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COMPARATIVE EVALUATION OF THE TRIBOLOGICAL PROPERTIES OF LOW- AND MEDIUM-CARBON STEELS AFTER HEAT TREATMENT AND SEVERE PLASTIC DEFORMATION

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Abstract. The paper presents the results of a comparative tribological study of structural steels with a carbon content of 0.1% and 0.45%. The following thee conditions are studied: initial (hot rolled), after heat treatment (improvement) and after improvement with subsequent severe plastic deformation (SPD) processing by equal-channel angular pressing (ECAP). It is established that the materials after different types of processing have different structural states, and demonstrate different shear strength of adhesive bonds and adhesion (molecular) components of the friction coefficient in contact with the tool steel of the R18 type. At the same time, it is revealed that the greatest effect of hardening due to microstructure refinement is observed on the specimens of low-carbon steel. Medium-carbon steel after SPD processing has approximately the same tribological properties as after heat treatment.

1. INTRODUCTION

The technologies of metallic materials hardening by severe plastic deformation (*SPD*) processing are gaining ground at the present time. One of the most effective methods is equal-channel angular pressing (*ECAP*) [1,2] and its modification - *ECAP-Conform* [3], which has a considerable potential for the industrial production of long-length products in the form of rods.

It is known that harder materials provide for lesser wear and a lower friction coefficient [4]. For alloys, in most cases, there are ways to increase hardness through various types of heat treatment [5,6].

A technology providing an efficient and multiple increase of strength has been developed by the present moment. The technology is based on *SPD* processing and enables producing high-strength bulk billets from metallic materials [7]. One of the *SPD* techniques is equal-channel angular pressing (*ECAP)* [3], which is carried out in several cycles of deformation. The essence of this technique for increasing the material strength lies in the maximum grain structure refinement down to ultrafine-grained and nano-sizes [1,8,9].

SPD techniques enable significantly expanding the application fields of various metallic materials due to an effective increase of strength. Previous comprehensive tribological studies of steel with a carbon content of 0.1% showed [10,11] that a material processed by SPD via ECAP demonstrated a

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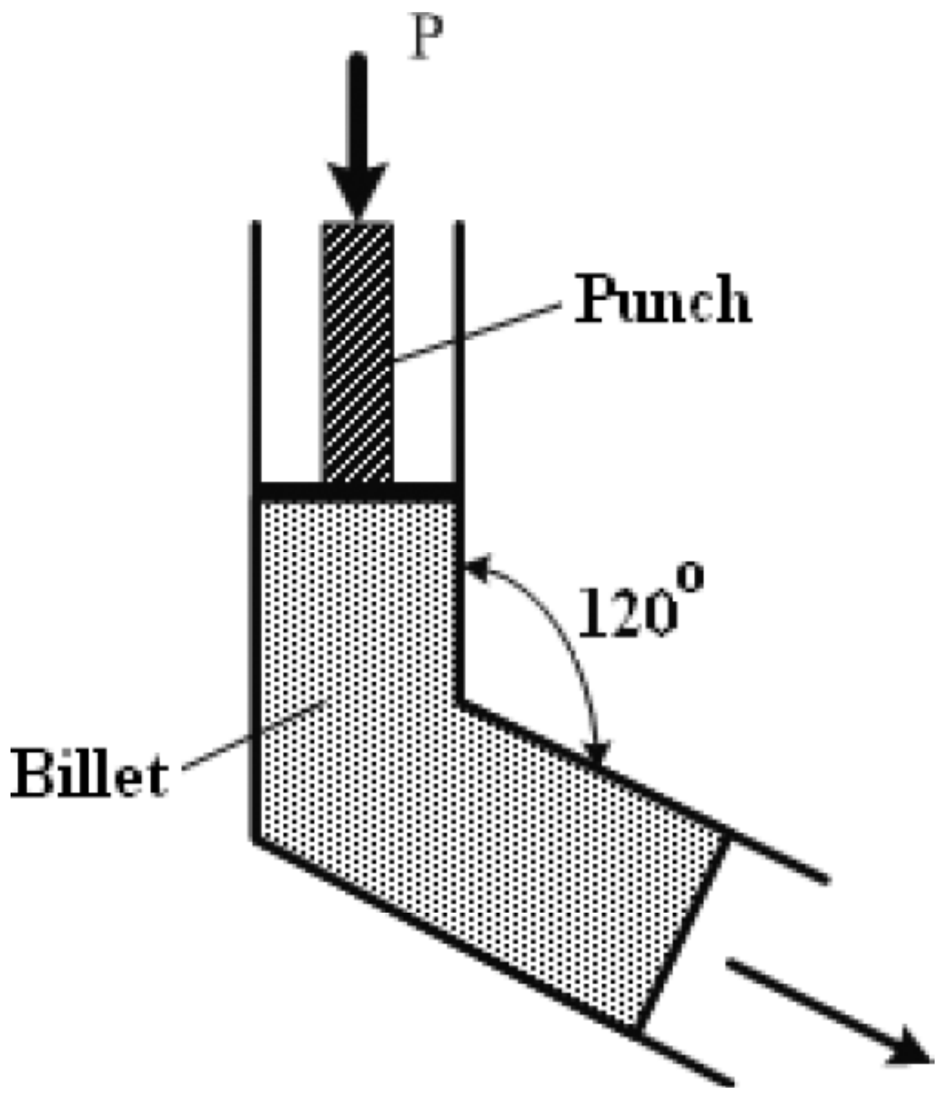

Fig. 1. Principle of an SPD technique – equal-channel angular pressing (ECAP).

lower friction coefficient and an enhanced wear resistance in a contact pair with tool steel. However, it is of great scientific and practical interest to justify the practicability of conducting SPD processing as one of the competitive methods for increasing the strength of materials that are subsequently to be exploited in friction units.

2. MATERIALS AND METHODS OF INVESTIGATION

The following materials were chosen as objects of study: a low-carbon steel with a carbon content of up to 0.1% (wt.%) and a medium-carbon steel with a carbon content of up to 0.45%. The samples after hot rolling were taken as ones in the initial state. The sample size was diameter 20 mm, length 100 mm.

The following heat treatment was conducted in order to relieve stresses and produce a homogeneous structure: holding at 880 °C for 1 hour, followed by water-quenching, then tempering at 600 °C for 1.5 hours.

The *ECAP* process was chosen for strain hardening of the initial material [9], its principle is displayed in Fig. 1. *ECAP* processing was performed in a facility with a channels intersection angle of 120° at a temperature of 400 °C with rotation of the workpiece about its longitudinal axis by 90 degrees after each cycle. The number of cycles was 4.

Here, in order to calculate the accumulated strain, the following formula was used [2,3]:

$$\varepsilon = N\frac{2\,\mathrm{ctg}(\varphi/2)}{\sqrt{3}}, \qquad (1)$$

where N is the number of cycles of deformation processing; φ is the angle of channels intersection.

The study of the structure was performed using optical and transmission microscopy with different magnifications. The grain size was determined by the intercept method [12].

For tribological studies, the methods for evaluation of the shear strength of adhesive bonds τ_n and determination of the adhesive component of the friction coefficient f_m [13] (Fig. 2a), the method for estimation of the friction coefficient f and wear rate J via the «*block - disk*» scheme [14] (Fig. 2b) were used.

