Nine PP systems were synthesized to investigate the coupling effect of elastic modulus and yield strength on its scratch behavior. Adopting an integrated approach of scratch test and finite element simulation, the tangential force, the residual scratch depth and the groove shoulder area are identified as the evaluation criteria of the scratch resistance of PP. With those identified criteria, the coupling effect of elastic modulus and yield strength on PP scratch is revealed that the PP with large yield strength and small elastic modulus owns a remarkable scratch resistance. The implication of the present work on designing the PP with good scratch resistant is also discussed.

**INTRODUCTION**

Polypropylene (PP) has been widely used in automotive industry. The scratch behavior of PP has drawn much attention since the scratch can significantly affect its surface aesthetics [1–5]. It has been found that crystallinity, additives, molecular weight, etc. have obvious effects on the scratch resistance of PP [6–9]. Those factors influence the scratch performance by altering the mechanical properties of PP, as well as changing the coefficient of friction between the PP and the scratch tip [8, 9].

The integrated approach of scratch test and finite element analysis is a practicable tool to obtain a better understanding of the scratch behavior of PP [10–13].

For the applications where the visual perception is preferred, it is very important to find the suitable criteria to quantitatively determine the scratch resistance of polymers [14–16]. The optical methods, e.g., the grey level [17] and the Delta-L method [18], have been adopted to determine the scratch resistance of polymers. Based on the principle of human vision, Jiang et al. [14] proposed a quantitative methodology to determine the occurrence of scratch visibility. Meanwhile, the geometric deformation parameters [19–21], the critical normal force [22–24], and the scratch hardness method [5, 25] have also been used as the indexes to evaluate the scratch resistance of polymeric materials.

It should be noted that the optical evaluation criteria of scratch resistance are not suitable in the numerical analysis. In the finite element (FE) simulation, Jiang et al. [26] utilized the tangential force and the residual scratch depth as the criteria to assess the scratch performance of PP. Hossain et al. [27, 28] adopted the residual scratch depth and the shoulder height as the indexes for scratch evaluation in their FE simulations. Although the evaluation criteria of scratch resistance have been widely used in the FE analysis, few work has been done to verify the suitability of the criteria according to an integrated approach of scratch test and finite element analysis.

To obtain guidance for designing the polymers with good scratch resistance property, extensive works have been performed to find the relationship between the scratch behavior of polymers and their mechanical properties [29–33]. Due to its convenience in parameter study, the FE simulation has been utilized to discuss the effect of mechanical materials’ parameters on the scratch performance of polymers [34, 35]. Adopting the elastic-perfectly-plastic constitutive model, Bucaille et al. [36] investigated the effect of elastic modulus on the scratch coefficient of friction. Jiang et al. [26] carried out the parametric study on elastic modulus, yield strength, Poisson’s ratio and coefficient of friction of PP using the elastic-perfectly-plastic model. Adopting the constitutive model considering the strain hardening and strain softening, Hossain et al. studied the effects of strain hardening [27], softening slope [28] etc. on the scratch resistance of polymeric materials. As the effect of single mechanical parameter on the scratch resistance has been investigated using the controlling variable method in the FE analysis, few work has been performed to investigate the coupling effect of mechanical parameters. In the process of preparing material, changing components, such as additives and fillers, is a practical tool to obtain good scratch resistant polymeric materials [7, 9]. As the components change, it is extremely difficult to control only one set of mechanical property without changing others [27]. To perform a comparative study between experimental and FE simulation results, it is necessary to investigate the coupling effect of material parameters on the scratch behavior.

In this article, first, an integrated approach of scratch test and finite element simulation was adopted to verify the criteria to assess the scratch resistance of PP. Then the coupling effect of elastic modulus (E) and yield strength (σ_y) on PP’s scratch performance was discussed experimentally and numerically using the verified criteria. The obtained results could be taken as a useful guidance for designing the good scratch resistant PP.
EXPERIMENTS

By changing catalyst and additives, nine PP systems were synthesized and provided (Kingfa Co. LTD. of China). Although the trademark and content of catalyst and additives were not available, the material systems themselves are still useful to investigate the coupling effect of elastic modulus and yield strength on the scratch behavior of PP. The PP specimens were injection molded in planar dumbbell shape with same gauge area (4 mm × 10 mm) and gauge length of 80 mm (total length: 150 mm). The tensile tests were carried out using MTS 858 BIONIX test machine at a displacement rate of 5 mm/min. Four identical tests were performed for each test condition.

