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14. ABSTRACT
This project provides a fundamental understanding on an innovative material design, i.e., implanting thin interfaces inside layered materials to enhance impact resistance. Its technical merit is simplifying a complicated problem to discover key parameters in controlling failure mechanisms. Four mechanisms related to impact damage reduction or impact resistance increase were found. First, thin interfaces lead to reduction of the maximum impact force of layered materials, and for some layered polymer specimens, the reduction was up to 60%. Second, low Young's moduli of thin interfaces are necessary conditions to reduce the maximum impact force. Third, impedance

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Report Title

Final Report: STIR: Mechanisms of Enhancing Impact Resistance of Layered Materials Using Thin Polymeric Interfaces

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STIR: Mechanisms of Enhancing Impact Resistance of Layered Materials Using Thin Polymeric Interfaces

Principal Investigator (PI): Luoyu Roy Xu
New Mexico State University

1. STATEMENT OF THE PROBLEM STUDIED

Unique material interface phenomenon: thin interfaces/adhesive layers arrested cracks

As shown in Figure 1, two layered Homalite brittle polymers with different adhesive bonding exhibited very different impact failure patterns in PI's previous research (Xu and Rosakis, 2003). Surprisingly, the strong bonding was not able to stop any impact damage/cracks, but the dynamic cracks were trapped along a weakly bonded interface that had Loctite 5083 adhesive, which is a type of Acetoxy silicone. Figure 2 displays a sequence of high-speed photographs of the impact failure progress of the specimen shown in Figure 1(b). Figure 2(b) reveals that the number of photoelasticity fringes—i.e., the stress wave across the weak interface (the upper horizontal line)—was dramatically reduced by the soft and thin (20 μm) adhesive film. After a long time-period (440 μs) of wave motion within these two layers, cracks initiated from the dark impact zone. These cracks accelerated and eventually branched as shown in Figure 2(c). As soon as the resulting branches approached the interface, they were arrested (Figure 1(b)). Although the exact reasons of the inability of these cracks to penetrate the weak bonding are complex, this observation suggests a viable design methodology to prevent the spread of impact damage. Included in the caption of Figure 2 is a YouTube video based on 80 high-speed photos obtained from the experiment for Figure 1(b). The dynamic cracks were still trapped by the weak interface, even when the impact speed was increased from 20 m/s to 46 m/s. These results are highly repeatable and promising to design new and impact-resistant layered materials and structures. This objective can be achieved by

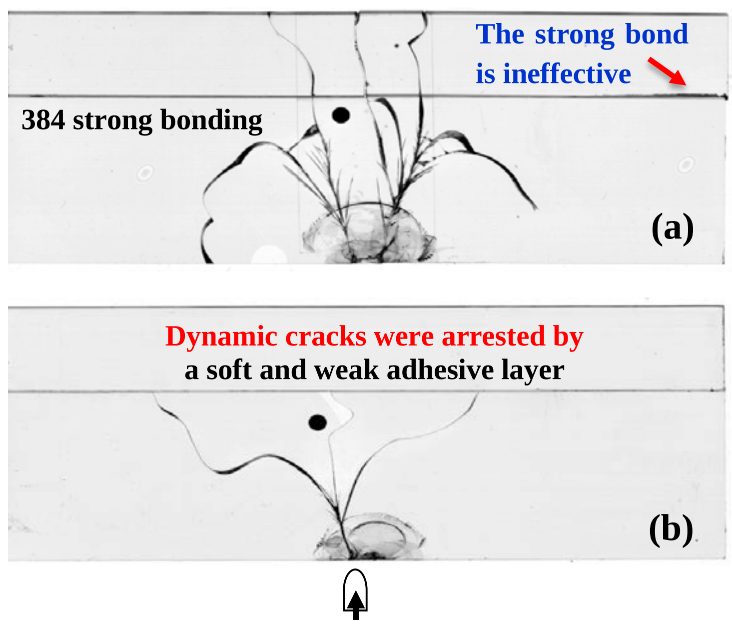

Fig. 1. *Failure patterns of two polymer specimens with different interfacial bonding subjected to the same gas gun impact (20 m/s) (a) 384 strong bonding (b) 5083 weak bonding in PI's previous paper (Xu and Rosakis, 2003).*

incorporating special thin interface layers within the original material system without other changes to increase impact resistance. However, fundamental issues regarding the trapping of cracks are still not unclear. For example, we do not know which parameter plays the major role in the crack arrest process**:** the adhesive density or modulus, or the stress wave mismatch of the adhesive with the base polymer? Obviously, answers to these questions will lead to better material designs. It is interesting to notice that weak interfaces exist in natural and engineering materials. For example, San Andreas Fault in California has very long weak interfaces, and each printing surface is a weak interface of 3-D printed materials. Therefore, investigation of weak interfaces has broad applications in science and technology**.**