To evaluate the shear strength of adhesive bonds and the molecular component of the friction coefficient, the tested samples were cut out in the form of disks with a diameter of 20 mm and a thickness of 5 mm, a spherical indenter with a sphere radius

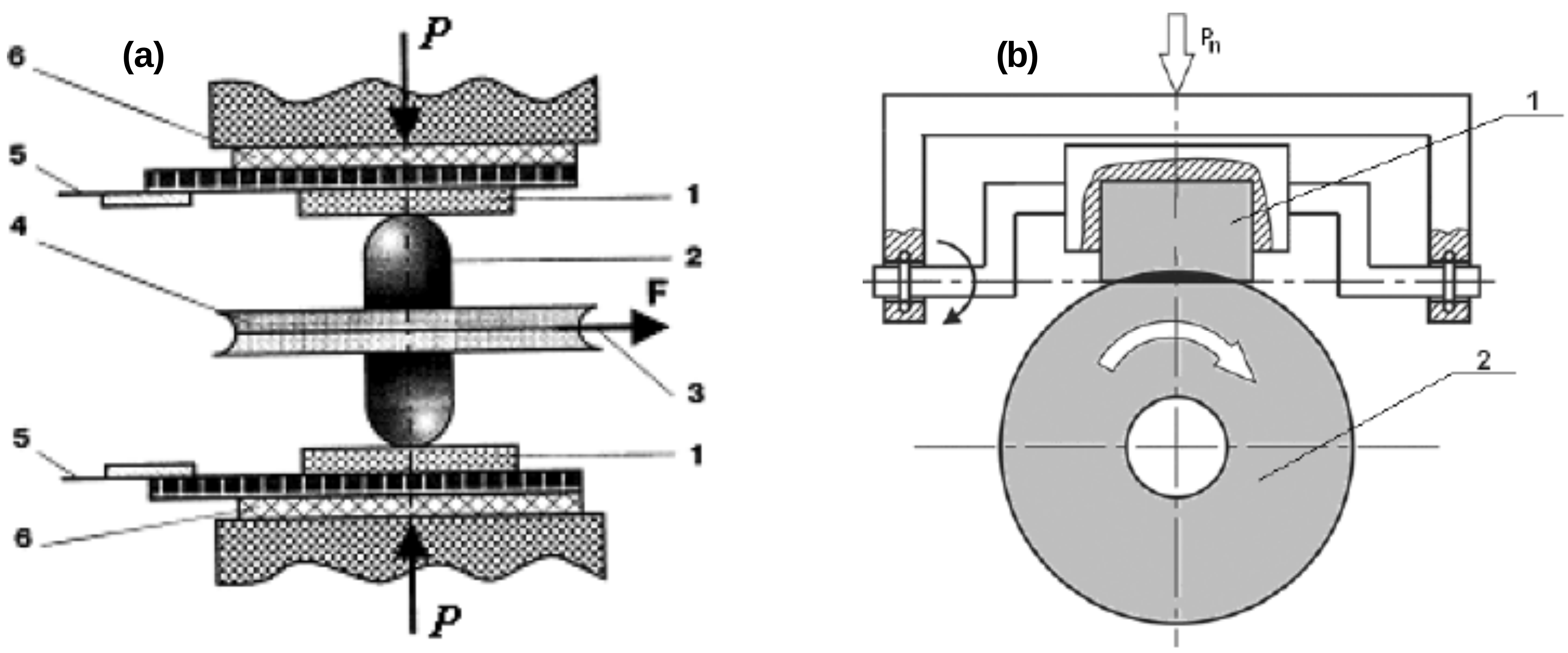

Fig. 2. Schemes of tribological tests: *a* – method for evaluation of the adhesive component of the friction coefficient: 1 – tested samples; 2 – spherical indenter; 3 – cable; 4 – disk with a groove; 5 – current conductor lines; 6 – electric insulating pads; *b* – method for determination of the integral value of the friction coefficient: 1 - tested sample; 2 – rotating steel disk.

of 2.5 mm made from a high-speed tool steel Fe - 6W - 5Mo. The tests to determine the shear strength of adhesive bonds were carried out at temperatures of 20, 200, and 400 °C on a one-ball adhesion meter according to the scheme shown in Fig. 2a [13]. The initial roughness of the contact surfaces between the tested samples and the indenter was in the range from 0.06 to 0.16 μm according to the *Ra* scale.

The shear strength of adhesive bonds μ_n (MPa) was determined from the relationship:

$$\tau_n = 0.75 \cdot \frac{M}{\pi \cdot \left(\frac{d_{1,2}}{2}\right)^3}, \quad (2)$$

where $d_{1,2}$ are the diameters of prints on the tested sample, mm; *Ì* – the indenter rotation torque, *N,* mm.

The adhesive (molecular) component of the friction coefficient is calculated as:

$$f_m = \frac{\tau_n}{p_r}, \quad (3)$$

where p_r is the normal pressure, MPa.

$$p_r = \frac{P}{\pi \cdot \left(\frac{d_{1,2}}{2}\right)^2}, \quad (4)$$

where *P* is the compression force of the samples, *N*. In the conditions of the test, *P* = Const = 2400 N.

The total precision of evaluation of the adhesive component of the fricton coefficient, including equipment and instrument errors, does not exceed ±1%.

Samples in the form of a cube with a side of 12.7 mm were used for testing according to the «block-disk» scheme (Fig. 2b). Disks with a diameter of 70 mm and a thickness of 20 mm were manufactured from a high-speed tool steel Fe - 6W - 5Mo. The initial roughness of the blocks and the disks was in the range from 0.06 to 0.16 µm according to the Ra scale. The tests were carried out at room temperature on a “Timken” tribometer with a disk rotation speed of 1000 min^{-1} and a normal load of 5 N during 15 min. The friction path was 3300 m. To determine the values of the wear rate, each sample was weighed before and after the test. After the tests the contact geometric area was determined. Then the wear rate value was calculated via the formula:

$$J = Q / qS_c L, \quad (5)$$

where *Q* is the sample weight loss, *N*; *q* is the density of the sample material, N/cm^3; S_c is the geometric area of the contact, cm^2; *L* is the friction path, cm.

The wear of the disks made of a high-speed tool steel Fe - 6W - 5Mo and quenched to the hardness *HRC* 58...65 was neglected due to its low value as compared to the wear of the tested samples.

3. RESEARCH RESULTS

3.1. Metallographic structural studies

Figs. 3 and 4 demonstrate the microstructures of the low- and medium-carbon steels, respectively, after different types of processing. The studied materials have an annealed structure in the initial state.

It can be seen from the analysis of microstructures that the investigated materials consist of a mixture of ferrite (bright areas) and pearlite (dark areas). Fig. 3 shows that the heat treatment that includes quenching and tempering (improvement) changes the grain size of the low-carbon steel, but only very slightly. After the heat treatment the structure practically did not change, and the sizes of ferrite and pearlite grains slightly leveled out. Subsequent *SPD* processing resulted in a significant grain structure refinement.

It can be seen from the example of the medium-carbon steel (Fig. 4) that heat treatment can rather effectively reduce the grain size. As a result of the martensite decomposition, tempering sorbite forms during tempering, which has the same hardness as quenching sorbite, but differs from it in terms of the shape of cementite particles: globules instead of plates. In its turn, one of the structural components of steels, sorbite, represents a finely-dispersed kind of pearlite.