Following the ASTM/ISO standards for the scratch test of polymeric materials [37, 38], a series of scratch tests with the scratch velocity of 100 mm/s were performed for PP using a home-made scratch machine referring to the literature [39]. The scratch distance was 100 mm. The diameter of the stainless steel tip was 1 mm. The linearly increasing scratch normal load from 0 to 15 N was employed in all the scratch tests. Four identical tests were performed for each scratch test condition. The scratch visibility of PP, which is related to the fish-scale formation since tests were performed for each scratch test condition. The scratch tip was 1 mm. The linearly increasing scratch normal load from 0 to 15 N was employed in all the scratch tests. Four identical tests were performed for each scratch test condition. The scratch visibility of PP, which is related to the fish-scale formation since tests were performed for each test condition.

The information of tangential force was not obtained due to the limitation of the scratch machine. The experimentally measurement of residual scratch depth, groove shoulder height and groove shoulder width and their correlation with scratch performance have been conducted in our previous work [12]. However, it is time and cost consuming to experimentally find an optimal combination of materials properties without meaningful guidance. This work tried to provide this guidance using a cost-effective FEM process, by first establishing the reasonable criteria to assess scratch performance in FEM and then unveiling the coupling effect of elastic modulus and yield strength on scratch behavior.

**TABLE 1. Elastic modulus, yield strength, and the critical normal load of PP samples.**

<table>
<thead>
<tr>
<th>Material No.</th>
<th>E /MPa</th>
<th>σ_y /MPa</th>
<th>F_c /N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,350</td>
<td>33</td>
<td>13</td>
</tr>
<tr>
<td>2</td>
<td>1,250</td>
<td>33</td>
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<td>3</td>
<td>1,200</td>
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<td>1,100</td>
<td>31</td>
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<tr>
<td>5</td>
<td>1,000</td>
<td>32</td>
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<tr>
<td>6</td>
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<td>8</td>
<td>650</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>9</td>
<td>550</td>
<td>23</td>
<td>8</td>
</tr>
</tbody>
</table>

*Data from Kingfa Science & Technology Co., LTD. of China.*

**FIG. 2. Cross section of the scratch-induced groove (D: residual scratch depth; H: groove shoulder height; W: groove shoulder width; A: groove shoulder area).**

**NUMERICAL MODELING**

Figure 1 shows the 3D FE model to simulate the scratch process of PP following the work of Jiang et al. [26]. Considering the symmetry, a half model with the dimension of 50 × 5 × 3mm³ was created in the commercial finite element package ABAQUS® (V6.10) [40]. A reduced integration element of C3D8R was adopted. Only the elements along the scratch path were refined to improve the computational efficiency. The adaptive remeshing technique was utilized to avoid element distortion due to the large deformation along the scratch path. The scratch tip of 1mm in diameter was modelled as an analytical rigid body. Both ends of the polymer substrate were fixed. The bottom of the substrate was restrained in z direction. As illustrated in Fig. 1, the process of scratch simulation was divided into three steps. Step 1 was an indentation process in which the scratch tip penetrated into the PP to a specified load condition. In Step 2, the scratch tip moved forward in the y direction from point A to B at a constant velocity. After arriving the point B, the scratch tip was stopped and then moved upwards to allow the elastic recovery.

