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Determination of the distorted surface layer thickness in machined optically transparent polymer articles

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The functional performance of the optical polymer articles and the service life thereof are defined to a considerable extent by the surface layer state. When machined, the surface layer of polymer articles differs in its properties from the initial material. The combined force and heat action during the cutting results in a complex final structure state of the surface layer. This fact requires investigations to determine the changed (distorted) layer depth after the machining and to study its influence on the functional properties of the optical polymer articles.

Функциональные свойства и долговечность работы изделий из оптических полимеров в значительной степени определяются состоянием их поверхностного слоя. При механической обработке поверхностный слой полимерных изделий приобретает свойства, отличные от свойств исходного материала. Взаимное проявление силового и теплового факторов в процессе резания приводит к сложному итоговому структурному состоянию поверхностного слоя изделия. Это требует проведения обстоятельных исследований для выявления глубины измененного (нарушенного) слоя после механической обработки и изучения его влияния на эксплуатационные свойства оптических полимерных изделий.

Articles made of optical polymers, when used as elements of complex detector systems in modern accelerators (CDF, SSC, LHCb, etc.), should be serviceable during prolonged periods (up to 10 years) under intense irradiation and continuous action of aggressive media (moisture, temperature, air components, etc.) in closed areas. To provide the effective service in those conditions, the optical articles should exhibit not only a high radiation resistance, but also a high stability of the optical characteristics. The functional performance of the optical polymer articles and the service life thereof are defined to a considerable extent by the surface layer state. The surface layer quality of optical polymer articles was studied comprehensively [1–3] and a considerable experimental data array has been accumulated during last few years. To date, it is just the microhardness measurement that is the most objective, sensitive, and easily available method to assess the surface layer state and to provide the physicochemical analysis of a material [1–3]. The hardness tests have advantage as compared to other mechanical tests in that the microhardness can be measured directly on working surfaces at small indentation size that does not affect the surface quality.

The surface layer quality is influenced by the initial material structure formed at the polymerization step and the material composition. The kinetic energy of destruction under subsequent machining causes changes in the material supramolecular organization, strength and rheology properties, the surface activity, swelling and

water absorption characteristics, as well as in the electrochemical and optical characteristics and color [4]. The various internal defects caused by variations in the material composition, the polymerization regime, and the heat treatment of the workpiece become revealed, such as air bubbles, flaws, random inclusions and structure inhomogeneities [5]. There is a direct relationship between the tensile strength, density, and microhardness [6]. A higher tensile strength corresponds to a lowered density and a higher microhardness. That relationship is valid for all the polymer samples obtained by various techniques and having various compositions and structures.

When machined, the surface layer of polymer articles differs in its properties from the initial material. The combined force and heat action during the cutting results in a complex final structure state of the surface layer and thus in a specific combination of its physical, mechanical, and other properties. This fact requires investigations to determine the changed (distorted) layer depth after the machining and to study its influence on the functional properties of the optical polymer articles. In the course of cutting, a micro-relief is formed at the polymer surface with non-uniform shape of hills and valleys and random distribution of the micro-roughness height and spacing. This phenomenon combined with the physicochemical state fluctuations in the surface layer results in that the areas with increased tendency to cracking are formed at the machined surface and the subsurface layer. The presence of areas with varying physicochemical properties causes the prepositions for premature failure of the optical articles in the course of service. The formation of the surface layer inhomogeneous in its properties is due physically to specific features of the polymer material straining under machining. The surface layer straining and its strengthening under cutting results in formation of the increased density areas that are potential sources of the crack generation.

We have carried out the studies to establish the distorted layer thickness at a preliminary machining operation (cutting a polymer block into plates). The examinations were based on the study of the microhardness variations as a characteristic allowing to assess the physico-mechanical transformations in the polymer under the force and heat action during the blade treatment. The material was cut using a band-saw machine with a high-speed saw (R18). The tool geometry and the sawing regime were as follows: the relief angle $\alpha = 30°$, the rake angle $\gamma = 4°$, the saw thickness 1.5 mm, the cut width $t = 2$ mm, the rotation frequency $n = 600$ rpm, the medium-distilled water. The machined surface microhardness was determined using a PMT-3 instrument basing on the indenter trace [7]. As the indenter, a diamond pyramid was used having a square base and the top angle between opposite faces 136°. The instrument microscope magnification was 130°. The sample surface was clean and planar. The samples were prepared for testing using a SD-2 polishing machine, the polishing being reduced to the surface de-burring. Using a 16K20 engine lathe and right-hand cutter (rake angle $\alpha = 21°$, relief angle $\gamma = 21°$, R18 high-speed steel), the polymer was taken off layerwise at 0.05 mm layer thickness and the surface microhardness was measured at each step. The mechanical take-off contributes additionally to the material change, but, since these changes are the same at each step, the microhardness variation character in depth can be estimated.

