J Mater Sci (2010) 45:2649–2654
DOI 10.1007/s10853-010-4243-8

Quantitative determination of scratch-induced damage visibility on polymer surfaces

J.-I. Weon · S.-Y. Song · K.-Y. Choi · S.-G. Lee · J. H. Lee

Received: 2 November 2009 / Accepted: 18 January 2010 / Published online: 3 February 2010

Abstract A new methodology to quantify scratch-induced damage visibility on polymer surfaces is proposed. The color image analysis using a hue–saturation–intensity (HSI) color space combination provides satisfactory results in quantifying scratch visibility and in monitoring surface damage features along the scratch path. The effectiveness of the HSI color image analysis methodology is validated via comparison of the results from a model of polypropylene blend using three linearly increasing normal load conditions. The scratch damage transitions are correlated with the HSI color transitions and show good agreement. Implication of the present finding for the evaluation of scratch visibility resistance of polymers is discussed.

Introduction

One of the major concerns on polymer scratch research is the standardization of test methodologies and appropriate evaluation techniques that can precisely quantify the scratch damage resistance of polymers [1–5]. Recently, two internationally recognized test methods, i.e., ASTM standard (D7027-05) [6] and ISO standard (19252:2008) [7], for obtaining meaningful and reproducible results on the scratch behaviors of polymers have been developed. However, both of the standards only emphasized the test methodology and observation of the surface damage features, without explicit reference to quantification of the scratch visibility resistance of polymers [8–16]. Both of the standards utilize a 1-mm diameter steel ball as the scratch tip. During an increasing normal load test (e.g., 1–50 N), the mar and ironing phenomena are clearly observed in an early stage of the scratch testing; sometimes, it even occurs at the beginning of the test [5].

To illustrate how the applied normal load (P) influences the stresses generated on the polymer surfaces, a schematic is drawn in Fig. 1a. The stress magnitude at the initial point is theoretically infinite since the contact area of the ball indenter to the polymer surface is very small. As P is gradually increased, the contact area will also become larger. Therefore, to experimentally determine the stress magnitude imposed on the polymer surface, the scratch widths and the corresponding contact areas should be monitored during the movement of the indenter tip. It should be noted that the stress magnitude in an early stage of the scratch test cannot be easily obtained if the inertial effect due to the acceleration of the scratcher head movement from static to a velocity of 100 mm/s is present. Significant stress magnitude fluctuation will occur on the polymer surfaces as the scratch tip moves until the inertia effect diminishes, which usually corresponds the scratch tip movement of about 0.5 mm.

The second issue comes from the determination and quantification of scratch visibility [12, 17–20]. It is non-trivial to determine the visibility onsets of mars and scratches on polymer surfaces because it involves a lot of unquantifiable factors that may affect how a viewer recognizes scratch damage with un-calibrated eyes. There are still some shortcomings in the determination of the scratch visibility onset using both standards proposed. These deficiencies arise from the determination of value referred to as

J.-I. Weon (✉) · S.-Y. Song · K.-Y. Choi
Reliability Assessment Center for Chemical Materials, Korea Research Institute of Chemical Technology, Yuseong-gu, Daejeon 305-600, Korea
e-mail: jiweon@krict.re.kr

S.-G. Lee · J. H. Lee
Chemical Materials Information Bank, Korea Research Institute of Chemical Technology, Yuseong-gu, Daejeon 305-600, Korea

