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# TESTS OF SCRATCH RESISTANCE OF POLYMER MATERIAL SURFACES

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## Abstract

*The paper presents the results of comparative tests of resistance to scratching of two polymer samples made via the extrusion method. The first sample was a homogenous low-density polyethylene Lupolen 2426 H, while the second sample was a two-layer polymer of the same thickness with an outer layer of polypropylene Marlex HGX-030SP and an inner layer of Lupolen 2426 H. The Micro Scratch Tester and the Dektak 150 profilometer were used to perform the appropriate measurements. The following values were recorded: coefficient of friction, force of friction, depth of indenter penetration and residual depth after scratching. Surface profilograms and boxwhisker diagrams of hardness, width of the gap and area of the crack cross-section were made. The results of the research indicate the possibility of applying polypropylene to a layer protecting low-density polyethylene against mechanical damage, especially against scratches.*

**Keywords:** Polyethylene, Polypropylene, Scratch resistance, Scratch test, Profilometer


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# 1 INTRODUCTION

Scratches may occur during manufacture, assembly, transport and operation under expected operating conditions [1]. In a scratch-test, the material surface resistance is measured based on the characteristic parameters of scratch resistance, e.g. the friction force. Quantitatively, the degree of scratch resistance can be also related to the scratch width, depth, (Rd) or the produced groove volume [8]. The scratch itself is also subject to macroscopic qualitative evaluation. A scratch on a polymer material surface causes a concentration of stress and decreases durability under operating conditions, under which tensile, bending and impact loads occur, also with a fatigue character [4]. In consequence, structures with this type of damage tend to show “stress whitening”, which has an adverse impact on the appearance of the surface. This phenomenon is connected with the formation of cohesive micro-damage, which reflects and refract lights waves. This is particularly important for applications in which surface aesthetics is essential [9, 10]. In the paper [11], it was confirmed that the scratch stress value is connected not only with the indenter shape and applied load, but also with the velocity. It is also influenced by the structural properties of the polymer material, i.e. the rigidity, hardness and flexibility. Based on the research included in the papers [12, 13], it was established that to obtain good scratch resistance, it is necessary to maintain balance between rigidity and flexibility. The importance of these parameters was well explained using the example included in the paper [2]. Diamond, being the hardest and most rigid material, is resistant to indentation and scratching. However elastomer, “perfect rubber” according to [2], is flexible - capable of major deformations, completely reversible (non-permanent) after the load is removed. Theoretically, these two materials feature the highest scratch resistance due to surface deformation and cohesive damage caused by contact stresses. The high share of crystalline phase in the material contributes to scratch resistance as well [12, 13]. However, most polymer materials are susceptible to damage in the form of scratches. A scratch test and scratch evaluation method was described in technical standard ASTM G 171 [14].

The purpose of the paper is to prove the possibility of increasing the scratch resistance of products made of materials subject to mechanical factors during storage, packaging, transport, assembly and cleaning, due to the specifics of their use.

# 2 TEST CHARACTERISTICS

## 2.1 Test object

The test objects were cylindrical components made of polyethylene pipe and two-layered polypropylene-polyethylene pipe with a circular shape of cross-section (Fig. 1). Due to the dimensions of provided samples, they were cut using a laboratory cutter. The low-density polyethylene called Lupolen 2426H, used to produce a uniform polyethylene pipe, was

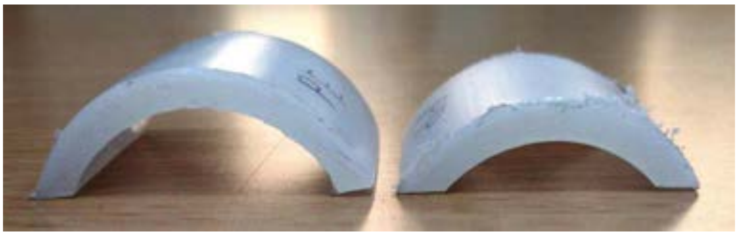

Figure 1: Samples used in scratch resistance tests.

