IMPACT DAMAGE AND STRENGTH DEGRADATION OF FUSED SILICA

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ABSTRACT

Fused silica in service can suffer from strength degradation due to a localized contact load or particle impact that can cause cracking about the indentation or impact site. This cracking generally consists of radial, lateral, and cone cracks and is independent of whether the indenter or particle is sharp or blunt or whether the impact is subsonic or hypervelocity. The impact site is generally characterized by a shallow pit surrounded by an array of microcracks. The pit is formed by the fragmentation of the glass due to the intersecting radial, lateral, and cone cracks. With either static indentation or particle impact, it is the radial crack that controls strength degradation. The applicability of indentation fracture mechanics in predicting this strength degradation is discussed.

INTRODUCTION

Fused silica is used in a wide variety of diverse applications from optical glass fibers to the windows of the Space Shuttle. Strength degradation in service is often caused by damage due to a localized contact load or particle impact. Particle impact can range from subsonic to hypervelocity (or dynamic loading). It has been observed that under both sharp (Vickers) and blunt (spherical) indenters [1], as well as subsonic sharp and spherical impact [2,3], cone, radial, and lateral cracks form in fused silica. Since fused silica is an anomalous glass that densifies under indentation, it is believed that this densification essentially blunts out a sharp indenter or particle so that cone cracks form in addition to radial and lateral cracks. At hypervelocity particle impacts (greater than 3 km/s) relatively shallow pits, surrounded by an ensemble of microcracks, are produced [4,5]. At these velocities both the impacting particle and target material fragment and are thought to behave hydrodynamically during impact.

Based on the microscopic characterizations in refs. 2 and 3, Fig. 1 illustrates the cracking sequence on blunt particle impact (subsonic) of fused silica. Above a certain critical impact load, ring cracks are initiated from pre-existing flaws that lie just outside the area of contact between the particle and target surface. As the impact load increases, more ring cracks are formed further out from the contact area until eventually these ring cracks will veer outwards to form a Hertzian cone crack. This Hertzian cone crack will continue to form and grow with increasing impact loads until eventually densification occurs underneath the impacting particle and radial/median and lateral cracks form. On unloading, the median cracks link-up with the radial cracks to form a semi-circular radial crack and the lateral cracks grow to their final size. A residual pit is formed by the densification and the glass debris caused by the intersecting cone, radial, and lateral cracks.

Based on models for cracking under static indentation [6], indentation fracture mechanics has been successful in predicting contact-induced strength degradation of various glasses and ceramics under subsonic particle impact [6,7]. These indentation models predict the extent of cracking and strength degradation as a function of indentation load (or impact energy) and target material properties (toughness, hardness, and elastic modulus). For hypervelocity impacts there is currently no theoretical model for predicting the extent of cracking and corresponding residual

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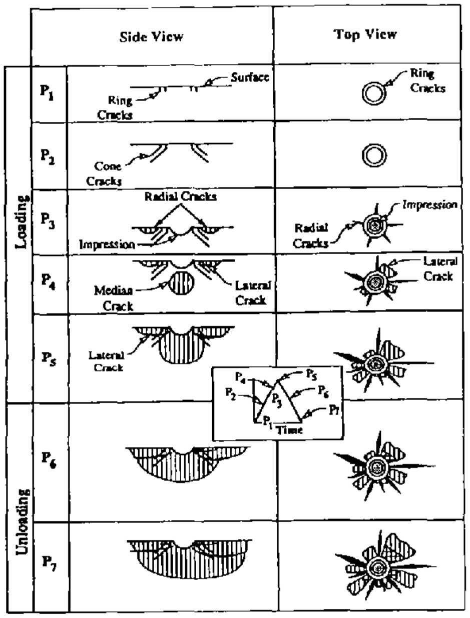

Figure 1. Evolution of cracking produced by subsonic impact of a spherical particle on fused silica.

