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New criteria for evaluating the scratch-resistance properties of polypropylene

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Several suitable measures of scratch resistance are assessed, and polypropylene with large yield strength and small elastic modulus is found to exhibit the best quality.

Polypropylene (PP) is widely used in the automotive industry for applications that require pleasing aesthetics (i.e., a smooth surface) and good structural integrity. The formation of scratches on PP, however, lessens the aesthetic nature of its surfaces. It is therefore critically important to find a suitable criterion for assessing the scratch-resistance behavior of polymers (i.e., in an effort to design PP with good scratch-resistance properties).[1–3]

In the past, researchers have used a variety of evaluation approaches to investigate how the mechanical properties of PP (such as elastic modulus and yield strength) affect its scratch characteristics.[4,5] Techniques that have been proposed and implemented include the optical method,[1] the critical normal force,[6,7] the tangential force,[5] as well as geometric deformation parameters.[5,8–11] However, few studies have been focused on verifying the suitability of these different measures—i.e., through an integrated approach of a scratch test and finite-element (FE) analysis—even though the effect of a single mechanical parameter on scratch resistance has been investigated using the FE method. For instance, the effects of elastic modulus, yield strength, Poisson's ratio, and the coefficient of friction on PP scratch behavior have previously been studied with the use of a simplified model,[5] but the coupling effect of material parameters on scratch behavior has received little attention thus far.

In our work, we therefore adopted an integrated approach in which we combined a scratch test with a FE simulation (using an elastic–perfectly plastic model) to assess the suitability of different criteria for evaluating the scratch resistance of PP. We then used our identified criteria to experimentally and numerically evaluate the coupling effects of elastic modulus (E) and yield strength (σ_y) on the scratch performance of PP.[12] For our tests, we obtained nine synthesized PP systems from Kingfa Science and Technology Co., Ltd (China). In addition, we

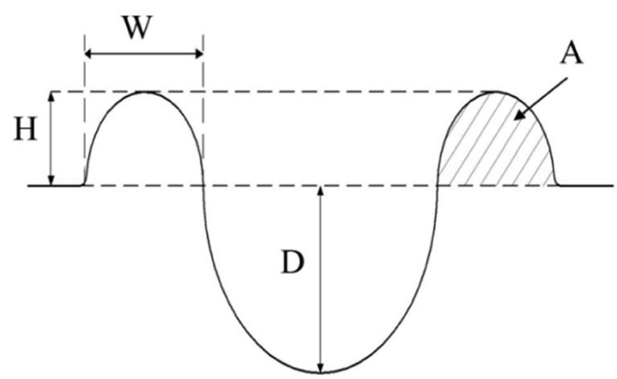

Figure 1. Schematic cross section of a scratch-induced groove. D: Residual scratch depth. H: Groove shoulder height. W: Groove shoulder width. A: Groove shoulder area.

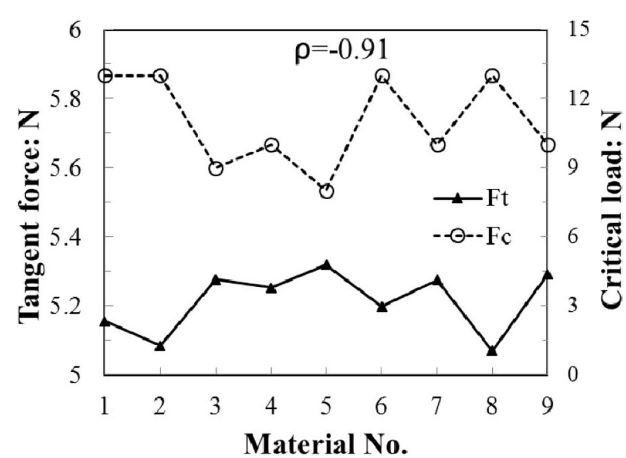

Figure 2. Comparison of the critical normal load (F_c) and tangential force (F_t) of the nine polypropylene (PP) samples (as listed in Table 1). ρ: Spearman correlation coefficient.