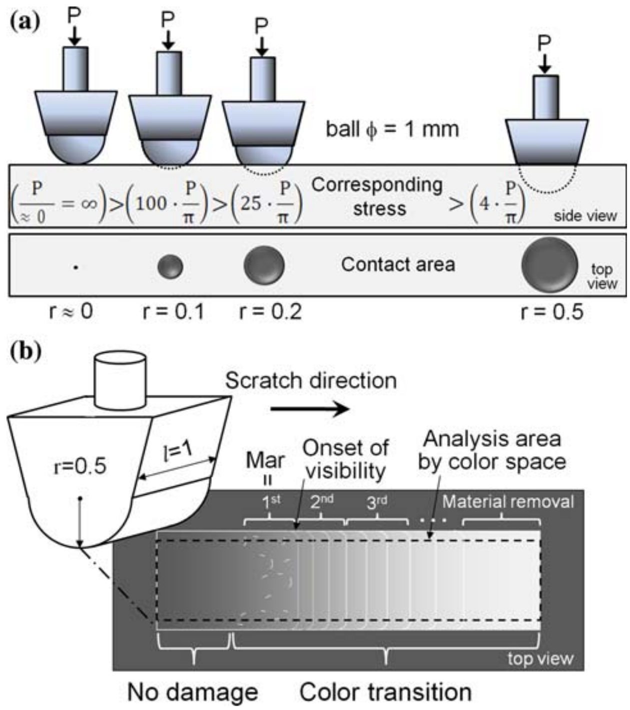

Fig. 1 Schematics of scratch behaviors in polymers: **a** contact area and corresponding stress magnitude applied to the polymer surface for a ball-type stylus tip. The applied normal load is *P*, and **b** the stylus tip geometry and the corresponding surface damage illustrated by the HSI color image analysis methodology proposed in this study

the critical normal load for the onset of the corresponding surface damage feature, i.e., whitening and cutting, even though several image analysis techniques were employed [7–10]. These measurements are prone to be dependent on the competency of the operator. In addition, the critical normal load determined is not a normalized value. They are scratch tip geometry dependent. In other words, a new value (i.e., material property) that normalized by the corresponding contact area, similar to the definition of yield stress (N/m^2) and impact resistance (J/m), needs to be expressed to quantify the whitening point and the initiation of cutting.

Finally, it is difficult to quantify the scratch damage visibility of colored polymers containing various kinds of pigments using the current ASTM and ISO standards. Polymers with various colors for aesthetics reasons have been used for automotive interior and exterior parts. The scratch visibility of colored polymer surfaces is more complex because additional light absorption and reflection at different wavelengths take place on colored polymer surfaces. Until now, the scratch damage analyses with an 8-bits gray scale, not a 24-bits color scale, have been carried out to quantify the scratch visibility. Those approaches are not suitable for evaluating scratch visibility of colored polymer surfaces.

The main objective of this article is to propose a new approach that can quantitatively determine the scratch damage visibility onset of polymers. The effectiveness of the new approach for determining the scratch visibility resistance of a typical automotive plastic is demonstrated. The observed scratch damage transition is correlated with the corresponding scratch visibility transition. The implication of the present approach for effective evaluation of the scratch visibility resistance of polymers is also discussed.

Experimental

Model material and scratching test conditions

A polypropylene blend that contains 15 wt% of talc, 25 wt% of ethylene–octene rubber (EOR), and ~1 wt% of carbon black pigment was provided by Hyundai EP Co., Ltd, for the present study. The as-received plaques having dimensions of 345 × 98 × 3 mm were injection molded. Scratch tests were carried out at room temperature using a CETR UMT-2 machine. The scratch length was set to be 50 mm. A constant scratch velocity of 1 mm/s with three linearly increasing normal loads, ranging 1–30, 1–40, and 1–50, were performed. The tip used was a stainless steel cylinder with a diameter of 1 mm and a length of 1 mm. The detailed geometry of the stylus tip is shown in Fig. 1b.

Scratch damage analysis and quantification

Scanned images of the scratch tested surfaces were prepared using an Epson Perfection V700 Photo flatbed scanner, set at a resolution of 600 × 600 dpi and 24-bit color mode for the quantification of scratch damage. A commercial surface analysis software, QWin, using various color space models (e.g., HSI, RGB), was subsequently used to quantify the surface damage. In order to increase the reliability of experimental data and to exclude the unusual data on the edge region, as shown in Fig. 1b, a set of color coordinates within a 90% region of the scratch width was chosen: i.e., each row set along the scratch path was expressed as an average of the corresponding vertical values. The average value and standard deviation were recorded after performing five scratch tests of each sample. Optical microscopy (OM) observation, performed on a Hirox KH-7700 digital microscope, was used to observe the scratch damage and the damage transition along the scratch path.

Results and discussion

During the scratch test, there exist two orthogonal vectors, the applied normal force $(\vec{F}_n)$ and the resulting tangential force $(\vec{F}_t)$, on a scratched surface. The total force, termed