manufactured by LyondellBasell (Tab. 1) and included a slip and anti-blocking agent; it was primarily designed for film extrusion. In turn, to produce the two-layer pipe, the internal layer was coated with a polypropylene called Marlex HGX-030SP, manufactured by Saudi Polymers

Company (Tab. 2), while the internal layer was made of the same low-density polyethylene as the uniform pipe.

| Property | Test method | Value | Unit |
|---|---|---|---|
| Density | ISO 1183 | 924 | kg/m³ |
| Melt flow rate (MFR) | ISO 1133 | 1.9 | g/10min |
| Tensile stiffness modulus | ISO 527-1,2 | 260 | MPa |
| Tensile yield length | ISO 527-1,2 | 11.0 | MPa |
| Tensile strength | ISO 527-1,3 | | |
| - Longitudinal | | 25.0 | MPa |
| - Transverse | | 21.0 | MPa |
| Ultimate elongation | ISO 527-1, 2 | | |
| - Longitudinal | | 250 | % |
| - Transverse | | 600 | % |
| Vicat softening temperature (A50, (50 °C/h, 10N)) | ISO 306 | 94.0 | °C |
| Melting point | ISO 31046 | 111 | °C |

Table 1: Properties of the low-density polyethylene, Lupolen 2426 H, by LyondellBasell.

| Property | Test method | Value | Unit |
|---|---|---|---|
| Density | ASTM D1505 | 906 | kg/m$^3$ |
| Melt flow rate (MFR), conditions: 230°C/2.16 kg | ASTM D1238 | 3 | g/10min |
| Tensile strength, 50.8 mm/min | ASTM D638 | 37 | MPa |
| Izod notch impact strength, 23°C | ASTM D256 | 31 | J/m$^2$ |
| Elasticity modulus | ASTM D790 | 1590 | MPa |
| D-type hardness | ASTM D2240 | 70 | - |
| Heat deflection temperature, 0.46 MPa | ASTM D648 | 101 | °C |

Table 2: Properties of polypropylene under the trade name Marlex HGX-030SP, by Saudi Polymers Company.

## 2.2 Test method

The test of scratch resistance was conducted on the Micro Scratch Tester (MST), manufactured by Anton Paar, acc. to the diagram shown in Fig. 2. A Rockwell indenter in the form of a diamond cone with a curvature radius of 100 μm was used. The indenter was loaded using the constant normal force (Fn) of 2 N, with the velocity of 5 N/s.

Then, a scratch was made along the segment of 2 mm, with the velocity of 3 mm/min. During the test, the following parameters were recorded at a frequency of 30 Hz: friction coefficient (μ), friction force (Ft), indenter penetration depth (Pd) and remaining depth after scratch (Rd). A “prescan” and “postscan” were completed to identify the surface profile.

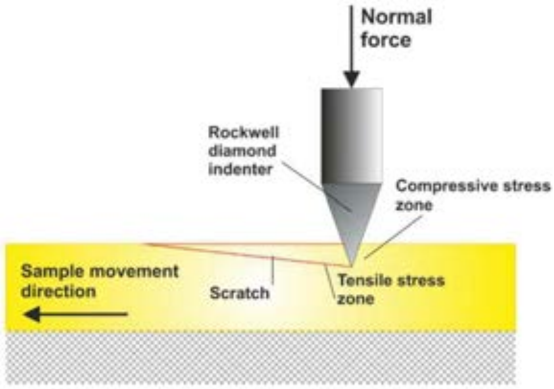


Figure 2: Scratch resistance test diagram.

The scratch was evaluated using an optical microscope coupled with the MST. This device only enabled the measurement of scratch width, SW (Fig. 3).