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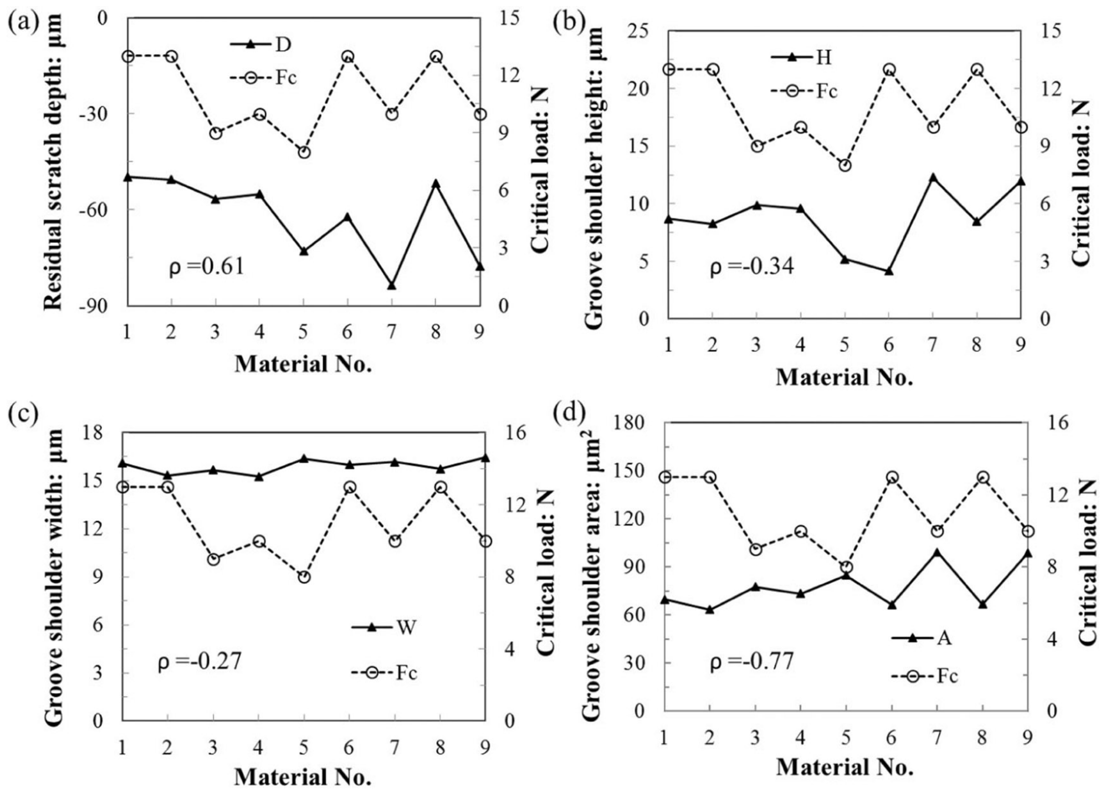

Figure 3. *Comparisons of F_c and geometrical deformation parameters (as shown in Figure 1) for the nine PP samples. Comparisons with F_c are shown for (a) the residual scratch depth, (b) groove shoulder height, (c) groove shoulder width, (d) groove shoulder area.*

Table 1. *Elastic modulus (E), yield strength (σ_y), and critical normal load (F_c) of the nine PP samples. Data provided by Kingfa Science and Technology Co., Ltd (China).*

Material No.	E (MPa)	σ_y (MPa)	F_c
1	1350	33	13
2	1250	33	13
3	1200	30	9
4	1100	31	10
5	1000	32	13
6	900	26	13
7	800	21	10
8	650	20	10
9	550	23	8

modeled the geometry of a scratch groove according to the parameters illustrated in Figure 1.

The E and σ_y values that we obtained from the tensile tests on the nine PP systems are given in Table 1. We also present values for the critical normal load (F_c)—which gives rise to 'fish-scale' damage—that we measured during the scratch tests for each PP sample. We find that a reduction of E does not necessarily cause a decrease in F_c. Unfortunately, it is impossible to test how σ_y affects F_c because these two parameters change simultaneously.