The stress-strain relationship of PP was treated as the isotropic elastic-perfectly-plastic model. As reported by Jiang et al. [26], the simplified constitutive model shows a similar tendency for the scratch behavior of PP with the true stress–strain curve model. The complex material properties, such as viscosity [41–44], should be considered to quantitatively describe the scratch deformation in the future work. To cover the ranges of E and σ_y of the prepared PP specimens, the values of E used in the FE simulations range from 500 to 1,350 MPa, as well as σ_y from 20 to 33 MPa, respectively. A constant scratch normal load (F_n) of 10 N was applied for all PP specimens. Because only a half model was considered, the F_n in the FE simulations onset point of scratch visibility, L is the total scratch distance. The information of tangential force was not obtained due to the limitation of the scratch machine. The experimentally measurement of residual scratch depth, groove shoulder height and groove shoulder width and their correlation with scratch performance have been conducted in our previous work [12]. However, it is time and cost consuming to experimentally find an optimal combination of materials properties without meaningful guidance. This work tried to provide this guidance using a cost-effective FEM process, by first establishing the reasonable criteria to assess scratch performance in FEM and then unveiling the coupling effect of elastic modulus and yield strength on scratch behavior.
RESULTS AND DISCUSSION
Identification of the Criteria to Assess Scratch Performance

Table 1 lists the values of $E$ and $\sigma_y$ of the PP samples from the tensile tests. Not listed in Table 1, the elongation at break of all the PP specimens exceeds 400%. Obtained from the scratch tests, the critical normal loads ($F_c$) of the PP specimens are also shown in Table 1. The elastic modulus and yield strength varied by less than 5%, and critical load varied less by 8%. Only the average values of the test results are shown in Table 1. It could be found from Table 1 that a reduction of $E$ does not necessarily cause the decreasing of $F_c$ (for example, Material No. 1 and 2). However, the parameter analysis of $\sigma_y$ could not be conducted since the simultaneous change of $E$ and $\sigma_y$. Coupling effect of $E$ and $\sigma_y$ should be investigated.

If the material property and the contact condition of the tip and substrate are pre-set, a larger tangential force ($F_t$) could result in a more severe scratch damage [26]. Meanwhile, the geometrical deformation, i.e., residual scratch depth ($D$), groove shoulder height ($H$), groove shoulder width ($W$) and groove shoulder area ($A \approx 0.5^*H^*W$) (see in Fig. 2), whose relationship with scratch visibility have been established in the previous literatures [12, 14], is adopted to assess the scratch performance [20, 26]. In the FE simulation, the information of the $F_t$ obtained as the reaction force of the reference point of the rigid tip in the scratch direction, as well as the geometrical deformation parameters, were obtained to identify the possible criteria by comparing with $F_c$ from the scratch tests.

Figure 3 shows the comparison of the $F_c$ obtained from the experimental results with the $F_t$ acquired from the FE results of all the PP specimens. It is obvious that the PP with a higher $F_c$ shows a smaller $F_t$. As one of the best nonparametric measures of the dependence between two variables, Spearman’s rank correlation coefficient [45] was conducted to find out the relationship between $F_t$ and $F_c$. With the Spearman correlation coefficient $\rho = -0.91$, there is a strong negative correlation between $F_t$ and $F_c$. Thus, $F_t$ could be a proper index to assess the scratch performance of PP.

![FIG. 3. Comparison of the critical normal load ($F_c$) and tangential force ($F_t$) of the PP samples. $\rho$ is the Spearman correlation coefficient.](image)

![FIG. 4. Comparisons of the critical normal loads ($F_c$) and the geometrical deformation parameters of the PP samples: (a) residual scratch depth ($D$); (b) groove shoulder height ($H$); (c) groove shoulder width ($W$); (d) groove shoulder area ($A$). $\rho$ is the Spearman correlation coefficient.](image)
The correlations between $F_c$ from the experimental results and the geometrical deformation parameters from the FE simulations are illustrated in Fig. 4. From Fig. 4a, there is a good correlation between $D$ and $F_c$ with $\rho = 0.61$. It can be found from Fig. 4b and c that weak correlations exist between $F_c$ and $H$ ($\rho = -0.34$), as well as between $F_c$ and $W$ ($\rho = -0.27$). Meanwhile, a strong negative correlation ($\rho = -0.77$) between the groove shoulder area $A$ and $F_c$ is shown in Fig. 4d. Since a shallower $D$ and a smaller $A$ mean a better scratch resistance, the residual scratch depth and the groove shoulder area are the suitable criteria to assess the scratch resistance of PP.

**Coupling Effect of Elastic Modulus and Yield Strength**

The experimental data indicates that $E$ and $\sigma_y$ change simultaneously for different PP specimens. This makes it difficult to find the relationship between the mechanical properties, such as $E$ and $\sigma_y$, and the scratch resistance of PP. To solve this problem, the coupling effect of $E$ and $\sigma_y$ on the scratch behavior of PP is investigated in this section.