SPD processing does not provide such a significant effect in terms of structure refinement, as observed for low-carbon steel.

3.2. Tribological tests according to the “block- disk” scheme

When conducting tribological tests of friction pairs “low-carbon steel - tool steel” and “medium-carbon steel – tool steel” according to the *“block – disk”* scheme, a different character of variation of the friction coefficients was established. Table 1 lists the friction coefficient values after tribological tests for a period of 150 s (run-in period) obtained at room temperature for the samples with different microstructures.

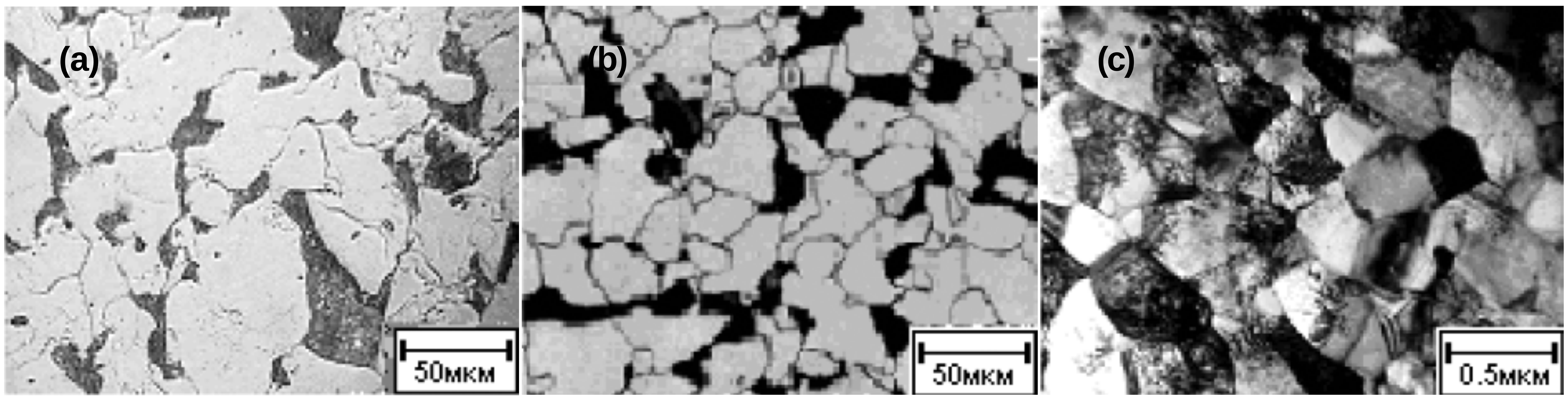

Fig. 3. Microstructure of the steel with a carbon content of 0.1%: a – CG structure, the average grain size is 70 mm; b - after heat treatment, the average grain size is 50 μm; c - after heat treatment and four ECAP cycles, the average grain size is 0.5 μm.

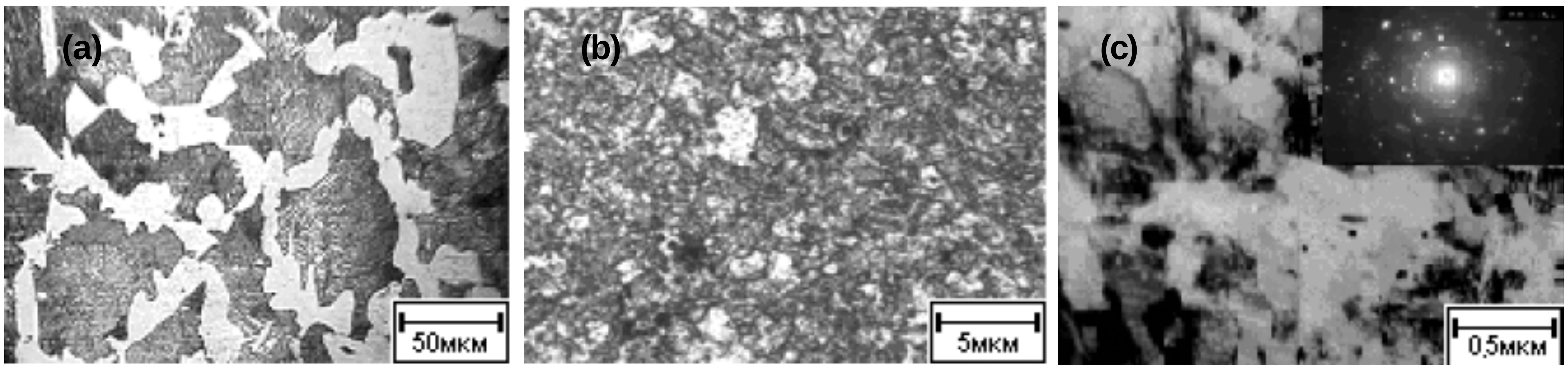

Fig. 4. Microstructure of the steel with a carbon content of 0.45%: a - CG structure, the average grain size is 70 mm; b - after the heat treatment, the average grain size is 3 μm; c - after heat treatment and four ECAP cycles, the average grain size is 0.4 μm.

The analysis of the obtained results shows that for the low-carbon steel, *SPD* processing by *ECAP* after heat treatment is an effective procedure in terms of reducing the friction coefficient due to strain hardening of the material. For the medium-carbon steel, heat treatment without subsequent deformation processing is quite effective. This is due to the fact that the hardness, strength and impact strength of sorbite is higher than that of pearlite. In this case, these two processes - heat treatment and *SPD* processing - are competing. Thus, there is no need to subject steel with high carbon content to *SPD* processing, in case it is intended for subsequent application in friction units.

The curves displayed in Fig. 5 demonstrate that for the low-carbon steel, it is the material with an ultrafine-grained structure produced by heat treatment followed by SPD processing via ECAP that has the lowest values of the friction coefficient.

It seems probable that the friction conditions become more favorable due to an increase in strength of the low-carbon steel, as well as a more uniform distribution of pearlite particles. Such conditions of friction, to some extent, can be comparable with the friction in a sliding bearing [15]. As a result, the integral value of the friction coefficient decreases. Thus, we observe the formation of a "third body" [16], which consists of fine particles of pearlite and carbides.

In addition, this option - *SPD* processing by *ECAP* after heat treatment - provides a smooth transition to the steady friction regime, which facilitates reduction of the wear rate. Fig. 6 displays the results of evaluation of wear rate in the form of a histogram.

Table 1. The values of the friction coefficients for the low- and medium-carbon steels after different types of processing.