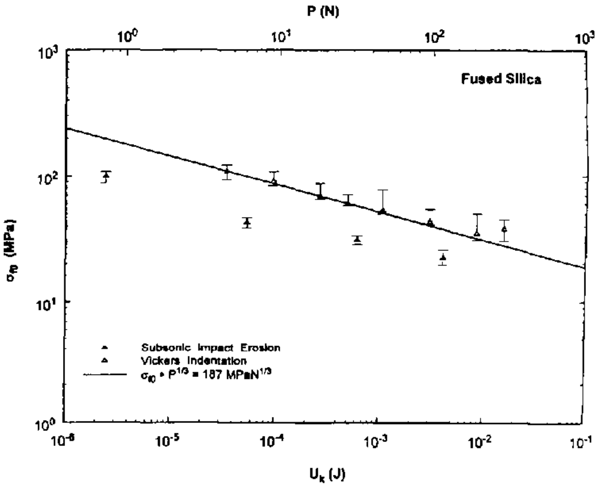

Figure 2. Comparison of the inert strength after Vickers indentation [11,12] and subsonic impact [13] of fused silica. The solid line represents the best-fit line through the indentation data, giving $\sigma_{f_0}P^{1/3} = 187$ MPa N$^{1/3}$.

strength [4,8,9]. However, recently the current authors have proposed to model the irregular pit-crack defects produced by hypervelocity impacts as a spherical cap surrounded by a circumferential crack. This model was used to estimate the extent of crack growth during strength tests [10] of hypervelocity impacted fused silica targets. It is the purpose of this paper to compare in fused silica subsonic and hypervelocity impact damage and strength degradation to that produced by static indentation and to determine the applicability of indentation fracture mechanics in predicting strength degradation of subsonic and hypervelocity impact damage.

SUBSONIC PARTICLE IMPACT

Figure 2 compares the inert strength after Vickers indentation [11,12] to that after multiple sharp particle impact (particle velocities less than ~150 m/s) [13]. For this comparison, the equivalent subsonic indentation load, P, for impacts was calculated by relating the impacting kinetic energy, U_k, to the work required to plastically deform the target material, namely [7]:

$$P = \alpha \xi H^{1/3} U_k^{2/3} \tag{1}$$

where H is the hardness of the target material, α is a constant related to the fraction of energy transferred to the target material and ξ is a geometric constant (equal to 4.8 for the Vickers geometry). In Fig. 2 α was taken to be 0.5, ξ to be 4.8, and H to be 7.6 GPa [1].

Indentation fracture mechanics predicts that for either radial or cone cracks the inert strength parameter ($\sigma_{f_0} P^{1/3}$) should be constant for both indentation and impact data [6,7,12]. It is evident

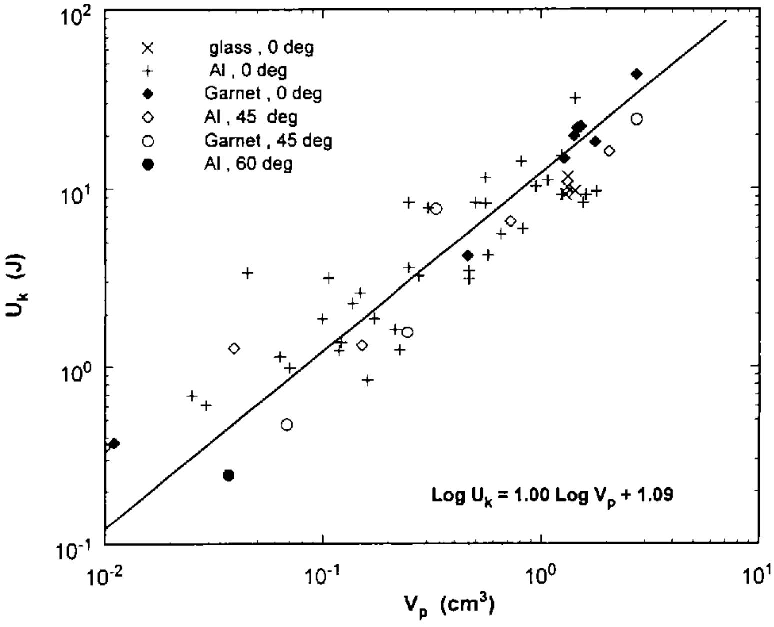

Figure 3. Hypervelocity impact data [8] of fused silica targets relating the kinetic energy of the impacting particle, using the normal velocity component, to the volume of the pit produced by the impact.

