

April 24, 2003

RE: Preliminary Testing of Windshield Coating

Dear

Between the dates of March 21, 2003, and April 23, 2003, American Glass Research was consulted in regards to preliminary testing of an experimental windshield coating. During conversations, it was mentioned that the coating was being evaluated as a potential surface protection agent, where it was proposed by that the coating could improve the ability of flat glass to resist contact bruising damage. To this end, we were asked to examine the effect of the coating on non-flexural impact resistance, as well as other relevant windshield properties such as water wetting i.e. surface energy, scratch resistance, and coefficient of friction. This report summarizes the findings of our analyses.

CONCLUSIONS

1. Measurements indicated a 44% reduction in the coefficient of friction in coated glass samples relative to the uncoated set, indicating that the applied coating was lubricious and would improve the resistance of the surface to frictional damage. This was corroborated by a visible increase in scratch resistance in the coated glass.
2. Contact angle measurements indicated that the coating acted to reduce wetting of the surface by water. This behavior was confirmed via sheeting tests, where it was found that water did not have an affinity for the surface of the coated glass, and "ran off" in a thin rivulet rather than sheeting.
3. Testing indicating that the coating did not have a statistically significant effect on impact resistance at angles of 0 degrees (directly perpendicular) as well as 10

degrees. However, there was a statistically significant difference at impact angles of 30 degrees, most likely due to the reduced coefficient of friction. In general, there was also a slight upward trend in the average impact resistance at all impact angles, however, this behavior cannot be confirmed statistically and as such further testing would be required to substantiate this result.

EXPERIMENTAL PROCEDURE

In this study, all of the testing was conducted in a comparative manner, where the properties of coated plate glass were contrasted with those of normal, uncoated samples. To accomplish this, one hundred 2" by 2" square slides of fresh, 1/8"-thick flat glass were cut and cleaned with a mild soapy solution of water and Alconox® Powdered Precision Cleaner. The slides were then rinsed completely clean and allowed to dry in ambient atmosphere in preparation for coating and subsequent testing.

During manufacture of flat glass via the float process, the surface characteristics of the side that is in contact with the tin bath ("tin-side") will be slightly different with respect to the side that is in contact with the atmosphere ("air-side"). This behavior is attributed to the incorporation of tin metal into the glass on the tin-side surface, and is detectable via fluorescence under short-wave ultraviolet light. Since car windshields are typically oriented with the air-side facing outward, the samples were carefully examined under UV light for tin-side/air-side determination, where all consequent testing was conducted on the air-side of the samples.

For each of forty slides, the product was applied to the clean glass surface as instructed by where the product was sprayed on and then "buffed, much like using a window cleaning product" with low-lint wipers. During these applications, special care was taken to apply the coatings to all the slides in a consistent and uniform manner. As also instructed, two coats were applied to each slide, where the slides were allowed to dry for half an hour between applications and were given a further 24 hours to dry after both coats were applied.

An examination of the wetting characteristics of the coated glass was conducted via the contact angle method. Under this test, a microdroplet of pure water was placed on the surfaces of ten coated samples and five uncoated samples, at each of five locations per slide. Under high magnification in an optical comparator, the angle between the droplet and the surface can then be measured, and is proportional to the surface energy of the sample in question. Uncoated glass tends to exhibit relatively high surface energies, and so when a droplet of water is placed on the surface, it will tend to "spread" or "sheet" and the subsequent angle will be less than 20 degrees. In following, if the coating application makes the water less apt to "wet" the surface, then one would expect the droplet to bead up rather than sheet, thus forming higher contact angles in comparison to the uncoated glass. This behavior was also qualitatively tested via a sheeting reaction test, where a

stream of water was impinged on the surface of the both coated and uncoated sets and the relative behavior of the water to either "sheet" or "run off" was evaluated.

To examine the coefficient of friction of uncoated and coated glass slides, an Instron tensile tester was utilized. Under this test, the glass samples were placed on a sliding platform and a 1/8"-radius, stainless steel probe was placed in contact with the sample surface. Loads were then introduced onto the probe via weights, the entire assembly of which was later measured on a calibrated scale to determine the perpendicular force applied to the samples. The Instron then measured the force required to laterally slide the sample under the normal force at a speed of 2 inches per minute. The coefficient of friction for the stainless steel contact item under this configuration was then calculated directly from the measured force and the known perpendicular load. This test was performed on each of five coated and uncoated samples, where three parallel passes were made at different locations for each sample. In addition, a qualitative evaluation of the scratch resistance was subsequently accomplished by examination of the glass surfaces for frictive damage under the aforementioned loading configuration.