Material	Friction coefficient, *f*		
	Initial state after annealing	Heat treatment (quenching + tempering)	Severe plastic deformation after heat treatment
Low-carbon steel	0.151 ± 0.001	0.135 ± 0.001	0.110 ± 0.001
Medium-carbon steel	0.139 ± 0.001	0.100 ± 0.001	0.119 ± 0.001

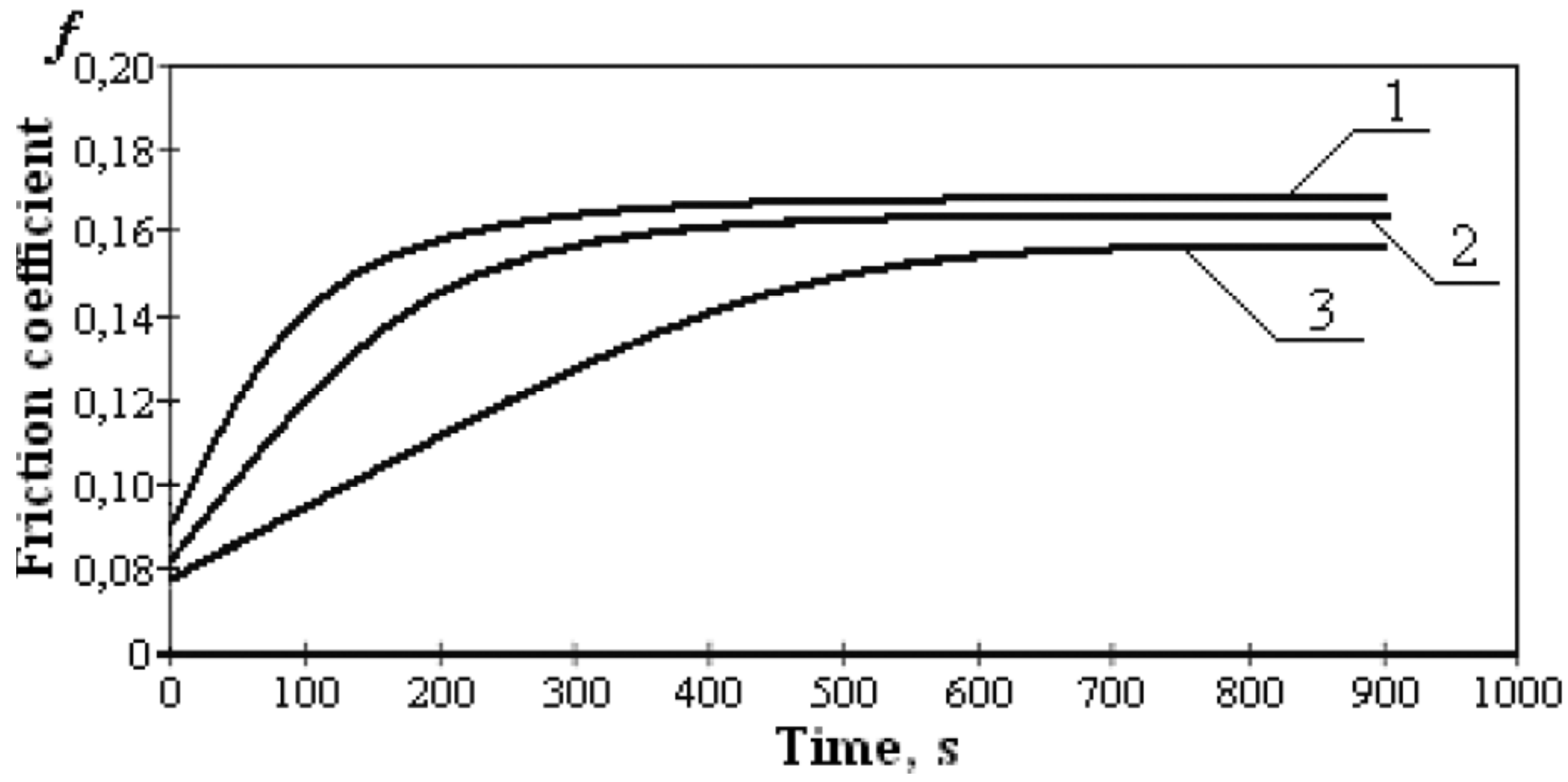

Fig. 5. Dependence of the friction coefficient on the time of testing of the contact pair “low-carbon steel - tool steel Fe - 6W - 5Mo”: 1 – initial material (coarse-grained after anealing); 2 - material after heat treatment; 3 - material with a UFG structure after heat treatment and SPD processing by ECAP.

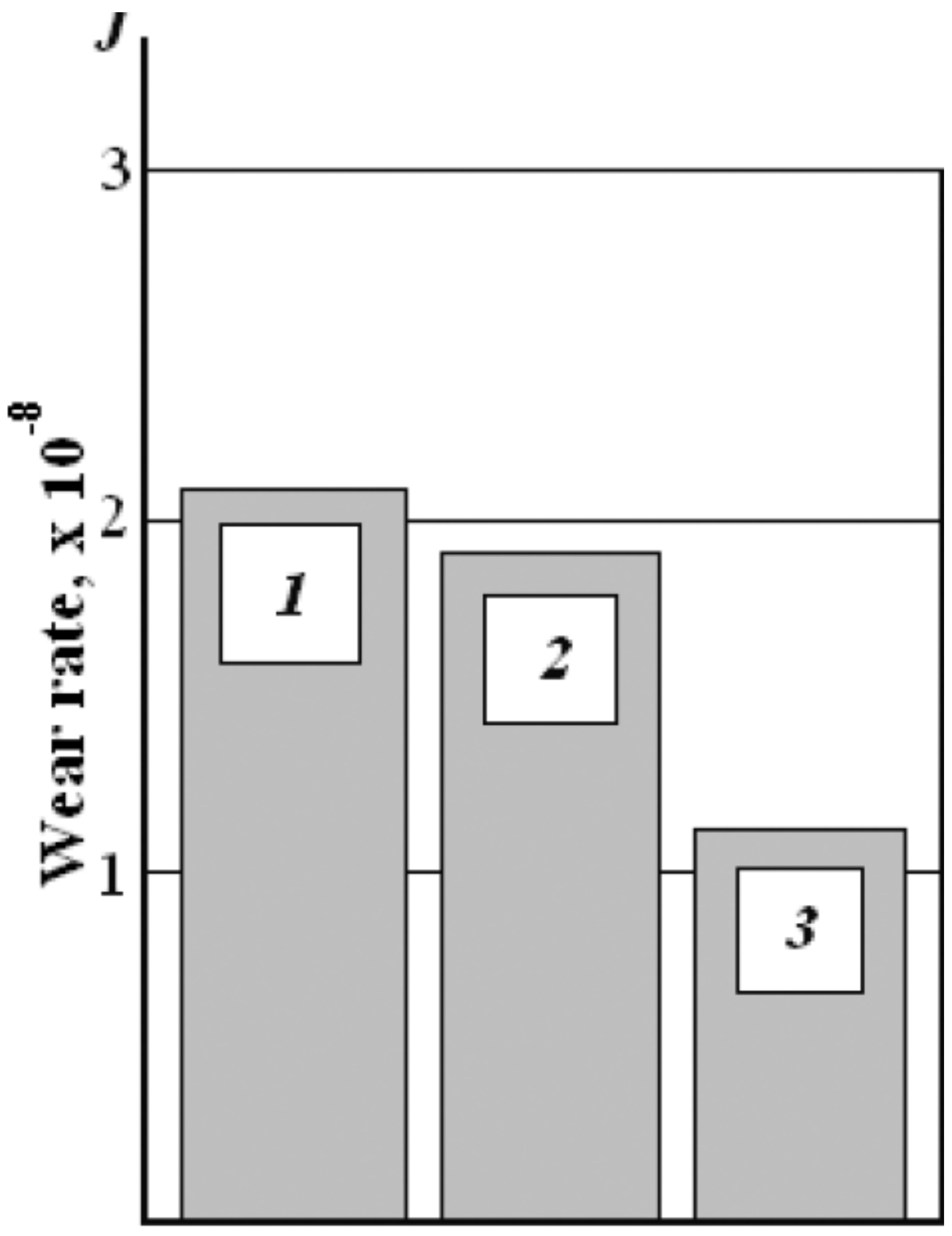

Fig. 6. Wear rate of the low-carbon steel depending on the structural state of the investigated material: 1 - initial material (coarse-grained, hot-rolled); 2 - material after heat treatment; 3 - material with a UFG structure after heat treatment and SPD processing by ECAP.