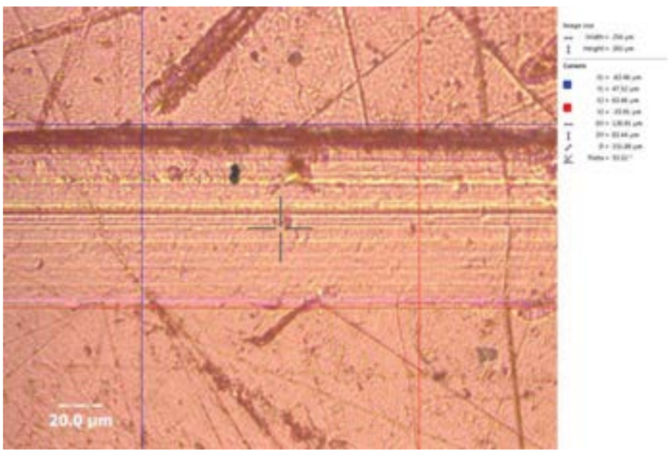


Figure 3: Measurement of scratch width was made using an optical microscope.

Due to the small differences in the width of scratches measured using the optical microscope on the surface of both tested materials, a higher precision measurement method was used. In the tests, the Dektak 150 contact profilometer was used. The profilometer enables 2D topography measurements and 3D surface measurements with the resolution of 0.01 μm on the Z-axis. The equipment includes 2 measuring tips (replaceable styli) with a curvature radius of 2 μm and 12.5 μm. In the subject tests, a stylus with a curvature radius of 2 μm was used, to which a force equivalent to 3 mg was applied. The measurement resolution was determined at 0.1 μm. The measurement path was in the range of 500 – 1000 μm (Fig. 4). The use of a profilometer enabled the discovery of the character of material deformation. The formation of the scratch is connected with the formation of permanent plastic deformations not only on the bottom of the groove but also on its lateral edges in the form of the so-called plastic pile-up. Scientific papers on the scratch resistance of polymer materials, e.g. [1, 4, 15], reported that the scratch width should be measured including the plastic pil-ups on groove edges, which is impossible to determine using the optical microscope, i.e. it is impossible to identify the highest points of plastic pile-ups (Fig. 5).

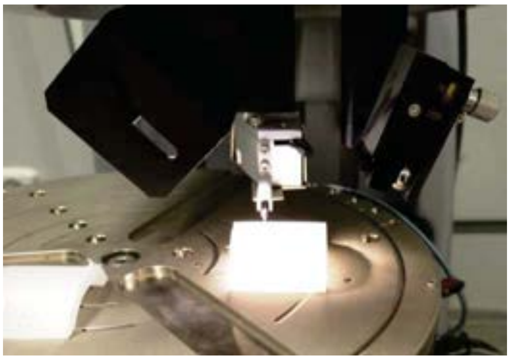

Figure 4: Measurement of surface profile at the scratch point.

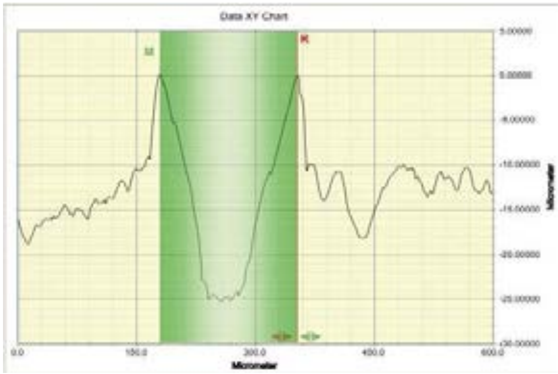


Figure 5: Measurement of slot width (SW) as the distance between the highest points of plastic "pile-ups" (the width of the green area) and the surface area of the slot section $S_{ar}$.

For a better illustration of the magnitude of the damage to the surface of tested materials, the surface area of the groove section, Sar, was measured as well. The horizontal axis "0" was routed through the highest points of plastic pil-ups. The vertical lines limiting the measurement range, "M" and "R", passed through these points as well. In consequence, the surface area was measured in the area limited by the axis "0", the lines "M" and "R" and the surface profile. Is worth noting that the parameter Sar was not considered in the evaluation of scratches in papers [1, 4, 15], however it was often used in papers in the field of tribology. Based on the obtained results of scratch geometry examination, the scratch hardness, Hs, was calculated as well. The Hs parameter was calculated according to the formula included in the paper [11]:

$$Hs = \frac{4 \cdot x \cdot Fn}{\pi \cdot SW^2} \tag{1}$$

where:

Hs - scratch hardness in $N/mm^2$,

Fn - normal force in N,

SW - slot width in mm,

x - parameter assumed in the range of 1÷2, in this report the value of 1 was assumed, according to [16].

