

Reliability Evaluation of Thin, Lightweight Laminates for Windshield Applications

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ABSTRACT

The use of lightweight materials to produce automotive glazing is being pursued by vehicle manufacturers in an effort to improve fuel economy. As glazing's become thinner, reduced rigidity means that the critical flaw size needed to create fracture becomes much smaller due to increased strain under load or impact. This paper documents experiments focused on the impact performance of several alternative thin laminate constructions under consideration for windshield applications (including conventional annealed soda-lime glass as well as laminates utilizing chemically strengthened glass), for the purpose of identifying new and unique failure modes that result from thickness reduction. Regulatory impact tests and experiments that focused on functional performance of laminates were conducted. Given the increased sensitivity to flaw size for thin laminates, controlled surface damage was introduced to parts prior to conducting the functional performance tests. Damage levels were selected based on teardown characterization of real world windshield parts that had been in-service.

Regulatory impact testing showed that even very thin (< 2.3 mm total glass thickness) laminates could comply with requirements, as long as parts were properly laminated. Functional performance tests were more discriminating.

External ball bearing impact experiments showed that as unstrengthened glass laminates became thinner, a fundamental shift in failure mode occurred, and there was an increased prevalence of fracture of the interior ply due to biaxial flexure. Laminates made with a thin interior ply of chemically strengthened glass did not experience fracturing of the interior ply. Ring-on-ring testing of annealed (unstrengthened) glass showed significant reduction in retained strength when minor use case surface damage was present; whereas compressive stress in chemically strengthened glass made it relatively unaffected by the use case damage. This difference between the two materials is the likely underlying cause of the shift in failure modes observed when impacted by the ball bearing.

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INTRODUCTION

Automotive manufacturers have been actively seeking new ways to eliminate weight from vehicles to help improve fuel economy. Weight reduction of glazing is particularly attractive because it offers the additional benefit of improved driving dynamics resulting from lowering the vehicle's center of gravity. Windshields may account for as much as 30-60% of the total glazing weight in a vehicle and therefore offer the greatest opportunity to achieve significant weight reduction [1]. Conventional windshields are comprised of two plies of annealed soda-lime glass (ASLG) bonded together with a resin inter-layer, typically of 0.8 mm poly-vinyl butyral (PVB). Since the windshield employs two plies of glass, it contains a total of four distinct glass surfaces (two per ply). These surfaces are referred to by a numbering system that starts at the exterior of the outer ply (surface #1) and progresses to the innermost surface of the inner ply (surface #4). Figure 1 shows this nomenclature schematically, and the surfaces will be referred to as S1, S2, S3 and S4 in this paper.

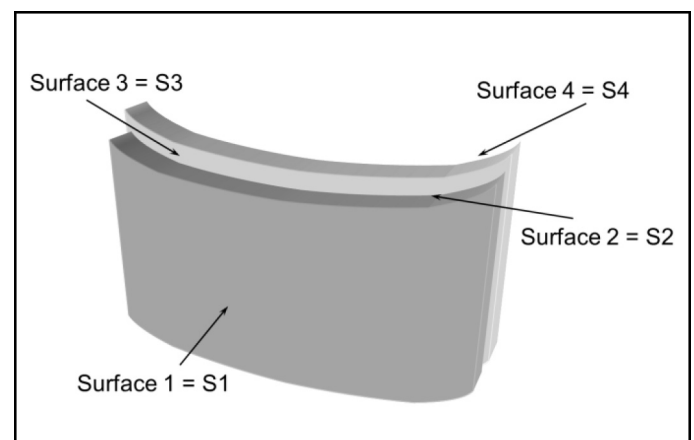


Figure 1. Schematic view of windshield assembly showing the four distinct glass surfaces.

To achieve weight reduction in windshield glazing, reduction in thickness of the individual glass plies is the simplest and most effective approach. Thickness of each ply can vary, but a traditional configuration of a 2.1 mm outer-ply with a 2.1 mm inner-ply (2.1 ASLG/2.1 ASLG) is a frequently utilized construction. An alternative “thin” windshield construction used in the industry for many years utilizes an asymmetric design with a 2.1 ASLG outer ply laminated to a 1.6 mm ASLG inner ply (2.1 ASLG/1.6 ASLG).

As the industry continues to explore the opportunity to further decrease the weight of windshield glazing, it is important to determine the limit in thickness reduction at which performance of the product becomes compromised. Mechanical performance of the windshield is important and is one area that may be adversely affected by reducing glass ply thickness. Windshields must maintain a reasonable level of performance in resistance to impact events to provide an adequate level of occupant protection and to minimize customer dissatisfaction due to fracture of the product. Use of alternative materials, such as chemically strengthened glass like Corning's® Gorilla® Glass for Auto (GGfA), and designs that employ greater degrees of asymmetry, may better enable weight reduction for windshield glazing. One such construction that has previously been disclosed is a laminate consisting of a 2.1 ASLG outer-ply with an inner-ply of 0.7 mm GGfA [2]. This paper explores the effect of further thickness reduction for conventional laminates made of two plies of ASLG and for advanced hybrid laminates utilizing one ply of ASLG with a second ply of GGfA. Special consideration is given to new failure modes resulting from glazing thickness reductions.