Another picture is observed when analyzing the results of the tribological studies of the medium-carbon steel. Fig. 7 shows the variation of the friction coefficient depending on the time of testing.

It is visible here that the lowest values of the friction coefficient in the studied time interval at room temperature are observed for the medium-carbon steel after heat treatment (quenching + tempering).

In the accepted test conditions, growth of the friction coefficients is observed for both the low-carbon steel and the medium-carbon steel, regardless of their structural state. This can be accounted for by growth of the actual contact area in the process of the tribological tests according to the chosen scheme.

The graphs (Figs. 5 and 7) and histograms (Figs. 6 and 8) show that the friction coefficient and the wear rate are lower for the low-carbon steel after heat treatment (quenching + tempering) and subsequent *SPD* processing as a result of strain hard-

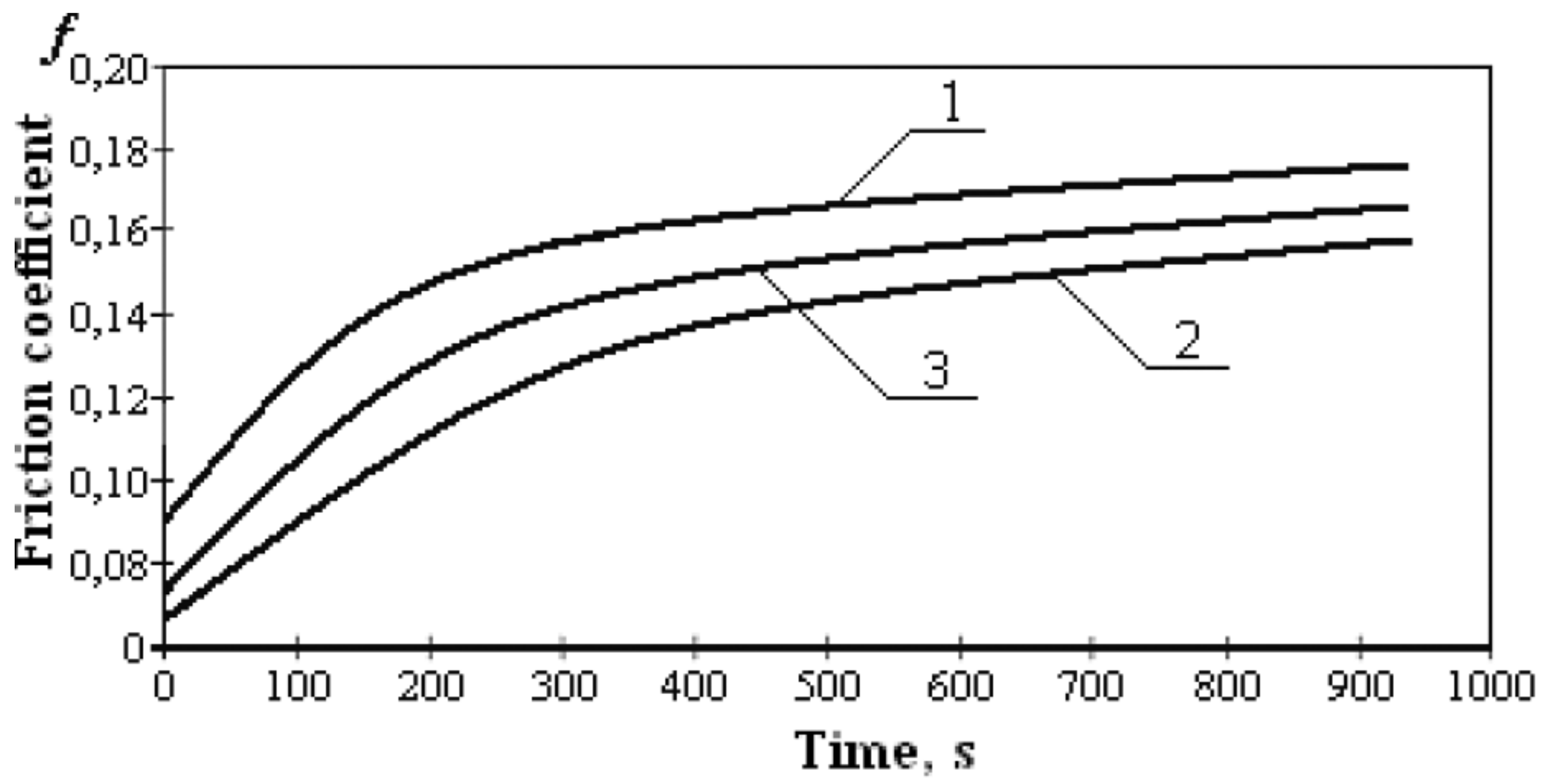

Fig. 7. The dependence of the friction coefficient on the test time of the contact pair «medium-carbon steel - tool steel Fe - 6W - 5Mo»: 1 - initial material (coarse-grained, hot-rolled); 2 - material after heat treatment; 3 - material with a UFG structure after heat treatment and SPD processing by ECAP.