We also calculated the tangential force (F_t) in the FE analysis for each of our PP specimens. These results are shown in Figure 2 compared with our F_c results, and we see that PP samples with higher F_c exhibit smaller F_t. Indeed, we calculated a strong negative correlation between these two parameters (with a Spearman correlation coefficient of −0.91). Our results, therefore, indicate that F_t could provide a suitable index for evaluating the scratch-resistance performance of PP. To that end, the correlations between F_c and values for various geometrical deformation parameters (as shown in Figure 1, and calculated in the E simulations) are illustrated in Figure 3. We have thus also confirmed that the residual scratch depth (D) and groove shoulder area (A) measures are potentially suitable for assessing the scratch resistance of PP.

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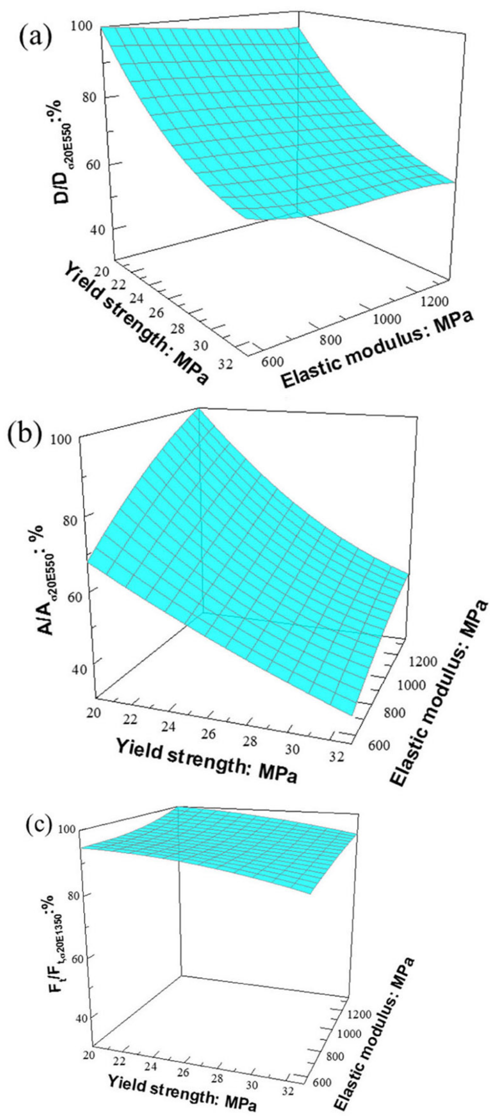

Figure 4. *Coupling effect of E and σ_y on the scratch behavior of PP. Results are shown for (a) D, (b) A, and (c) F_t. All data are non-dimensionalized by their corresponding maximum values. For example, $D/D_{\sigma 20E550}$ means that D is normalized to the case where σ_y is 20MPa and E is 550MPa.*

The results of our numerical study into the coupling effects of E and σ_y on the scratch behavior of PP are shown in Figure 4. We find—Figure 4(a)—that there is no obvious change in D with increased E, whereas σ_y has a significant effect on D. Furthermore, we observe that a larger σ_y value causes smaller D and gives rise to a better scratch resistance. For a small σ_y value (i.e., 20MPa)—see Figure 4(b)—we find that A increases rapidly with increasing E. This trend, however, is less significant for a larger σ_y (33MPa). Nonetheless, the effect of σ_y on A is consistent for all values of E. We calculate that the PP sample with the largest σ_y (33MPa) and the smallest E (550MPa) values has the smallest A. From the results in Figure 4(c), we also observe a slight reduction in F_t with increased σ_y and a slight F_t increase with greater E. Although the coupling of E and σ_y does affect F_t, this influence is not as strong as on D and A. It is clear that E and σ_y have coupling effects on the scratch behavior of PP no matter which criterion is used, and materials with larger σ_y and smaller E exhibit remarkably good scratch resistance.

In summary, we have identified new criteria—the tangential force, residual scratch depth, and groove shoulder area—for evaluating the scratch resistance of PP. Within the elastic modulus and yield strength ranges that we have investigated, we find that PP with a large yield strength and a small elastic modulus exhibits the most preferable scratch-resistance performance. Our findings are therefore helpful for guiding the design of PP with improved scratch resistance. In our future work we plan to adopt a suitable constitutive model for our FE simulations that will be able to deal with the complexity of polymers. With this model we will be able to consider a number of factors, including the rate of deformation and its temperature-dependent behavior. We believe that this approach will enable us to more fully understand the damage mechanism behind scratches in PP.

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