Lastly, to determine the effect of the coatings on impact resistance, an AGR pendulum impact tester was adapted for use with flat glass samples as shown in Figure 1. Under this configuration, the sample platform was adjusted to produce impact at varying angles while the impact speeds (and resultant forces) were adjusted by altering the pendulum angle. In this preliminary study, a 0.094"-radius, round stainless steel tip was used for all impact tests, where the tip was placed in contact with the sample surface prior to pendulum release. For ten each of both uncoated and coated samples, the slide surface was impacted at different locations and at speeds ranging from 20 to 70 inches per second (ips) in increments of 10 ips. These impacts were conducted at each of three angles with respect to vertical: 0° (directly perpendicular), 10° and 30°. All of the samples were then inspected with the aid of an optical microscope, and the lowest speed level at which glass damage appeared was noted. During these tests, any failures due to flexure (bending) stresses were disregarded since the goal of the study was to determine the effects, if any, on contact bruising only. Furthermore, impacts at speeds higher than 70 ips were not utilized due to the near-100% frequency of failure from bending stresses at those levels.

RESULTS

The results of the surface energy analyses are displayed in Table I, where it was found that the contact angle values for the coated slides were much different than those for the uncoated slides, and indicated that the coating had a significant effect on the surface energy characteristics of the glass. As seen in the table, all of the values obtained for the coated glass were significantly and consistently higher than the uncoated glass, which indicated a considerable reduction in surface energy. The implication of this result is that, in comparison to bare glass, water does not wet the surface of the coated glass efficiently, which is beneficial for windshield applications. Furthermore, this behavior was confirmed via a simple sheeting reaction test, where a water stream impinged on the

coated glass surface "ran off" in a thin rivulet, which was noticeably different than the bare glass where the water actively spread on the surface prior to running off.

Measurements of the coefficient of friction were performed on both coated and uncoated glass, and the results are displayed in Table II. From these tests, it was found that the coefficient of friction under this configuration was 0.16 for uncoated glass, which was consistent with the approximate literature value of 0.18. When the samples were coated, however, the force required to laterally move the sample decreased significantly, and consequently the calculated value for the coefficient of friction dropped by 44% to 0.09. This result indicated that the coated surfaces were more lubricious, and as such would have a higher scratch resistance. In direct support of this hypothesis, examination of the tested slides found that while the uncoated slides exhibited considerable frictive damage under the aforementioned loading configuration, the coated samples did not exhibit any damage, as shown in Figure 2.

The results of the impact tests are summarized in Table III. As mentioned previously, the values imparted in the table represent the minimum speed level required to create damage at each of three impact angles. From the table, it can be seen that there was a slight difference in the averages between the two sets for all three data sets, where in each case the average was higher for the coated sets. To evaluate whether this trend was real, a student t-test at a 95% confidence level was performed on the data sets. In the case of both the 0° and 10° data sets, it was found that the differences in the averages were not statistically significant. However, in regards to the 30° data set, the difference was found to be statistically significant, even at a more stringent 99% confidence level.

These results indicate that, despite a slight upward trend, the applied coatings had no statistically significant effect on the average impact resistance of the glass at angles near perpendicular (0°, 10°) but became more important at higher angles. The most likely explanation for this behavior is that as the impact angle increases, the relative contribution of the coefficient of friction becomes more influential to the impact response. As seen in Figure 3, the impact damage pattern at 30° had an appearance consistent with a "glancing" blow—which would have both direct- and frictionally-oriented elements to the contact—as opposed to 0° contact where the tip is driven directly into the glass with no element of lateral motion. In following, one would expect that at angles deviating further from perpendicular, the lubricious nature of the coatings would likely play a larger role in resisting the frictional element of the impact, as prescribed by the significant decrease in the coefficient of friction.

DISCUSSION

On the whole, the results of our analyses indicated that the coating material had a significant effect on the surface properties of glass. Coefficient of friction measurements indicated a 44% reduction, indicating that the coating was lubricious and would improve the resistance of the surface to frictional damage. Indeed, this behavior was confirmed

upon examination of samples after the friction testing, and was corroborated by a decrease in damage when impact testing at a 30° angle. Contact angle measurements and sheeting tests also indicated that the coating acted to reduce wetting of the surface by water, leading to beading action desirable in windshield coating applications.

In addition to the aforementioned benefits in surface properties, there was also a discernible trend in the impact testing that may indicate a slight increase in the general impact resistance brought on by the coating. However, due to the sample size utilized during these preliminary tests, this claim cannot currently be supported by statistics and, as such, remains anecdotal at this time. To this end, if further interest remains in elucidating the effect of the coatings on surface strength, a detailed follow-up analysis via impact testing with an increased number of samples is highly recommended, where any improvements in surface strength would be conclusively confirmed with true statistical data.

Please call if you have any questions regarding these analyses. An invoice covering our services is enclosed.