## 3 TEST RESULTS

### 3.1 Results of measurements on the MST scratch tester

The characteristic parameters of the scratch damage on the surface of the tested materials is presented in plots (Fig. 6 – 9). In the plot (Fig. 6), average curves corresponding to the permanent scratch depth (Rd) are juxtaposed. The shape of Rd curves is different, which is most probably connected with the damage formation mechanism (Fig. 10 and 11).

In Figure 7, the indenter penetration depth under normal load (Pd) is presented. The indentation, Pd, included plastic and elastic deformations of the material surface. Higher Pd values were noted in the PE material. The penetration depth in the PE material was two times higher than in the PP material.

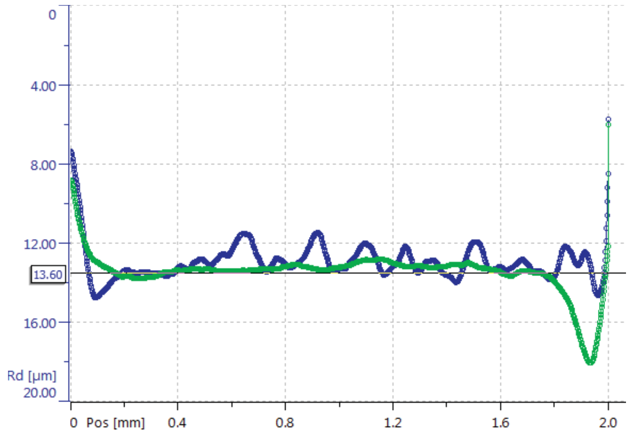


Figure 6: Average permanent scratch depth (Rd) on the surface of tested polymer materials (**PE, PP**).

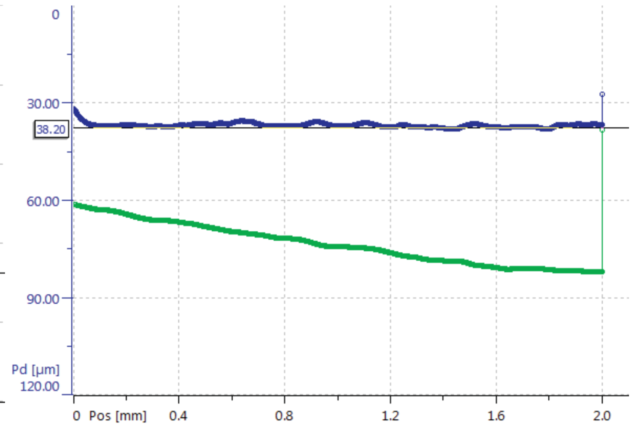


Figure 7: Pinpoint penetration depth (Pd) during scratch test (under normal force of 2 N) (**PE, PP**).

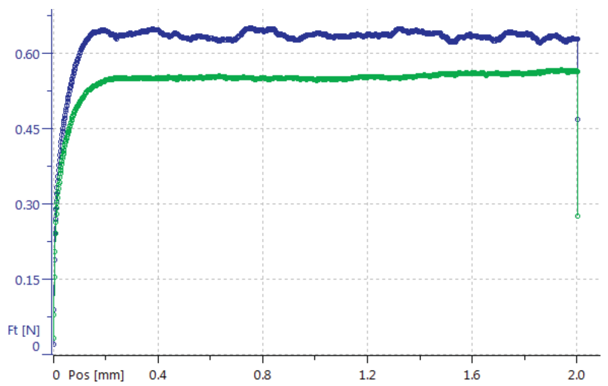


Figure 8: Average courses of friction force (Ft) during scratch test (under normal force of 2 N) (**PE, PP**).

