Research the hardness of polymer materials after turning

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Abstract. The paper presents the results of experimental studies to determine the hardness of the treated surface depending on the conditions and machining type of workpieces made of textolite, caprolon and fluoroplastic. The experimental methodology and explanation of the reasons for changing the hardness of the treated surface for the investigated variants of machining the materials are under study. The results of studying the influence of the phenomenon of elastic aftereffect of the polymer materials after workpieces machining are obtained.

The properties of machined surfaces are mainly formed in the final stage of manufacturing. In the manufacture of polymer parts, as a rule, the final stage is cutting to ensure a satisfactory external appearance, to change the configuration obtained in the shaping process, and to ensure dimensional precision and required quality of the machined surface. The surface quality is characterized by the roughness and the physic mechanical properties of the surface layer. The quality of the surface layer determines the strength of the part, the strength of joints with clearance, the stability of mobile joints, the wear resistance, the corrosion resistance, and the optical, chemical, and antifrictional properties.

One of the main physic mechanical properties of structural materials is the hardness. The hardness, determined by impressing a tool tip, characterizes the resistance to plastic deformation; the hardness measurements may be regarded as local mechanical tests of the surface layers of the material. The hardness measurements may be of universal significance. Hardness data provide the basis for determining the hardening coefficient, the residual stress, the degree of surface- layer destruction, the yield point, the strength, and the true fracture strength of the material.

The machining of metals and alloys is accompanied by cold hardening of the surface layer, as we know [1]; the accompanying degree of hardening of the blank may be estimated. However, cutting metals differs significantly from cutting polymers. Accordingly, investigating the hardness of the machined polymer surface is of great scientific and practical importance and provides additional information on polymer properties, permitting more efficient use of polymer components.

In the present experiments, we determine the hardness of the machined polymer surface as a function of the machining conditions and the holding time after machining.

The materials investigated are thermoplastic and thermo reactive plastics, used in manufacturing: specifically, caprolon, fluoroplastic, and textolite, in the form of round

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blanks (diameter 40 mm). These materials differ considerably; their manufacturing technology is also different. Round textolite samples consist of a pressed laminar material, manufactured by winding; it consists of several layers of cotton fabric steeped with thermo reactive binder (based on phenol formaldehyde resin). Caprolon blanks are produced by chemical shaping, i.e., by polymerization of caprolactam directly in a mold. The production technology for fluoroplastic-4 blanks includes the following stages: pelletization of the blanks from powder in molds, sintering of the pellets in furnaces, and cooling in the furnace, in air, or in water.

The initial stage in the experiments is to measure the hardness of the blanks before machining, in accordance with State Standard GOST 4670-91, by pressing a steel ball into the tested sample (Brinell method). Then a single section of the blank is turned, while the remainder undergoes complex machining (preliminary compression + subsequent turning). The hardness of the machined surface is then determined. In the preliminary compression of the blank, the following condition is observed [2]

$$\sigma_{in} < (0.6\text{-}0.8)\,\sigma_e, \tag{1}$$

where σ_{in} is the stress created in the blank by the compression/tension force; σ_e is the limit of forced elasticity of the polymer. (For textolite, σ_e must be replaced by the fracture stress σ_f.)

The final stage in the experiment is to investigate the long-term stability of the blank's hardness after turning and complex machining. The holding time adopted is 120 hours. The storage conditions (temperature, moisture content, level of illumination) remain constant throughout the experiment. A universal screw-cutting lathe is used to turn the blanks. The cutting conditions and the tool material and dimensions are selected on the basis of data in [3]. Comparative evaluation of the change in strength of a particular material for each machining method may be based on the hardening coefficient

$$N = (HB_m - HB_{in}) / HB_{in}, \tag{2}$$

where HB_m is the hardness of the blank's machined surface; HB_{in} is the initial hardness of the untreated surface.

Positive N indicates increase in hardness of the machined surface; negative N indicates softening.

The table 1 presents data on the hardness of the initial material and the machined surface, as well as corresponding values of the hardening coefficients.