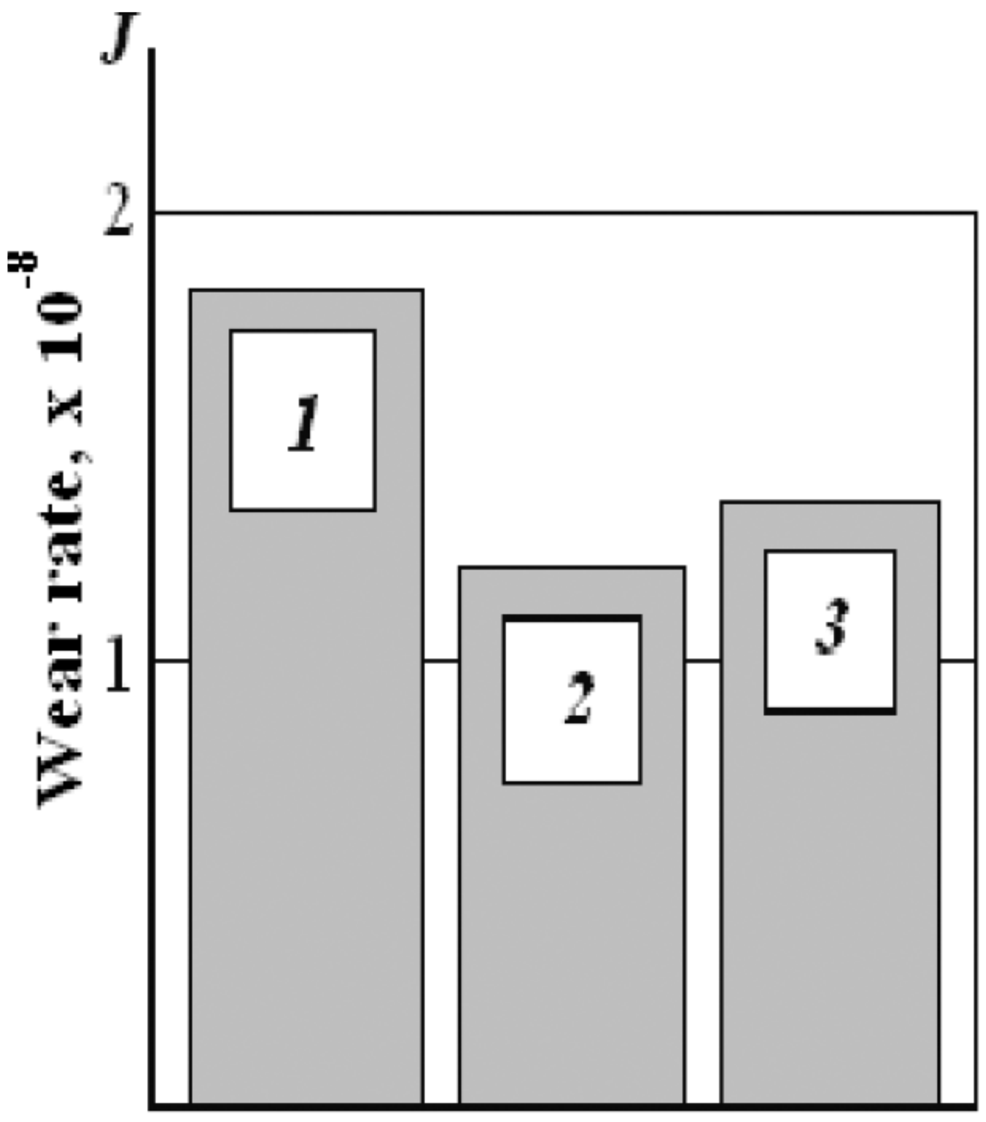

Fig. 8. Wear rate for the medium-carbon steel depending on the structural state of the investigated material: 1 – initial material (coarse-grained, hot-rolled); 2 - material after heat treatment; 3 - material with a UFG structure after heat treatment and SPD processing by ECAP.

ening due to the formation of a *UFG* structure during the deformation processing.

Therefore, from the point of view of tribology, a positive effect is achieved on the medium-carbon steel due to heat treatment, and a subsequent *SPD* processing has an insignificant effect.

3.3. Estimation of the shear strength of adhesive bonds

Figs. 9 and 10 present the results of the tribological studies to determine the shear strength of adhesive bonds τ_n depending on the pressure p_r in the friction contact at different temperatures and the variation of the molecular component of the friction coefficient depending on the temperature, for the low-carbon steel samples. The results of similar studies of the samples of the medium-carbon steel are presented in Figs. 11 and 12. The curves in Figs. 10 and 12 are plotted as a result of processing of the

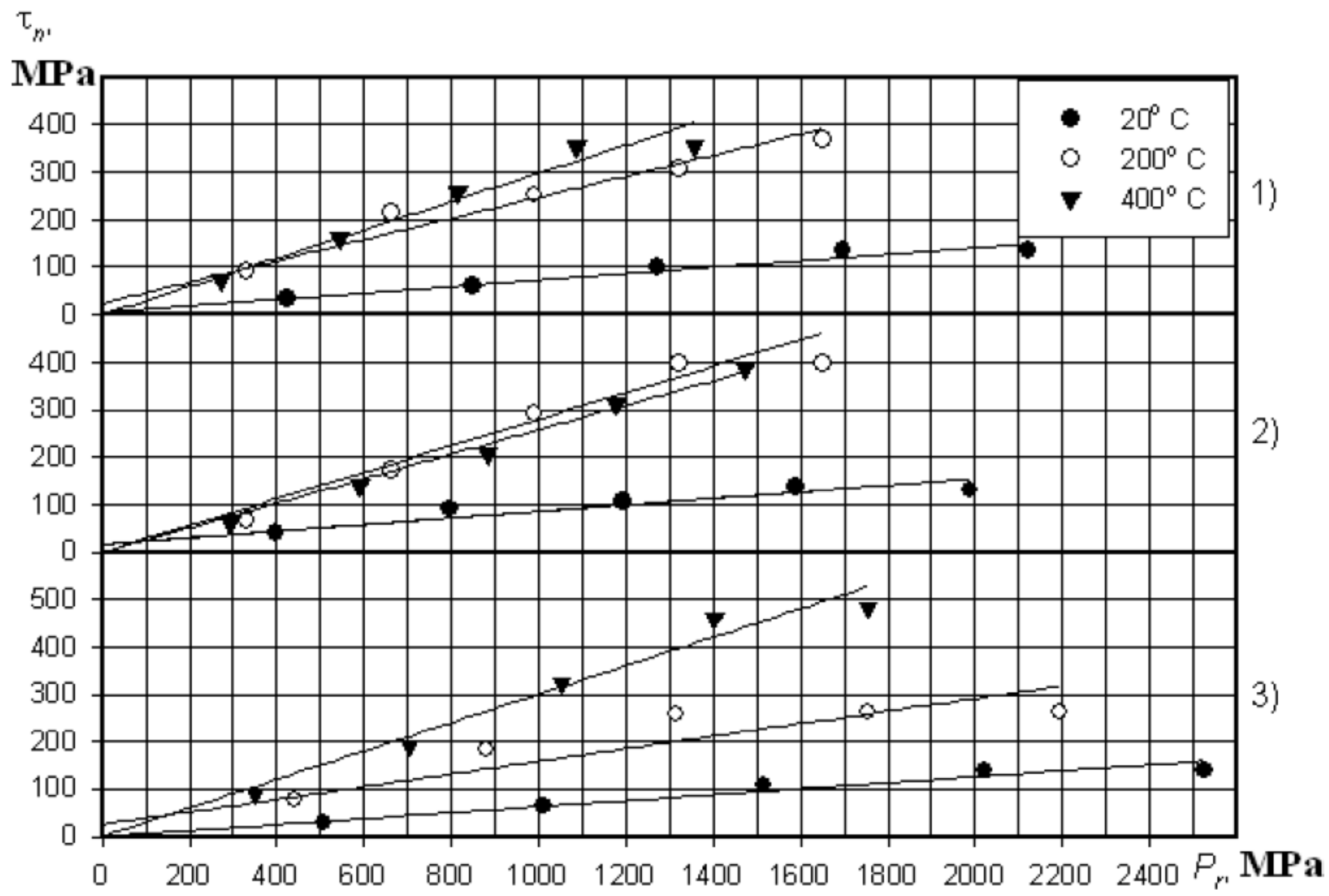

Fig. 9. Dependence of the shear strength of adhesive bonds on the normal pressure in the tribological coupling “low-carbon steel - tool steel Fe - 6W - 5Mo” at different temperatures and under different types of treatment of the investigated material: 1 – initial material (coarse-grained, hot-rolled); 2 - material after heat treatment; 3 - material with a UFG structure after heat treatment and SPD processing by ECAP.