Mechanics of Thinner Glazing

Reducing the thickness of glazing significantly impacts the rigidity of the laminate. While predicting the rigidity of the laminate is complex due to the viscoelastic nature of the PVB and the effect of asymmetry of the two glass plies, the directional impact is simply illustrated by the equation for the flexural rigidity (D) of a monolithic plate:

$$D = (E t^3)/(12-v^2) \quad (1)$$

Where: E is the Young's modulus, t is thickness of the plate, and v is Poisson's ratio.

Reducing the rigidity of the laminate means that the laminate will deflect further for a given loading condition than thicker laminates would, giving rise to higher strain (ϵ) experienced by the glass. Glass obeys Hooke's law, which states that stress (σ) is directly proportional to strain:

$$\sigma = E \epsilon \quad (2)$$

Therefore a given load will result in significantly higher stresses experienced by the thinner glazing. The equation for beam bending of a monolithic bar illustrates that the stress is a function of the thickness squared:

$$\sigma = KL/(bt^2) \quad (3)$$

Where: K is a geometric constant as a function of the loading geometry, L is the applied load, b is the width of the bar, and t is the thickness. Again, the actual stress experienced in a laminate is more complex than the monolithic case, but the equation serves as an estimate of the effect.

From fracture mechanics, the critical flaw size (a_c) that results in fracture under stress is related through the material property of fracture toughness (K_{IC}):

$$a_c = [K_{IC}/(Y \sigma_f)]^2 \quad (4)$$

Where: σ_f is stress at failure, and Y is a shape factor that depends on the flaw geometry, e.g. Y= 1.1 for a penny shaped flaw and 1.98 for a shallow, but long flaw such as a scratch.

Combining equations 3 and 4 (assigning $\sigma = \sigma_f$) and simplifying, it is shown that the critical flaw size is proportionate to the thickness raised to the fourth power:

$$a_c \propto t^4 \quad (5)$$

This relationship demonstrates that any reduction in thickness makes survival of the article highly sensitive to the flaw distributions present. For example, if glass thickness was reduced by half, the flaw size needed to create fracture of the article would then be one-sixteenth of its original size. Therefore, when evaluating the suitability for use of thin windshield laminates, it is imperative that consideration be given to flaws that can be introduced over the product's useful lifetime and that representative flaws be introduced to the article prior to performing mechanical testing.

Introduction of Flaws to Windshields over Useful Life

Windshields experience a number of events leading to contact damage of the outer surfaces (S1 and S4) that can create new flaws over the product's lifetime. The inner two surfaces (S2 and S3) are protected as they are bonded to the PVB and should not incur additional damage post lamination. Gulati et al., have previously shown that damage accumulated on the exterior windshield ranged between 51-127 micrometers in depth for articles that had not fractured in-service [3]. Most use-case loading conditions of the windshield laminate occur from external sources such as by impact (e.g., from stones or other debris), from snapping of the wipers against the windshield, from ice scraping, or by other scenarios where the load is applied upon S1. While there may be scenarios that load the windshield glazing in the opposite direction (e.g. internal loads applied on S4 resulting in tension on S1 and S3), these events would seem to be infrequent and of low magnitude. Externally applied loads result in development of tensile bending stresses on S2 and S4. While the flaw distribution present on S2 should not change after the laminate has been manufactured, S4 will continue to accumulate

damage over the article's useful life. Therefore, determination of a representative flaw distribution of S4 was needed to conduct comprehensive evaluation of thin windshield laminates.

TESTING AND RESULTS

Characterization of Surface Four Windshield Flaws

To determine the severity of flaws accumulated on S4 while inservice, several used windshields were obtained for characterization. While the mileage and time of service was not known for some of the samples, one windshield's history was well known; it had been driven approximately 60,000 miles and had been in service for over 5 years. The other samples were also assumed to have had similar inservice life. The windshields were cut down into (approximately) six inch by six inch samples (with care given to protect S4). Samples were then stressed via ring-on-ring loading such that tension was applied to S2 and S4. A support ring radius (a) of 12.7 mm and a load ring radius (S) of 6.35 mm were used with a loading rate of 1.2 mm/minute. Ring-on-ring loading was used, not for the purpose of conducting strength testing of the samples, but rather as a convenient means to stress the samples so as to activate flaws on S4 and open them for examination. After ring-on-ring loading, parts were evaluated via fractography to characterize the different types of flaws present and to measure the critical flaw depths. It was found that the majority of the flaw depths were less than 16 micrometers but that some damage extended as deep as 32 micrometers. Figure 2 shows a histogram and statistical summary for the critical flaw depths measured.