Comparison of the experimental data shows that turning thermoplastic blanks with and without preliminary compression increases the surface hardness: the hardening coefficient is 0.21 and 0.15, respectively for caprolon, and 0.175 and 0.13 for fluoroplastic. The corresponding figures for textolite are -0.11 and -0.023. This indicates that the hardness of textolite declines on machining.

The increase in hardness of crystalline polymers (caprolon, fluoroplastic) on cutting may be explained as follows. As we know [4, 5], the machining of crystalline polymers is accompanied by structural change, with growth in the crystalline phase of the material. Polymer crystallization increases the hardness, elastic modulus, strength, and other mechanical characteristics, since the hardness, strength, and density of crystallized polymer are higher than for amorphous polymer. Thus, taking account of the elastoplastic deformation of the machined material in the cutting zone [6], we may conclude that the cutting of caprolon and fluoroplastic is accompanied by recrystallization and hardening of the surface layer on account of increase in the content of crystalline phase.

Table 1. Hardness data for blanks

Machining method	Brinell hardness, MPa, and hardening coefficient, %		
	caprolon	fluoroplastic	textolite
Turning	171.6 and 0.21	36.1 and 0.175	179.4 and -0.11
Preliminary compression + turning	164.8 and 0.15	34.4 and 0.13	191.8 and -0.023
Initial blank (no machining)	142.8 -	30.7 -	198.2 -

In addition, the surface layer of the untreated blank contains initial defects (cracks and microcracks), as a rule. Consequently, the volume of the part is characterized by a nonuniform thermal-stress distribution, resulting from the higher cooling rate of the surface layer than the internal layers, which, in turn, is due to the great specific heat and low thermal conductivity of the polymer. The interaction of the blank and the cutting tool removes the defective layer of material, which thereby increases the strength of the machined surface.

For caprolon and fluoroplastic, as shown by the hardening coefficients, the hardness of the machined surface is less after complex treatment (preliminary compression and subsequent turning) than after traditional turning. Preliminary compression of the blank leads to tensile stress within the blank after removing the compressive load. During the subsequent turning, the tensile stress is partially compensated by the compressive stress in the cutting zone, and the effectiveness of recrystallization is reduced. This reduces the content of crystalline phase in the material and hence its hardness.

In cutting laminar polymers of textolite type, the surface layer of the part loses its integrity, the external layer of polymerized binder is removed, and the reinforcing fibers are cut into pieces. This leads to the formation of a defective and disintegrated surface layer, whose physicochemical characteristics differ considerably from those of the initial structure. Preliminary compression of the blank leads to embrittlement of some of the material, which permits some decrease in the thermo mechanical destruction of the blank's surface layer in subsequent turning, as indicated by the increase in hardness of the textolite surface.

In the experiments, the supply in turning the blanks is 0.20 mm/turn. As we know [3,6], the longitudinal supply has a considerable influence on the geometric parameters of the machined surface of the polymer blank. The influence of the supply on the hardness of the blank's machined surface is of practical interest.

Experimental curves of the blank's surface hardness as a function of the supply are shown in Fig. 1. Analysis indicates that, for each material, regardless of the machining method, the hardness is approximately constant up to some supply value S_{opt}. Thus, $S_{opt} = 0.17$ mm/turn for caprolon, 0.15 mm/turn for fluoroplastic, and 0.13 mm/turn for textolite. Beyond S_{opt}, the surface hardness of all the blanks smoothly declines. Such hardness variation may be explained in that, beyond S_{opt}, the height of the micro irregularities on the machined surface increases. Greater surface roughness leads to splitting, embrittlement, and hence loss of strength of the material in plastic deformation.