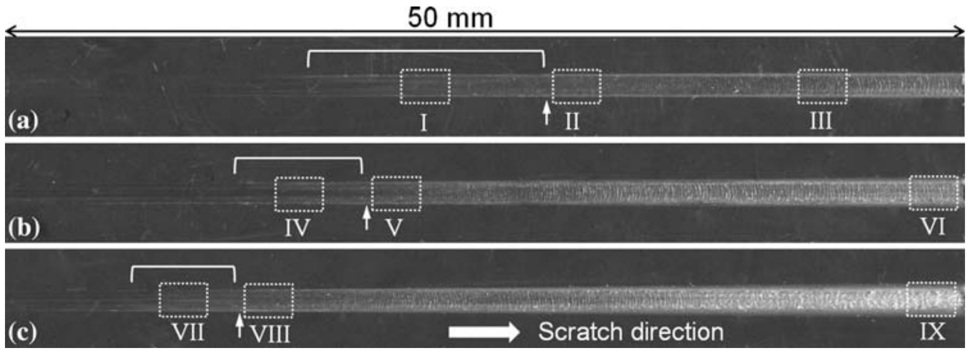

Fig. 2 Optically scanned images of scratch-induced PP blend surfaces with increasing normal load ranges of: **a** 1–30 N, **b** 1–40 N, and **c** 1–50 N. The *brackets* and *arrows* indicate the corresponding mar zones and onset of scratch visibility, respectively

"scratch force" $(\vec{F}_s)$, applied to the surface can be defined as the summation of the two vectors. Thus, in this study, the scratch resistance $(\vec{R})$, expressed in kN/m, is calculated by dividing the scratch force with the length of indenter tip.

Scratched surfaces of the PP blend under three different loading conditions were scanned using a commercial scanner and the representative photographs are shown in Fig. 2. It is evident that three zones can be distinguished without any post-processing using image analysis tools [17–20]: non-damage, mar, and scratch-induced damage zones. An increase in applied normal load leads to an increase in surface damage and in scratch visibility. In general, the damage features can be detected by significant light scattering from the scratched surface damage features. However, so far, it is nontrivial to quantify these damage features as well as the onset of scratch visibility.

Three-dimensional (3-D) color spaces are further utilized to quantify the observed surface damages and scratch visibility resistance. The change in the scratch damage mode transition is accompanied by the corresponding variation in color perceived from the scratch-induced surface. The severity of the surface damage can be captured by the color coordinates (e.g., HSI values) of the 3-D color models along the scratch path. As a result, the scratch damage and its transition can be determined by means of the corresponding color values. To establish relationships among the scratch damage features, their transition and the corresponding scratch visibility, the HSI color space model is employed. The HSI color space model is an attractive color model for image processing applications since it represents colors similarly to how the human eyes perceive colors. In the HSI model, each color is expressed by three components: hue (H), saturation (S), and intensity (I): the hue component describes the color itself, the saturation part signals how much the color is polluted with white color, and the intensity illustrates the brightness of the color. Figure 3 shows how the HSI color space represents colors. The values of HSI are assumed to be in the range of 0–255.

The surface analysis results of PP blend with respect to the three test conditions using the HSI color space are shown in Fig. 4. For all samples, the hue value remains constant along the scratch path, while there is a gradual increase in intensity and a decrease in saturation numbers. The amount of light scattering (i.e., whitening) along the scratch path increases with increasing applied normal load, with no change in color itself (hue value). In other words, the appearance of whitening directly causes intensity value to increase and a moderate decrease in saturation value. A careful observation indicates that the intensity and saturation value profiles are distinctively marked by the changes of their slopes that are obviously derived from the alteration of color, i.e., whitening, as scratching progresses. The first color transition region exhibits an increase in intensity number and afterward, the slope becomes flatter, followed by the repetition of the same trends along the scratch path. This implies that whenever the variation of the slope takes place, the change of surface damage features also occurs.

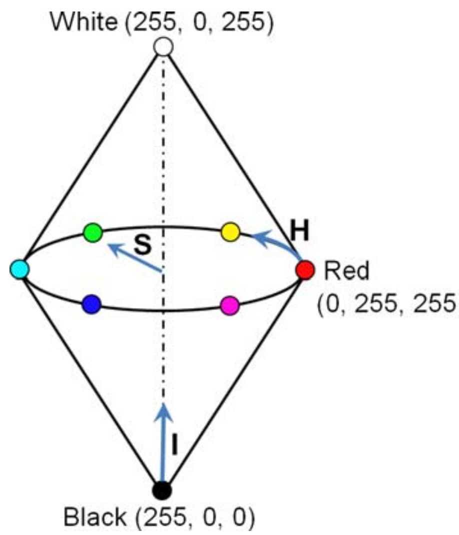

Fig. 3 Schematic diagram of HSI color model and its color coordinates

OM observations are further employed to correlate the observed damage morphologies with the corresponding color transitions in intensity and saturation values. Several regions of interest for scratch-induced PP blends are observed. Close-up views of regions that are marked with