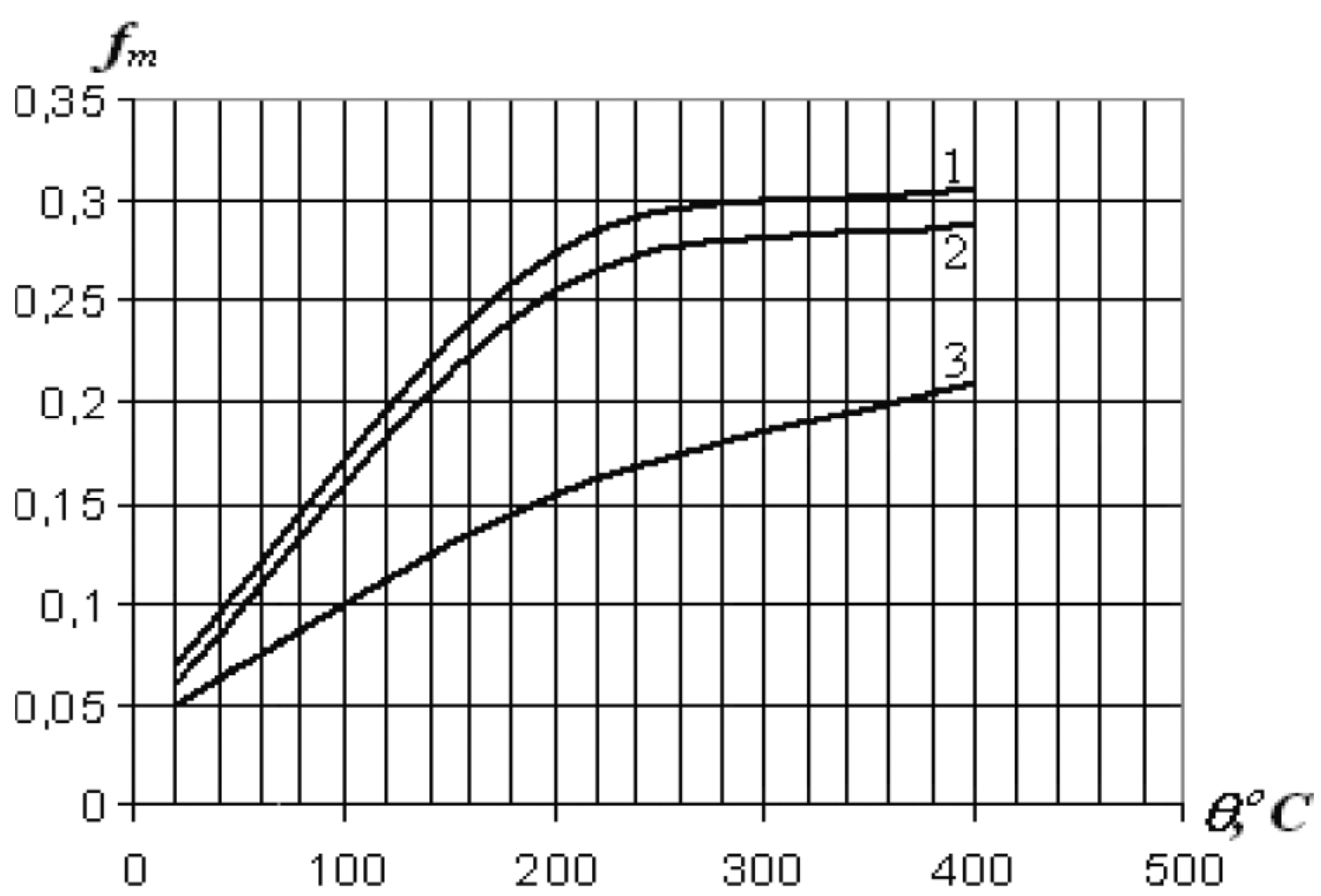

Fig. 10. Variation of the molecular component of the friction coefficient depending on the temperature (friction pair “low-carbon steel - tool steel Fe - 6W - 5Mo”): 1 – initial material (coarse-grained, hot-rolled); 2 - material after heat treatment; 3 - material with a UFG structure after heat treatment and SPD processing by ECAP.

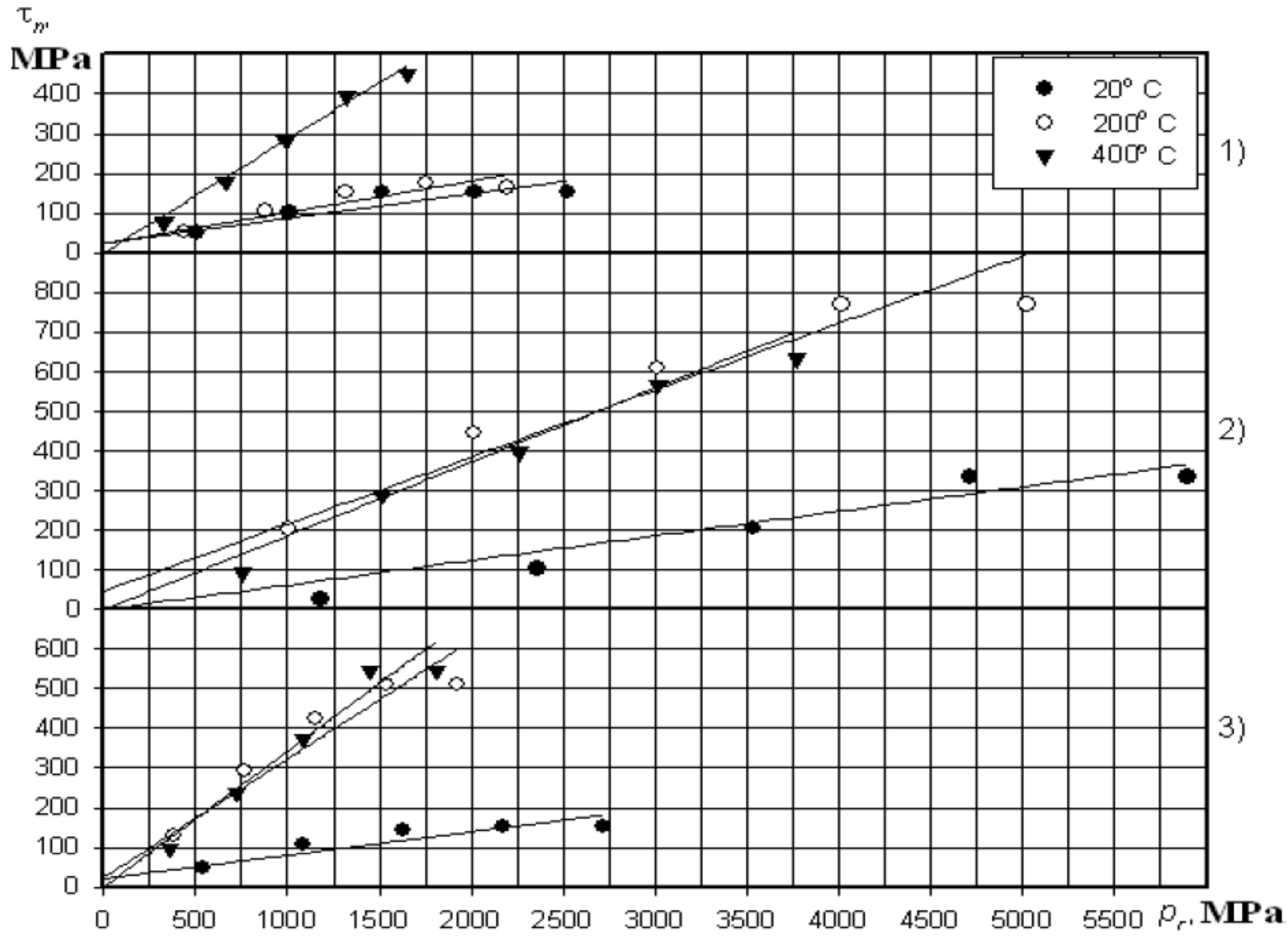

Fig. 11. The dependence of the shear strength of adhesive bonds on the normal pressure in the tribological coupling "medium-carbon steel – tool steel Fe - 6W - 5Mo" at different temperatures and under different types of treatment of the investigated material: 1 – initial material (coarse-grained, hot-rolled); 2 - material after heat treatment; 3 - material with a UFG structure after heat treatment and SPD processing by ECAP.