Sincerely,

AMERICAN GLASS RESEARCH

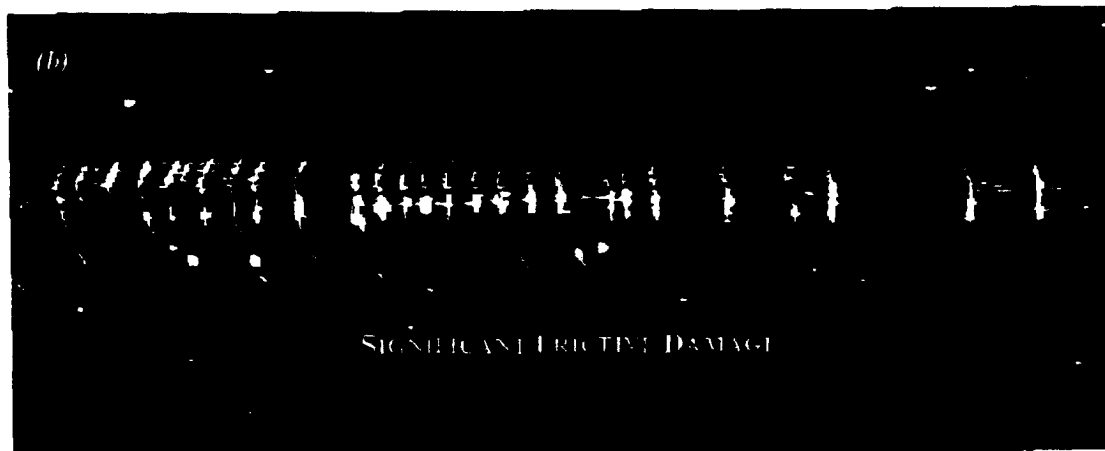
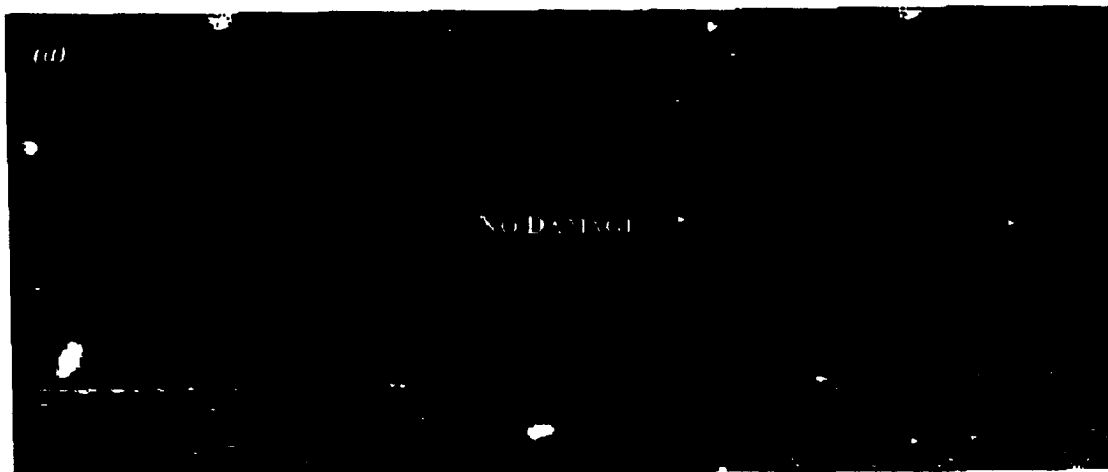
Nicholas J. Smith
Research Engineer

NJS/lmp

enclosures

FIGURE 2

(a) Example of Increased Scratched Resistance in Coated Glass,
As Compared to (b) Uncoated Glass Under Identical Loading Configuration¹



¹ - 1/8"-radius, stainless steel tip with 22 lb.
normal load pulled at 2 inches per minute

FIGURE 3

Damage Indicative of (a) Negligible Frictive Contribution in Perpendicular (0-degree) Impact,
As Opposed to (b) Significant Frictive Contribution in 30-degree Impact