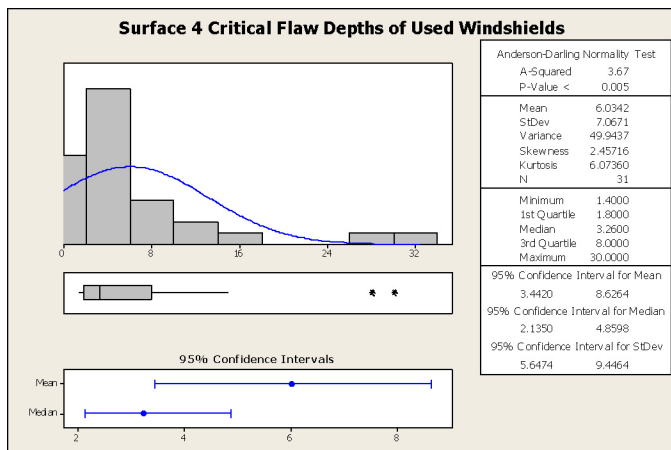


Figure 2. Histogram summary of critical flaw depths found on Surface 4 of in-service windshields. X-axis shows flaw depths in micrometers and Y-axis represents the frequency of occurrence.

The most frequently observed type of damage was that of sharp, frictive scratches (65%), followed by localized frictive contact (22%) and lastly, localized sharp indents (13%). Figure 3 shows an example of one of the more severe frictive contact scratches, while Figure 4 shows an example of a more frequently found frictive scratch.

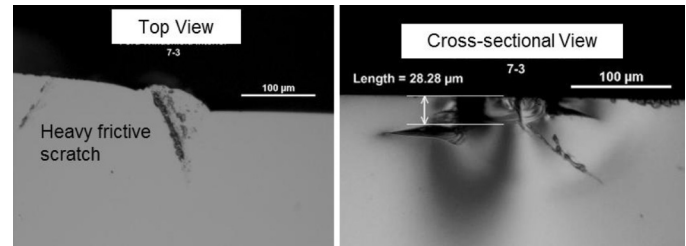


Figure 3. Photo-micrographs (top view & cross-sectional view) of sharp, frictive contact damage on S4 from a windshield with 60,000 miles in-service. The length of 28.28 μm represents the critical flaw depth of the damage.

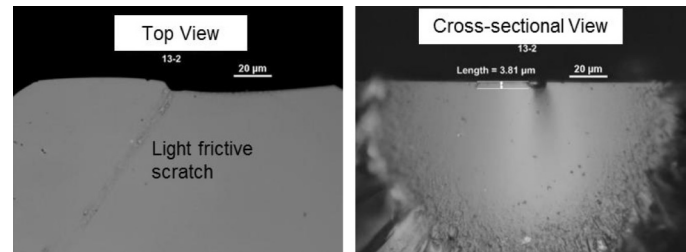


Figure 4. Photo-micrographs (top view & cross-sectional view) of the most frequently found damage type on S4 of used windshields: light, frictive scratches. Critical flaw depth for this sample was 3.81 μm .

Recreation of Surface Four Flaws

Consideration was given to what may have caused this type of frictive damage on S4 of the used windshields and several different use-case events were explored in an attempt to replicate morphology and severity of the damage. It was determined that the most likely cause of the damage was simple cleaning of the windshield with dust present on the surface. Several windshields were sampled in Corning, NY to determine the types of materials present on S4. SEM analysis revealed that the most common types of particles occurring on S4 were: silica, alumina, and salt (NaCl). To recreate the observed surface damage, ISO 12103-1, A4 coarse test dust was selected as an abrasion agent because its composition was similar to the dust that was observed on the field parts. The ISO dust contained approximately 68-76% silica and 10-15% alumina particles. To replicate the field damage, a small amount of the ISO dust was sprinkled on the surface of the test coupon and then lightly cleaned with glass cleaner and a tissue. The damage created was not visible to the un-aided eye. Samples were then evaluated via ring-on-ring, and fractography was performed to determine critical flaw depths. It was found that this simple, light cleaning method created damage very similar in morphology and severity to those observed on the inservice windshields. Figure 5 shows a histogram summary of the damage depths created with this cleaning method. By comparing critical flaw depth distributions in Figures 2 and Figure 5, it was shown that this damage introduction method has very similar distribution of flaw severity to that observed on the real-world parts. Figure 6 shows an example of the damage morphology created by the cleaning step.