This hypothesis is confirmed by microphotographs of chips (Figs. 2 and 3). In turning thermoplastic material such as caprolon, a continuous chip is obtained at $S = 0.15$ mm/turn (Fig. 2a), while that observed at $S = 0.25$ mm/turn is a continuous cleavage chip (Fig. 2b). With increase in S for textolite, larger particles are seen in the broken chip (Fig. 3). The change in chip formation indicates increased surface roughness.
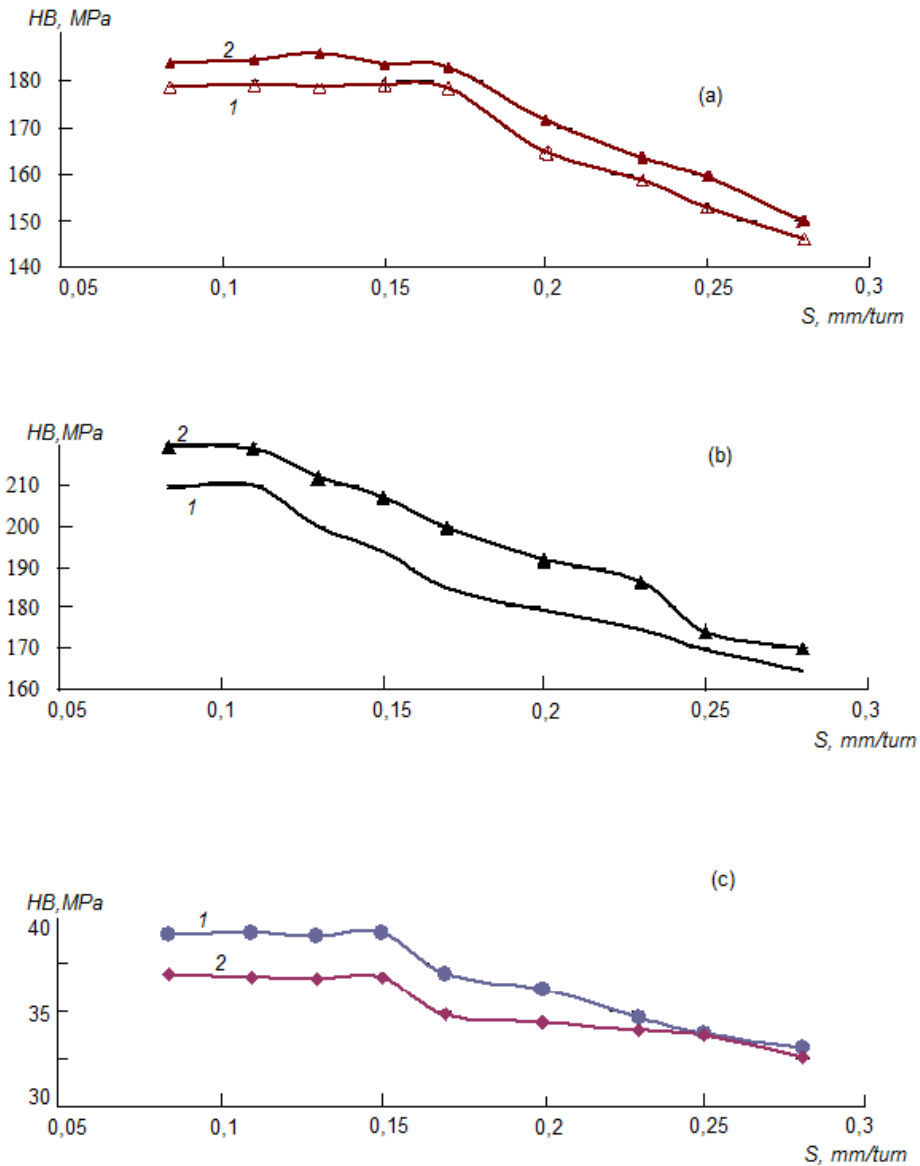
Fig. 1. Dependence of the surface hardness of caprolon (a), textolite (b), and fluoroplastic (c) on the supply in turning (1) and turning with preliminary compression (2).