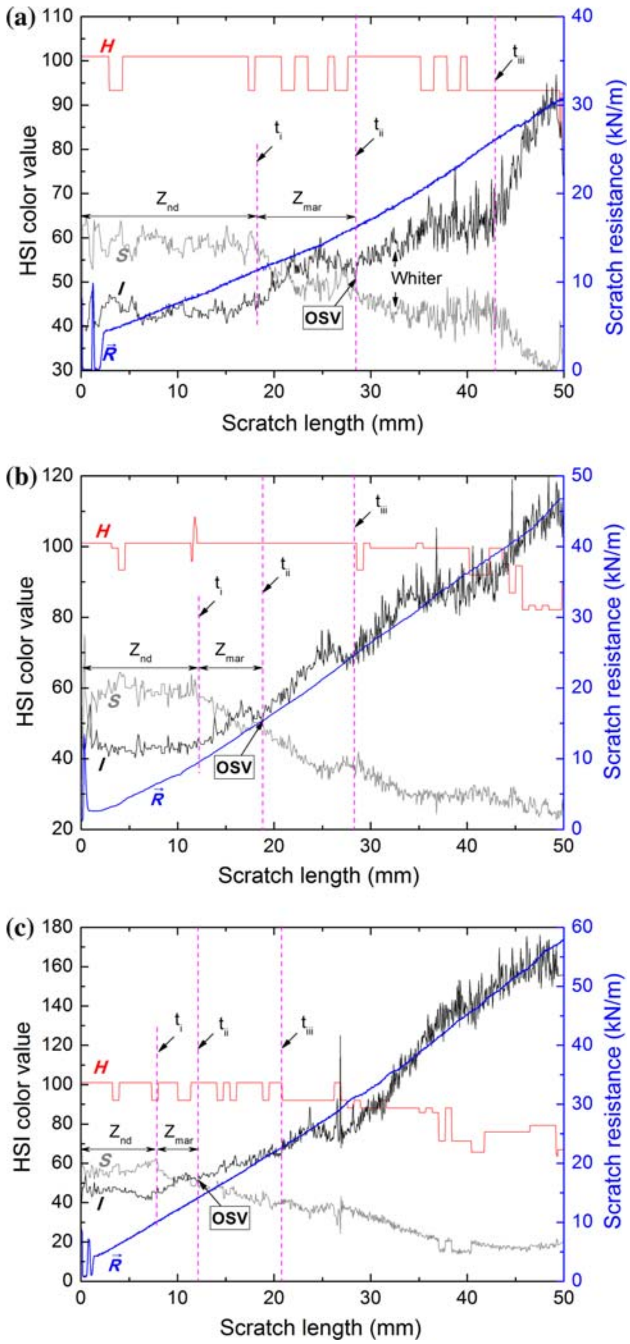

Fig. 4 HSI color image analysis results and the corresponding scratch visibility resistance of PP blend surfaces with different normal load ranges of: **a** 1–30 N, **b** 1–40 N, and **c** 1–50 N (*H*: hue value, *S*: saturation value, *I*: intensity value, $\vec{R}$: scratch resistance, Z_{nd}: no damage zone, Z_{mar}: mar damage zone, t_i: the first color transition point, t_{ii}: the second color transition point, t_{iii}: the third color transition point, OSV: the onset of scratch visibility)

numbering in Fig. 2 are shown in Fig. 5. Figure 5a–c shows in sequence the damage features at the first, second, and third color transition points for PP blend surface scratched with a load range of 1–30 N. In region I, mild damages by plastic ironing are observed at the beginning and then small cracks or fragments are initiated at the end of the stage. This feature is termed as "mar." A rough and wave-like sheared pattern is observed in region II. The wave-like patterns appear to be closely spaced. This indicates that the surface damage mode is changed due to the increase of applied scratch force. Interestingly, these damages can be perceived by the naked eyes, because of the intensive light scattering from the scratched path. Thus, the second color transition point can be defined as the "onset of scratch visibility." In addition, the onset of scratch visibility can be quantified and expressed by the term "Scratch Visibility Index (SVI)". SVI is defined as a set of intensity, saturation, and scratch resistance values $\left(I_c, S_c, \vec{R}_c\right)$, where the onset of scratch visibility occurs. The SVI can be readily obtained from the plot in Fig. 4.