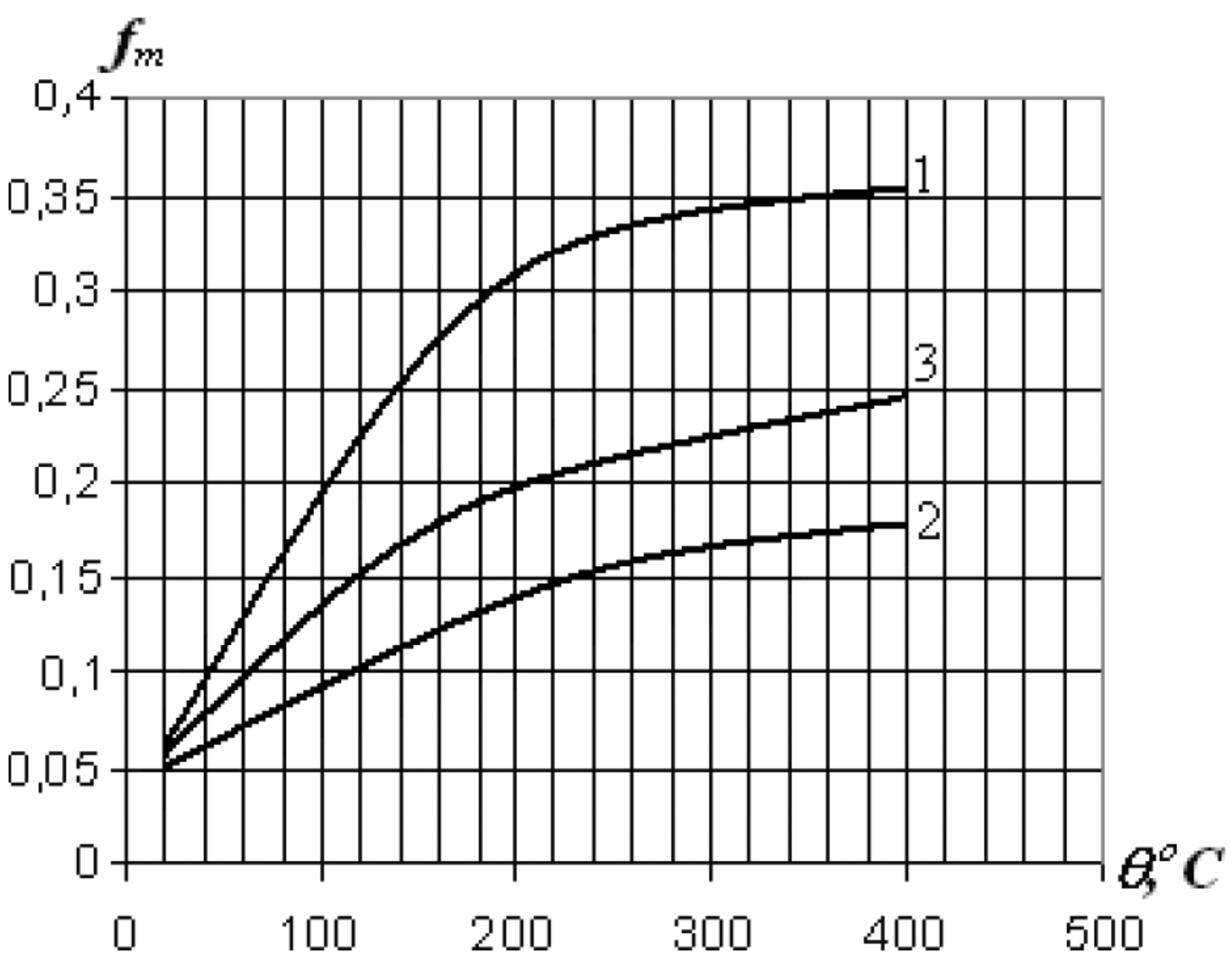

Fig. 12. Variation of the molecular component of the friction coefficient depending on the temperature (friction pair "medium-carbon steel - tool steel Fe - 6W - 5Mo" at different temperatures and under different types of treatment of the investigated material: 1 – initial material (coarse-grained, hot-rolled); 2 - material after heat treatment; 3 - material with UFG structure after heat treatment and SPD processing by ECAP.

data presented in Figs. 9 and 11 after the calculation of f_m.

These studies confirmed the linear nature of the dependence $\tau_n = f(p_r)$ in the conditions of elastic contact, as well as in the conditions of plastic strains at different temperatures θ. The presented diagrams show the variation of the shear strength of adhesive bonds depending on the normal pressure. It can be seen that the molecular component of the friction coefficient (f_m), which is determined from expression (3), increases with an increasing temperature. The value of f_m is determined as the tangent of the slope angle to the abscissa axis (i.e. as the relationship between the shear strength of adhesive bonds (τ_n) and the normal pressure (p_r)).

It has been established that an increase of the strength of adhesive bonds is accompanied by faster growth of the normal pressures p_r in a contact. The greatest effect is observed for the samples of the low-carbon steel with a *UFG* structure after *ECAP* processing. This is connected with a higher level of material hardening resulting from deformation processing. The bearing capacity of the contact decreases with increasing temperature [13], which results in an increase in the molecular component of the friction coefficient f_m (Fig. 10).

However, the presented dependences demonstrate that the values of the molecular component of the friction coefficient are lower for the low-carbon steel subjected to heat treatment followed by *SPD* processing by *ECAP*, in a contact with a tool steel, in the whole range of investigated temperatures. The data obtained for the initial sample with a *CG* structure and for the sample after heat treatment (without subsequent *SPD* processing) differ insignificantly in terms of both the value and variation character of f_m. This is due to the small difference in the average grain size of the samples in the initial and heat-treated states. The molecular component of the friction coefficient is directly connected with the structural state of the material.

For the medium-carbon steel (Fig. 11), the greatest effect, from the point of view of assessment of the shear strength of adhesive bonds, is observed after heat treatment, which is confirmed by the results of determination of the molecular components of the friction coefficient (Fig. 12, curve 2). The results of the tribological *studies, obtained on a one-ball adhesion meter, fully correlate with the results of* determination of the integral values of the friction coefficient, presented in Fig. 7.

4. CONCLUSION

1. It has been shown, using a low-carbon steel as an example, that severe plastic deformation processing by multi-cyclic equal-channel angular pressing enables an efficient enhancement of the strength of low-carbon steel due to grain structure refinement, which has a significant impact on the decrease in the total friction coefficient and its molecular component;
2. To improve the tribological properties of steels with a high carbon content, it is sufficient to perform heat treatment without subsequent SPD processing. This is confirmed by the studies conducted on a medium-carbon steel.

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