on 10–30%, which has a positive effect on increasing the wear resistance of these materials.

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