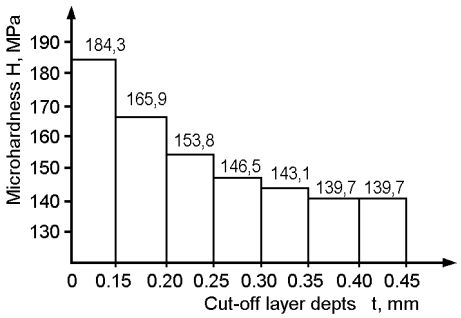

Fig. 1. Surface microhardness, H, as a function of depth, t.

All microhardness values were obtained at the same conditions (the load $P = 20$ g, the loading duration 10 s, exposure duration 6 s). The total number of measurements at each area for all samples exceeded 10. 10 samples were tested. The material was taken off layerwise until the constant microhardness value was obtained (Fig. 1). The imprint diagonal measurement results and the corresponding microhardness characteristics are presented in Table 1. As to first measurements (done immediately after the block cutting into plates), the imprint shape distortions are typical (local microcracks and strakes) evidencing the material brittlement [7]. This supposes that these layers of the material are more brittle

Table 1. Surface microhardness measured values

Cut-off layer, mm	Imprint diagonal D, μm (p = 20 g)	Imprint depth h, μm	Microhardness H, MPa
0.15	44.6	6.2	184.3
0.2	46.8	6.6	165.9
0.25	48.6	6.8	153.8
0.3	49.8	7.0	146.5
0.35	50.4	7.1	143.1
0.4	51	7.14	139.7
0.45	51	7.14	139.7

and imperfect in structure. Using the statistical data processing, the average microhardness values for each layer have been determined. After the 0.4 mm thick layer withdrawn, the microhardness is 139.7 MPa, or 75.8 % of the initial (for cut plates) one. The distorted layer thickness foe the cut workpieces is 0.40 to 0.45 mm (Fig. 1).

At the next work step, the distorted layer was studied formed under milling by single-tooth tools made of hard alloy, synthetic, and natural diamonds. The hard alloy tool was made of the VK8 material, the rake angle $\gamma = 20°$, the relief angle $\alpha = 20°$, the cutting edge rounding radius $R = 5$ mm. The synthetic diamond tool: ASPK material, $\gamma = 4°$, $\alpha = 20°$, the plate diameter 5 mm. The natural diamond tool: IR-292 special cutter with diamond insert, $\gamma = 4°$, $\alpha = 20°$, $R = 4$ mm. The polymer workpieces (10×20×250 mm^3 size) were machined using a FP-37N3 milling machine provided by a vacuum-holding worktable at the following cutting regime: $S_z = 0.03$ mm per tooth, $V = 1754$ m/min, $t = 0.05$ mm. The roughness and surface microhardness characteristics for polymer samples after various machining kinds are presented in Table 2. The scatter in the microhardness values makes it expedient to study the surface layer state of polymer articles after rough and finishing milling using hard alloy, synthetic, and natural diamond tools.

The expected distorted layer thickness after milling is much less than that after the polymer workpiece cutting. Therefore, the material was taken off layerwise at 5 μm steps using a microtome. After each step, the microhardness was measured at the load $P = 20$ g, the loading duration 10 s, and exposure duration 6 s. The results obtained are presented in Table 3. The experimental data obtained confirm quantitatively the suitability of the technique