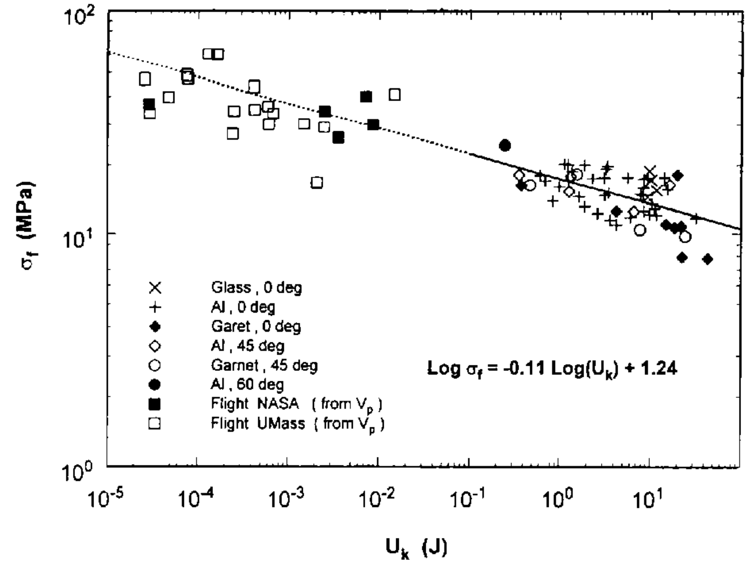

Figure 4. Comparison of the hypervelocity fatigue strength of laboratory impacted fused silica targets [8] to that of actual flight damaged Space Shuttle windows [8,16]. For the flight data the kinetic energy was estimated by Eq. (2). Regression line is based on the laboratory data.

from Fig. 2 that the Vickers indentation data is well predicted with $\sigma_{f_0}\ P^{1/3} = 187\ \text{MPa}\ N^{1/3}$. Although cone cracks can form on both indentation and sharp particle impact, it is believed that the strength for both the indentation and impact data in Fig. 2 is controlled by the radial crack rather than the cone crack for two reasons. First, the radial crack can have a residual stress acting on it due to the plastic/elastic mismatch at the indentation or impact site that supplement the applied stress [6,7]. Secondly, from microscopic observations the cone crack depth in fused silica is about 1/4 to 1/3 the depth of the radial crack [1,2]. Both these factors indicate that the cone crack in fused silica is far less deleterious than the radial crack. For example, the inert strength parameter $\sigma_{f_0} P^{1/3}$ of soda-lime glass for Vickers indentation (radial crack strength controlling) is about 120 MPa $N^{1/3}$ for as-indented samples and 171 MPa $N^{1/3}$ for indented, annealed specimens [6,14]; whereas, for spherical indentation (cone crack strength controlling) it is about 310 MPa $N^{1/3}$ [6,15]. The significantly greater value for the strength parameter of fused silica (187 MPa $N^{1/3}$) compared to soda-lime glass (120 MPa $N^{1/3}$) for Vickers indentation is undoubtedly related to the fact that some or all of the material displacement in indentation (or impact) can be accommodated by volume compaction in fused silica [6]; whereas, it has to be accommodated by plastic shear deformation in soda-lime glass. Shear deformation results in a larger plastic/elastic strain mismatch surrounding the indent or impact site [6]; hence a higher residual stress and a lower value of the strength parameter.

Although the indentation data in Fig. 2 correctly predicts the sensitivity of strength on impacting kinetic energy, the strength after particle impact is somewhat less than predicted from the indentation data. This implies that multiple impact flaws linked up prior to final fracture, thereby, causing strength to be reduced from that of a single impact flaw [7].

Another important observation in the data of Fig. 2 is that the extent of cracking is quite stochastic in fused silica with either indentation [1,11] or particle impact [2,3]. This variability in cracking corresponds to a large variability in the strength data in Fig. 2. In contrast, the distributions in strength and extent of cracking at a given indentation or impact load are relatively narrow for normal glass (soda-lime) and other ceramics. The large variability in the extent of cracking in fused silica is believed to be related to the interaction between cone and radial crack formation. When the cone crack forms first, it can initially shield the radial crack from the plastic/elastic mismatch residual stress, resulting in a smaller radial crack and higher strength.