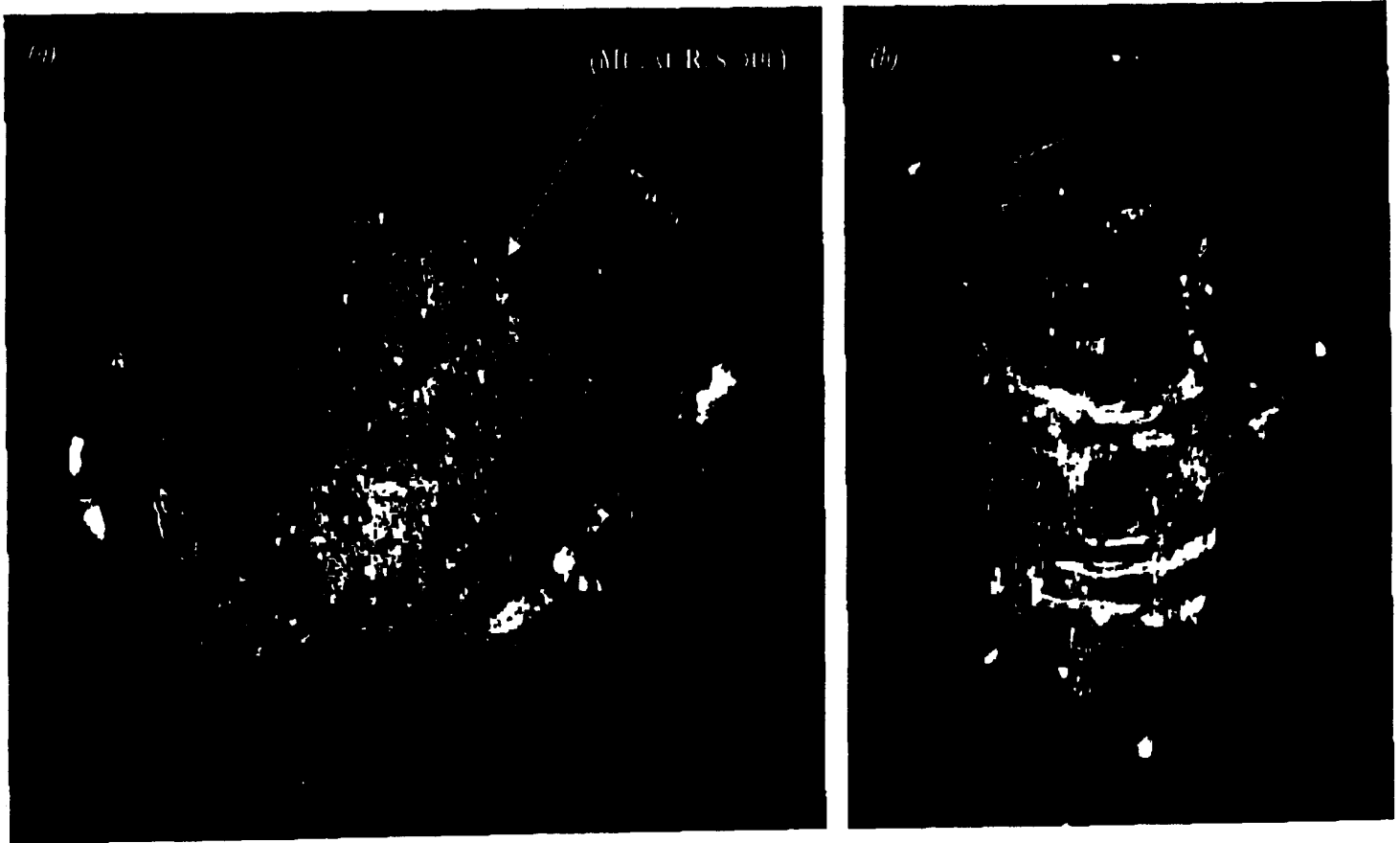


TABLE I

Results of Contact Angle Analyses

COATED SAMPLES	Contact Angle Measurements (degrees)					Averages
1	49	43	53	30	55	46
2	59	58	52	66	58	58
3	62	56	57	54	59	57
4	42	28	33	45	43	38
5	53	57	42	44	61	51
6	60	43	55	59	47	53
7	59	60	63	64	59	53
8	63	58	57	65	58	60
9	56	57	59	51	57	56
10	48	57	54	61	60	56

UNCOATED SAMPLES	Contact Angle Measurements (degrees)					Averages
1	15	16	11	14	17	15
2	11	14	14	15	17	14
3	19	16	16	18	19	18
4	16	15	18	17	15	16
5	16	20	16	16	15	16

TABLE II

Results of Coefficient of Friction Measurements

UNCOATED SAMPLES	Measured Force (lbs.)			Average
	1st pass	2nd Pass	3rd Pass	
1	3.726	3.103	3.785	3.54
2	3.582	3.322	2.685	3.20
3	5.925	4.211	6.711	5.62
4	2.841	2.659	2.362	2.62
5	2.513	2.543	2.336	2.46
Grand Average				3.49
Normal Force				22.04
COEFFICIENT OF FRICTION				0.16

COATED SAMPLES	Measured Force (lbs.)			Average
	1st pass	2nd Pass	3rd Pass	
1	1.992	1.987	1.960	1.98
2	2.056	2.062	1.987	2.04
3	2.012	2.059	1.960	2.01
4	2.021	1.980	1.960	1.99
5	1.929	1.931	1.960	1.94
Grand Average				1.99
Normal Force				22.04
COEFFICIENT OF FRICTION				0.09