The surface quality depends significantly on the elastic aftereffect of machining in the polymer blank. This leads to internal residual stress, which may change the hardness of the part after some time [5, 7]. This conclusion may be verified by measuring the hardness after turning and complex machining; the blanks are held after machining for up to 120 hours.
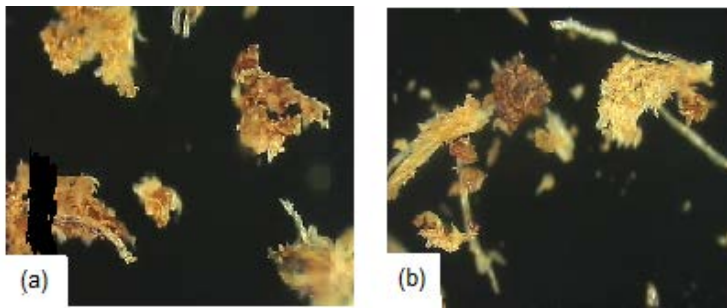
Fig. 3. Microphotograph of a chip fragment for the turning of textolite with $S = 0.13$ (a) and 0.23 (b) mm/turn.

The hardness of the surface after machining is plotted in Fig. 4 as a function of the holding time. As follows from analysis, the holding time after machining has little influence on the final result. The slight (5-8%) difference in surface hardness after turning and complex machining is due to the nonuniform phase distribution over the billet length and cross section and to the randomly distributed micro defects within the material. For textolite, the hardness fluctuations are largely due to its very heterogeneous structure.

Thus, on the basis of the results, we may state the following conclusions.

1. Turning caprolon and fluoroplastic-4 blanks increases the surface hardness.

2. Turning blanks after preliminary compression also increases the surface hardness, but by a smaller amount.

3. For textolite, the surface hardness is reduced, both in turning and in complex machining (preliminary compression + turning).

4. For each material, regardless of the machining method, the hardness is approximately constant up to some value S_{opt} of the supply, beyond which it smoothly declines.

5. Elastic recovery of the material after machining has no influence on the hardness in the selected conditions.
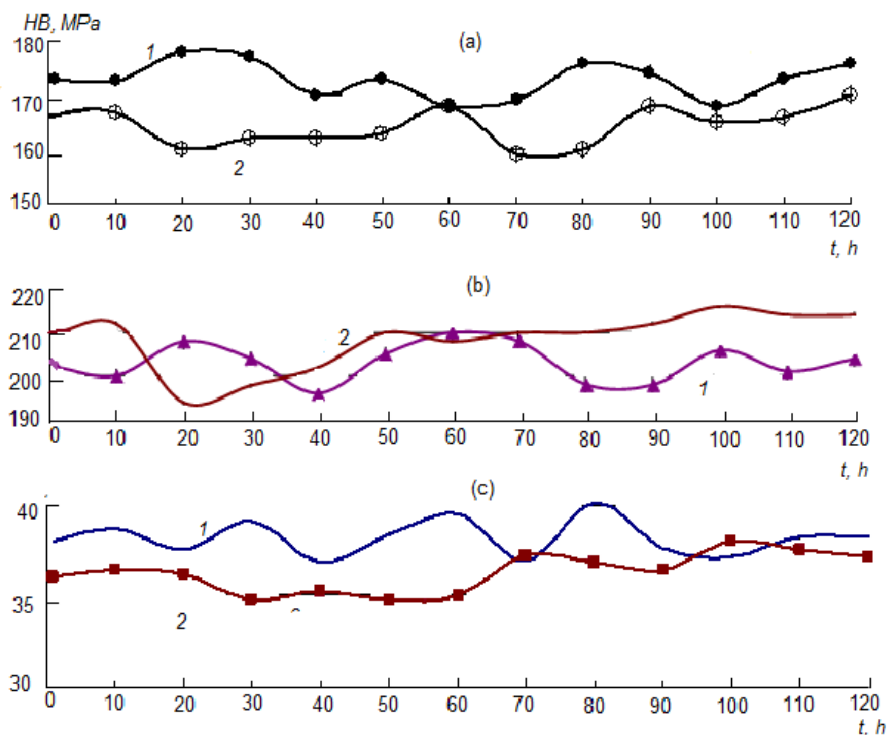
Fig. 4. Dependence of the surface hardness of caprolon (a), textolite (b), and fluoroplastic (c) on the holding time after turning (1) and turning with preliminary compression (2).

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