HYPERVELOCITY PARTICLE IMPACT

Hypervelocity (greater than 3 km/s) particle impact of fused silica causes extensive cracking (radial, lateral, and cone) about the impact site and the intersection of these cracks causes fragmentation of the glass. As a result a shallow pit is formed that is surrounded by an ensemble of microcracks [4,5]. Assuming that most of the impacting particles energy (U_k) goes into the formation of the pit, it would be expected that the volume of the pit (V_p) should be directly proportional to the impacting kinetic energy. Figure 3 shows hypervelocity impact data (U_k vs. V_p) obtained from laboratory tests of fused silica targets impacted at hypervelocities by spherical particles of aluminum, garnet, or glass [8]. Note that from the measured pit dimensions, the volume of the pit was calculated by assuming that the pit was a spherical cap. As expected, there is a strong, essentially 1:1 correlation, between the impacting energy and the volume of the pit formed. The data in Fig. 3 gives:

$$\log U_k = 0.80 \log V_p + 1.00 \tag{2}$$

Strength of both the fused silica targets impacted at hypervelocity [8] and of actual flight damaged windows on the Space Shuttle [8,16] have been measured. For the window data, disc

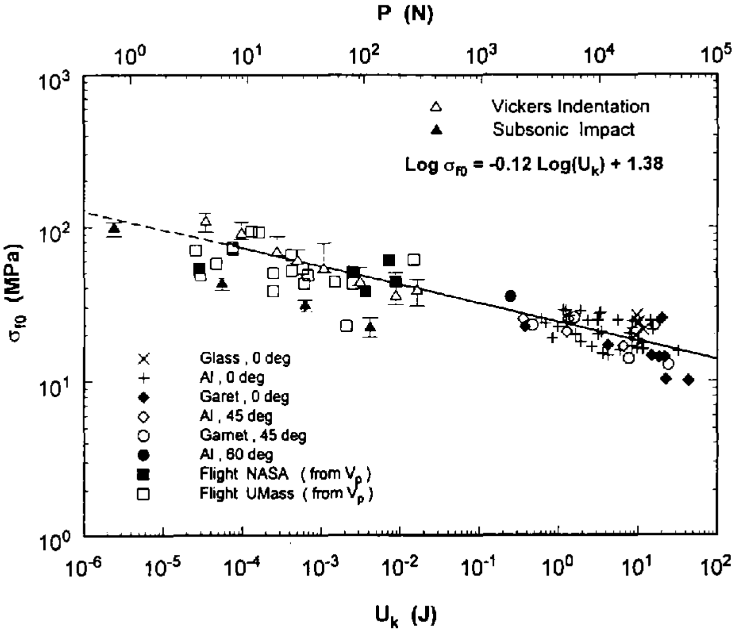

Figure 5. Comparison of the inert strength of fused silica obtained from Vickers indentation tests and subsonic particle impact (see Fig. 2) to that obtained from hypervelocity particle impact (see Fig. 4). Regression line based on hypervelocity laboratory data.

shaped specimens were cut from Space Shuttle windows such that the damage site was in the center of the disc. The fatigue strengths were measured in ambient air using a ring-on-ring test fixture, either at NASA [8] or UMASS [16]. From the measured pit dimensions, the energy of the impacting particle for the flight damaged windows was estimated from Eq. (2). Figure 4 compares the laboratory impacted strength (σ_f) data to that obtained from the actual flight damaged windows. Although there is considerable experimental scatter due to the stochastic nature of the cracking, it is evident that the strength of the flight damaged windows are reasonably well predicted from the laboratory impacted data.

To compare the impacted fatigue strength data in Fig. 4 to the indentation and subsonic inert strength data in Fig. 2, the irregular pit-crack defect produced by hypervelocity particle impact was modeled as a spherical cap surrounded by a circumferential crack [10,17]. This model was then used to predict the inert strength of the hypervelocity damaged windows (Fig. 5) by accounting for the subcritical crack growth that occurred during the strength test [10,16]. The reasonable agreement between the different sets of data in terms of the trend of σ_{f_0} versus U_k is quite significant given that the data spans over eight orders of magnitude of kinetic energy. The agreement is also important for it implies that a simple indentation test can be used to estimate strength of both subsonic and hypervelocity particle impacted windows.

SUMMARY

Localized contact loads, whether sharp or blunt or subsonic or hypervelocity, on fused silica can cause radial, lateral, and cone cracks to form. Since fused silica can densify to accommodate the indenter or particle volume, there is little or no residual stress about the indent or impact site. It is believe that for fused silica under all indent or impact conditions the radial crack controls strength but that the interaction between the various crack systems causes a large variability in the extent of cracking about the damage site and in the post-indention or impact strength. It is believed that static indentation data coupled with indentation fracture mechanics principles can be used to estimate strength degradation of both subsonic and hypervelocity particle impact.

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