Region III represents the corresponding damage feature around the third color transition. The wave-like fragments are broadened, signifying the increase of the severity of surface damage. The same damage feathers as those shown in Fig. 5a, b are shown in the samples with two different loading ranges of 1–40 N (Fig. 5d, e) and 1–50 N (Fig. 5g, h) in spite of the difference in scratching characteristics. It should be addressed that the three samples tested have the same intensity and saturation values on SVI, while the $\vec{R}_c$ values are slightly different (Table 1). This difference may be due to the effect of the loading rate against a constant scratch length. The above finding suggests that the HSI color image analysis methodology is effective in quantifying scratch visibility and in monitoring surface damage features along the scratch path. The loading rate mentioned above has also had an effect on the size of the non-damage and mar zones. An increase in the maximum normal load leads to a decrease in their sizes (Table 1). Figure 5f, i shows the material removal zone as a result of the rupture of the repeated wave-like patterns, leading to an intensified plastic deformation with higher light scattering and scratch visibility.

Conclusion

A new methodology using a HSI color image analysis tool is proposed to quantify scratch visibility resistance and surface damage features on polymer surfaces. The scratch visibility index, which is composed of the critical intensity value, saturation value, and scratch resistance to the point where the surface damage can be perceived by the visible eye, is presented to quantify the onset of scratch visibility. Microscopy study supports the detailed damage feature and transition in the scratch-induced surfaces of PP blend. Good agreement is found between the scratch damage feature transitions and their corresponding color transitions.