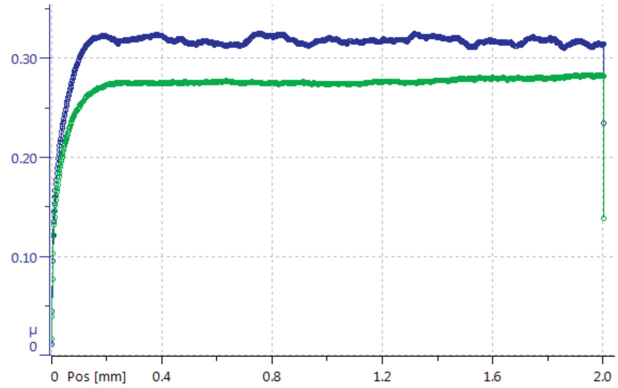


Figure 9: Average courses of friction coefficient (μ) during scratch test (under normal force of 2 N) (**PE, PP**).

In Figures 8 and 9, the average courses of the friction force (Ft) and friction coefficient (μ) are shown. The courses do not overlap. The friction force corresponding to the scratch resistance of the material is higher for the PP material. Also, a non-linear Ft and μ course for the PP material is shown, which is probably connected with the damage destruction. The PP material destruction mechanism differs from the PE destruction mechanism. For PP, cohesive damage in the form of conformal micro-cracks appear at the bottom of the groove.

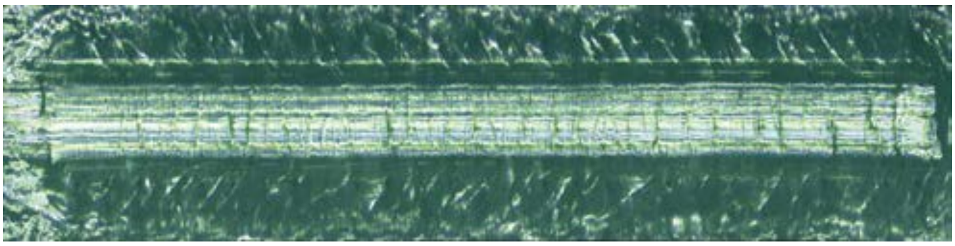

Figure 10: The optical microscope image of the scratched surface of the PP material (lens Olympus 20 x, aperture 0.4).

This type of damage is formed during a material grooving response test. The edges of the groove also show micro-cracks caused by material buckling under indenter (Fig. 10). This damage is reflected in the non-linear courses of Rd, Ft and μ curves. In case of the PE material, no such damage is noted. Only damage related to micro-cutting is visible, according to the indenter shift direction (Fig. 11).

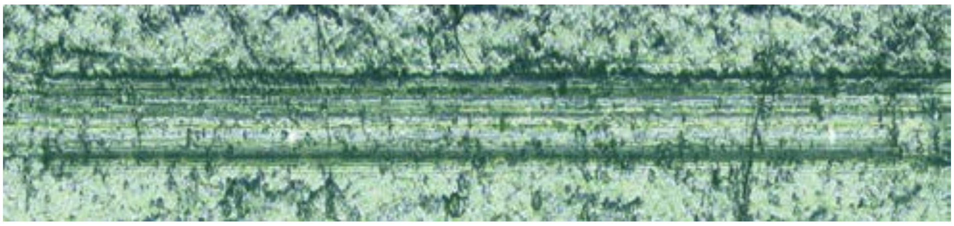

Figure 11: The optical microscope image of the scratched surface of the PE (lens Olympus 20 x, aperture 0.4).

### 3.2 Results of tests on the Dektak 150 profilometer

In Figure 12 and 13, the selected profilogram of the scratch damaged surfaces of tested materials are juxtaposed.