Seventeen sets of $E$ and $\sigma_y$ covering the ranges of $E$ and $\sigma_y$ were adopted for the FE simulations to investigate their coupling effect on the scratch performance of PP. The results are shown in Fig. 5. The identified criteria in Section “Identification of the criteria to assess scratch performance,” i.e., the residual scratch depth, the groove shoulder area and the tangential force, are nondimensionalized by their corresponding maximum values from these 17 sets of data.

As shown in Fig. 5a, the change of the residual scratch depth $D$ is not obvious with the increase of $E$, while $\sigma_y$ has a significant effect on $D$. The larger the $\sigma_y$ is, the smaller the $D$ is, which means a better scratch resistant performance.

It can be observed from Fig. 5b that, for a small $\sigma_y$ (20 MPa), the groove shoulder area increases rapidly with the increase of $E$. However, this tendency is not so significant at the situation with a large $\sigma_y$ (33 MPa). The effect of $\sigma_y$ keeps the same tendency in the whole range of $E$. The PP with $\sigma_y = 33$ MPa and $E = 550$ MPa, i.e. the largest $\sigma_y$ and the smallest $E$, owns the smallest groove shoulder area in the studied range of $\sigma_y$ and $E$.

In Fig. 5c, while an increase of $\sigma_y$ results in a slight reduction of $F_t$ of PP, a larger $E$ gives the PP a little bit greater $F_t$. Although the coupling effect of $E$ and $\sigma_y$ exists on the $F_t$, it is not as obvious as that on the geometric deformation parameters discussed in Fig. 5a and b.

From the discussions above, it is clear that $E$ and $\sigma_y$ have a coupling effect on the scratch behavior of PP. In the ranges of elastic modulus and yield strength investigated in this work, the material with large $\sigma_y$ and small $E$ owns a remarkable scratch resistance no matter which criterion is used. As discussed in the literature [26], for a representative volume element with the elastic-perfectly-plastic constitutive model under a given strain level, decreasing $E$ leads to the increasing of the elastic recovery, so does the condition of increasing $\sigma_y$. For the non-uniform stress field of PP scratch under the same $F_n$, a larger $\sigma_y$ means that the PP sample has a greater resistance to the plastic deformation, while the decreasing $E$ leads to a lower $F_n$, which will result into less scratch damage of PP. In the investigated range of $E$ and $\sigma_y$, it could be found that the more elastic recovery occurs, the better scratch resistance is.

Hossain et al. [28] found that the compressive behavior dominates the groove formation. In this work, since the elastic-perfectly-plastic material model, which is not an unreasonable assumption for PP materials, was used in FEM, the elastic modulus and yield strength from tensile test can be utilized without losing generality. In the future work, a capable constitutive model should be adopted for FEM simulation to consider the

FIG. 5. Coupling effect of elastic modulus and yield strength on the scratch behavior of polypropylenes: (a) residual scratch depth ($D$); (b) groove shoulder area ($A$); (c) tangential force ($F_t$). [Color figure can be viewed at wileyonlinelibrary.com]
effect of the tension–compression asymmetry [46] on the scratch behavior of polymeric materials.

It should be noted that although the coefficient of friction was not considered in our experimental work, additional FE simulations of PP scratch with different values of coefficient of friction were performed. The results indicate that, although the actual value may be different, the tendency of the material parameters’ effect on the scratch resistance is same for the studied conditions, no matter what value of the coefficient of friction is.

CONCLUSIONS

Nine PP systems were synthesized to investigate the coupling effect of elastic modulus and yield strength on the scratch behavior of PP using an integrated approach of scratch test and finite element simulation. It could be concluded that:

1. The residual scratch depth, the groove shoulder area and the tangential force (although not as sensitive as the other two criteria) are the suitable criteria to assess the scratch resistance of PP.

2. In the investigated ranges of elastic modulus and yield strength in this work, the PP with a large yield strength and a small elastic modulus gives the preferable scratch performance. This result provides a good guidance for the material scientist to design the PP with better scratch resistance.

REFERENCES