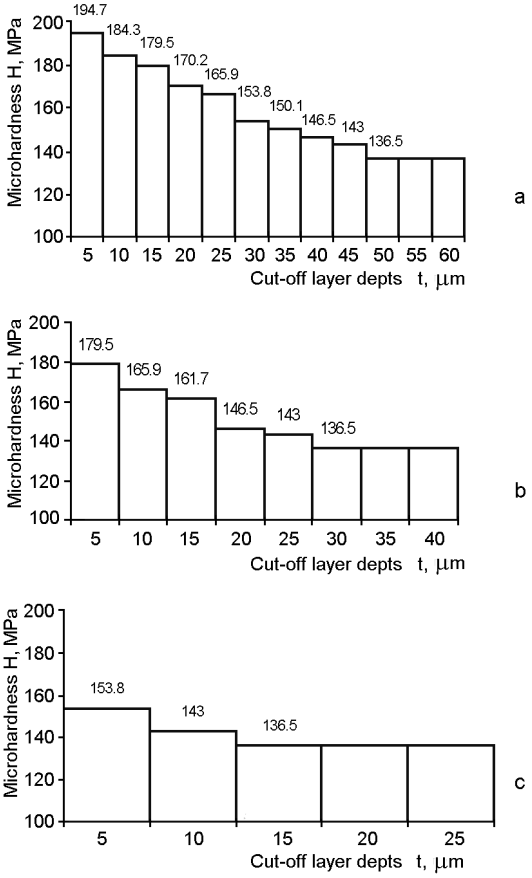

Fig. 2. Surface microhardness, H, as a function of depth, t, at the samples machined with VK8 hard alloy (a), ASPK synthetic diamond (b), and natural diamond (c).

used to study the surface layer state of the polymer articles. The layer-by-layer microhardness measurement technique exhibits the advantages of easiness, sensitivity, and objectivity.

The studies have shown that after rough milling by hard alloy tool, the distorted layer thickness is 0.05 mm while after semi-finishing by synthetic diamond tool, 0.03 mm. The diamond milling provides a

Table 2. Surface roughness and microhardness of milled samples

Sample No.	Tool material	Surface roughness parameters		Microhardness H, MPa
		R_a, μm	R_z, μm	
1	Hard alloy	2.84	14.7	357.64
2	Synthetic diamond	0.8	4.0	142.56
3	Natural diamond	0.06	0.3	130.03

Table 3. Surface microhardness measured values

Cut-off layer, μm	Imprint diagonal D, μm (p = 20 g)	Imprint depth h, μm	Microhardness H, MPa
The hard alloy tool (VK8)			
5	43.2	6.2	194.7
10	44.4	6.3	184.3
15	45	6.4	179.5
20	46.2	6.6	170.2
25	46.8	6.7	165.9
30	48.6	6.9	153.8
35	49.2	7.0	150.1
40	49.8	7.1	146.5
45	50.4	7.2	143
50	51.6	7.4	136.5
55	51.6	7.4	136.5
The synthetic diamond tool (ASPK)			
5	45	6.4	179.5
10	46.8	6.7	165.9
15	47.4	6.8	161.7
20	49.8	7.1	146.5
25	50.4	7.2	143
30	51.6	7.4	136.5
35	51.6	7.4	136.5
40	51.6	7.4	136.5
The natural diamond tool			
5	48.6	6.9	153.8
10	50.4	7.2	143
15	51.6	7.4	136.5
20	51.6	7.4	136.5
25	51.6	7.4	136.5

stable process of the surface structure formation in the polymer material and a minimum distorted layer thicknes of 0.015 μm. Thus, the hard alloy machining results in the most inhomogeneous physical and mechanical state of the surface layer. The distorted surface layer obtained at the synthetic diamond machining is a half so thick as that after the hard alloy machining. The minimum thickness and the highest homogeneity of the surface layer are attained at the diamond machining.

The instability in the surface layer properties may be one cause of the functional performance deterioration of the optical articles, in particular, of the internal reflection factor R_2. The established relationship between the machining conditions and the

distorted layer thickness will allow to determine the optimum treatment conditions, the cutting tool material, its geometry, and the cutting regimes providing the minimum distorted layer thickness in the optical polymer articles, thus attaining the best service characteristics thereof.

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Визначення величини порушеного поверхневого шару оптично прозорих полімерних виробів після лезової обробки

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Функціональні властивості і довговічність роботи виробів з оптичних полімерів в значній мірі визначаються станом їхнього поверхневого шару. При механічній обробці поверхневий шар полімерних виробів здобуває властивості, відмінні від властивостей вихідного матеріалу. Взаємний прояв силового і теплового факторів у процесі різання приводить до складного підсумкового структурного стану поверхневого шару виробу. Це вимагає проведення докладних досліджень для виявлення глибини зміненого (порушеного) шару після механічної обробки і вивчення його впливу на експлуатаційні властивості оптичних полімерних виробів.