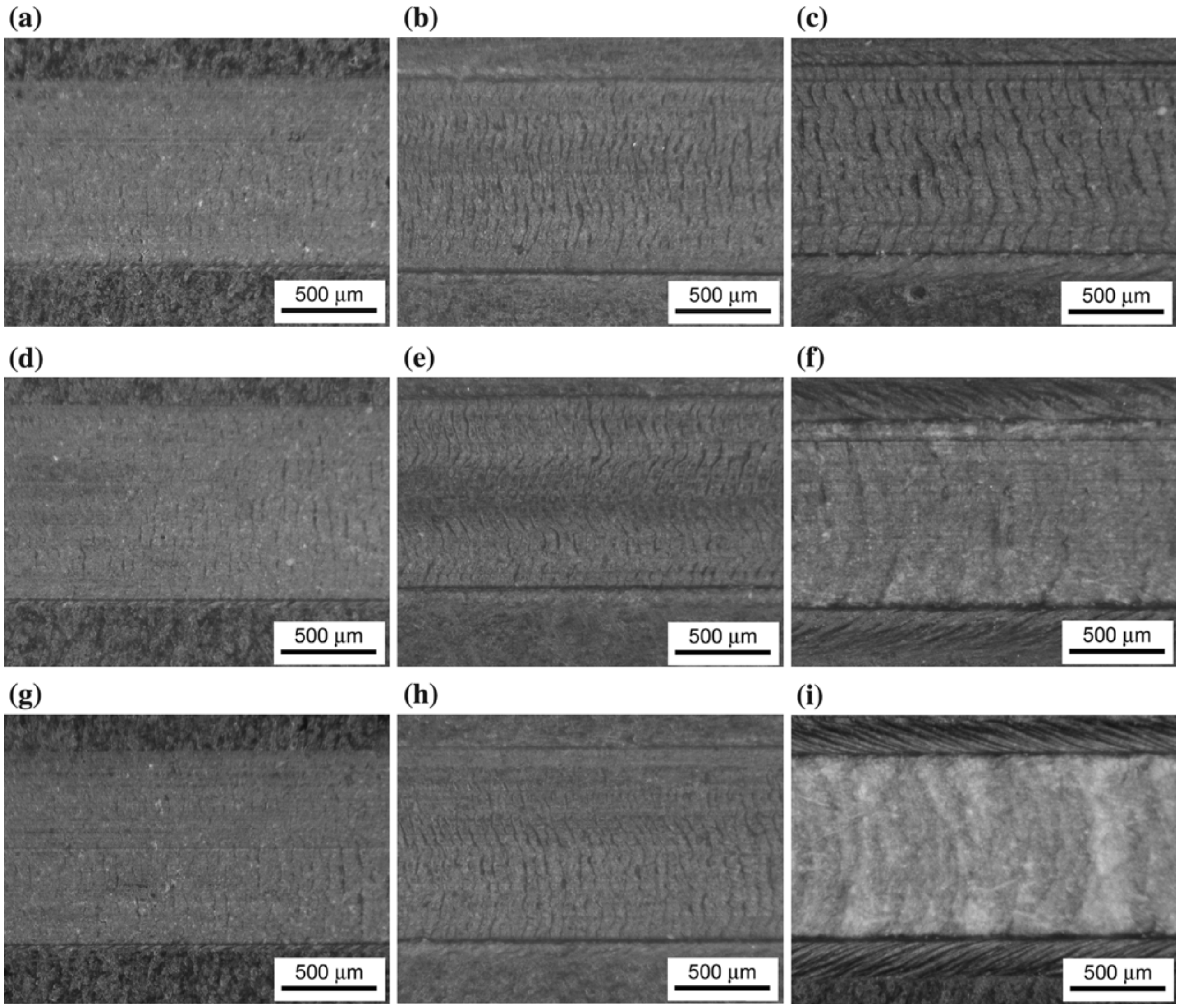

Fig. 5 OM micrographs of scratch-induced PP blend surfaces with various damage regions of interest. **a–i** Magnified micrographs taken from the areas as indicated in Fig. 2I–IX, respectively

Table 1 HSI color image analysis results for differently maximum normal load applied PP blends

Test condition	Scratch Visibility Index (SVI)			Mar region (mm)
	I_c	S_c	$\vec{R}_c$ (kN/m)	
1–30 N	51.3 ± 0.8	50.4 ± 0.9	16.2 ± 0.3	18.3–28.4
1–40 N	51.2 ± 0.4	50.8 ± 0.5	15.4 ± 0.5	12.1–18.8
1–50 N	51.1 ± 0.7	50.6 ± 0.6	14.2 ± 0.4	7.9–12.1

Acknowledgements Special thanks are given to Chemical Materials Information Bank (CMiB) funded by the Ministry of Knowledge Economy (MKE), for financial support. The valuable discussion with professor H.-J. Sue of Texas A&M University is also greatly appreciated.

References

1. Assender H, Bliznyuk V, Porfyrakis K (2002) Science 297:973
2. Uehara H, Asakawa T, Kakiage M, Yamanobe T, Komoto T (2006) Langmuir 22:4985
3. Wong JSS, Sue HJ, Zeng KY, Robert KYL, Mai YW (2004) Acta Mater 52:431
4. Baek KW, Lee SG, Lee JH, Choi KY, Weon JI (2009) Polymer (Korea) 33:273
5. Jiang H, Browning R, Sue HJ (2009) Polymer 50:4056
6. ASTM D7027-05 (2005) Standard test method for evaluation of scratch resistance of polymeric coatings and plastics using an instrumented scratch machine. ASTM International
7. ISO 19252:2008 (2008) Plastics—determination of scratch properties
8. Briscoe BJ, Evans PD, Pelillo E, Sinha SK (1996) Wear 200:137
9. Bull SJ (1997) Tribol Int 30:491

10. Briscoe BJ, Evans PD, Biswas SK, Sinha SK (1996) Polym Eng Sci 36:2996
11. Wong M, Lim GT, Moyse A, Reddy JN, Sue HJ (2004) Wear 256:1214
12. Wong M, Moyse A, Lee F, Sue HJ (2004) J Mater Sci 39:3293. doi:10.1023/B:JMSC.0000026930.12462.3d
13. Browning RL, Lim GT, Moyse A, Sue HJ, Chen H, Earls JD (2006) Surf Coat Technol 201:2970
14. Chen M, Osterholtz FD, Pohl E, Ramdatt P, Chaves A, Bennett V (1997) J Coat Technol 69:43
15. Xiang C, Sue HJ, Chu J, Coleman B (2001) J Polym Sci B 39:47
16. Jiang H, Lim GT, Reddy JN, Whitcomb JD, Sue HJ (2007) J Polym Sci B 45:1435
17. Browning R, Lim GT, Moyse A, Sun L, Sue HJ (2006) Polym Eng Sci 46:601
18. Browning RL, Jiang H, Moyse A, Sue HJ, Iseki Y, Ohtani K, Ijichi Y (2008) J Mater Sci 43:1357. doi:10.1007/s10853-007-2283-5
19. Moghbelli E, Browning RL, Boo WJ, Hahn SF, Feick LJE, Hue HJ (2008) Tribol Int 41:425
20. Moghbelli E, Sun L, Jiang H, Boo WJ, Sue HJ (2009) Polym Eng Sci 49:483