Figure 12: Profilogram of the scratch damaged surface of the PE material (SW = 0.334 mm, $S_{ar}$ = 2089 $\mu m^2$)

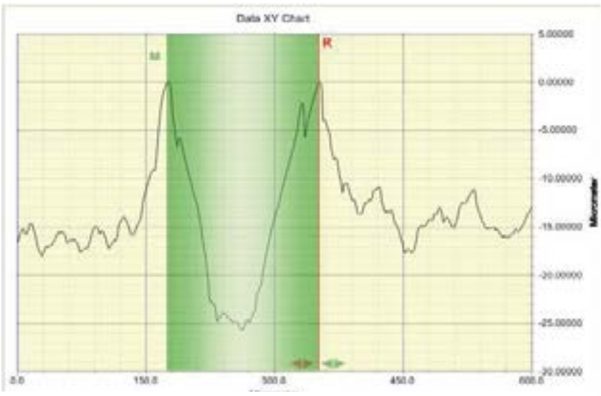


Figure 13: Profilogram of the scratch damaged surface of the PP material (SW = 0.177 mm, $S_{ar}$ = 2529 $\mu m^2$)

In Figures 14 and 15, box plots are presented, corresponding to the remaining slot width, SW, and the surface area of the scratch section, $S_{ar}$, respectively.

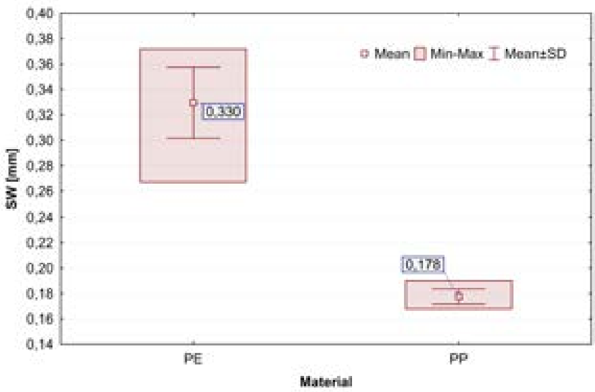


Figure 14: Box plot of the scratch width, SW.

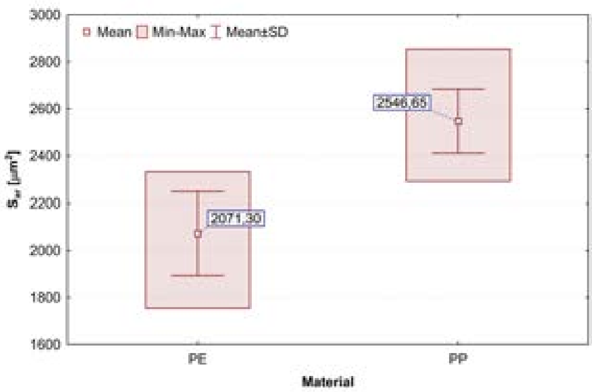


Figure 15: Box plot of the surface area of scratch section, $S_{ar}$.

In Figure 16, a box plot of the scratch test hardness, Hs, is shown.

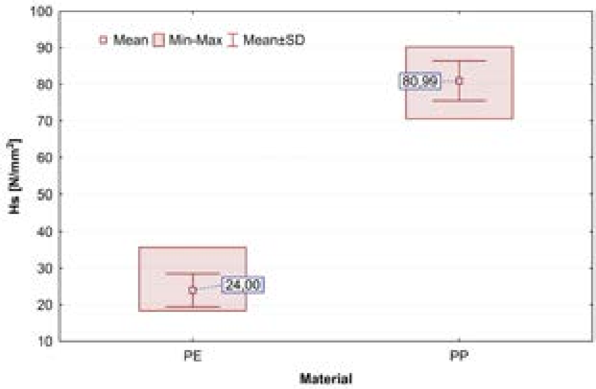


Figure 16: Box plot of the scratch test hardness, Hs.

## 4 CONCLUSIONS

The following major conclusions may be drawn from the completed tests:

- According to the methodology assumed in specialist literature, the measurement of magnitude of scratch damage is the corresponding scratch width (SW). The average scratch width on the surface of the PE material was almost two times greater than the average value of the same parameter for the PP material. Based on this criterion, the PP material features higher scratch resistance.
- In the quantitative evaluation of scratch resistance, the Hs parameter is useful as well. In specialist literature, it is used in comparative studies. The average value of this parameter for the PP material is more than three times greater than the Hs value of the PE material.
- The $S_{ar}$ parameter shows a reverse opposite to the SW and Hs parameters. However, it is not as commonly used in the scratch resistance tests of polymer material surfaces as the SW and Hs parameters.

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