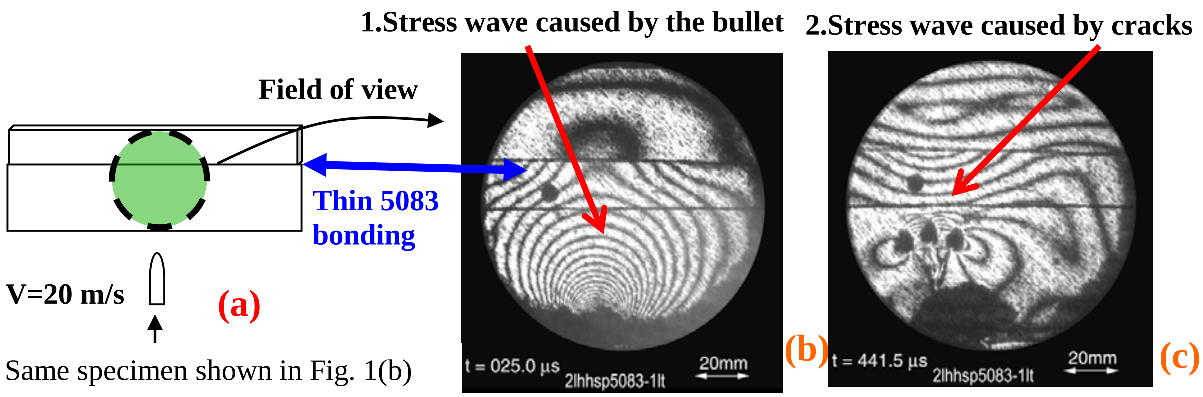

Fig. 2. *High-speed photographs of dynamic crack propagation in a two-layer brittle polymer specimen with 5083 bonding (Xu and Rosakis, 2003). A YouTube video based on high-speed photography provides more information,* https://www.youtube.com/watch?v=5EDG2VZXaQ8 **click to view**

2. SUMMARY OF THE MOST IMPORTANT RESULTS

Mechanism-1: Reduction of the maximum impact force

We performed more than 30 out-of-plane impact tests and Figure 3 displays the schematic diagram of a drop-weight impact test machine used. At first, impact tests were carried out on the polymer plates without any adhesive layers. Then, impact tests were carried out on the bonded specimens using 5083 adhesive at the same impact energy levels. Figure 3 shows very different maximum impact force variations for two Plexiglas (PMMA) specimens. At the impact energy of 20 J, the maximum impact force for the PMMA specimen with 5083 bonding reduced by 60%, as compared to an otherwise identical specimen without any bonding (Islam and Xu, 2016). For Polycarbonate specimens with 5083 bonding, the maximum impact force reduced by at least 20%, even though the maximum impact energy was 120 J. Moreover, their energy absorption increased by 130% compared to the identical specimens without 5083 bonding. As a result of reduced maximum impact force, the target is not easy to break or its impact resistance increases.

Mechanism-2: low Young's modulus of the interface/adhesive layer

In order to understand basic failure mechanisms, we investigate a simple low-speed impact or a contact mechanics problem first (Abrate, 1998). The first stage of projectile (or indenter) impact is a dynamic elastic indentation. So the indentation load (P) of a spherical indenter is a function of the indention depth (h) and the indenter radius (R) based on Hertz's law (Fisher-Cripps

2004):

$$P = \frac{4}{3}\sqrt{R}E_r h^{\frac{3}{2}} = C \quad h^{\frac{3}{2}} \tag{1}$$

where C is the "contact stiffness," and E_r is the "reduced modulus." Suresh and co-workers employed simplified contact mechanics theory (Andrews et al., 2001), and found that the maximum impact force is achieved at the same impact speed of the projectile and the target (no penetration), and is determined by impact energy (W) and the contact stiffness C:

$$P_{max} = 1.73 \sqrt[5]{W^3 C^2} \tag{2}$$

Therefore, at fixed impact energy, decreasing the contact stiffness will decrease the maximum impact force.

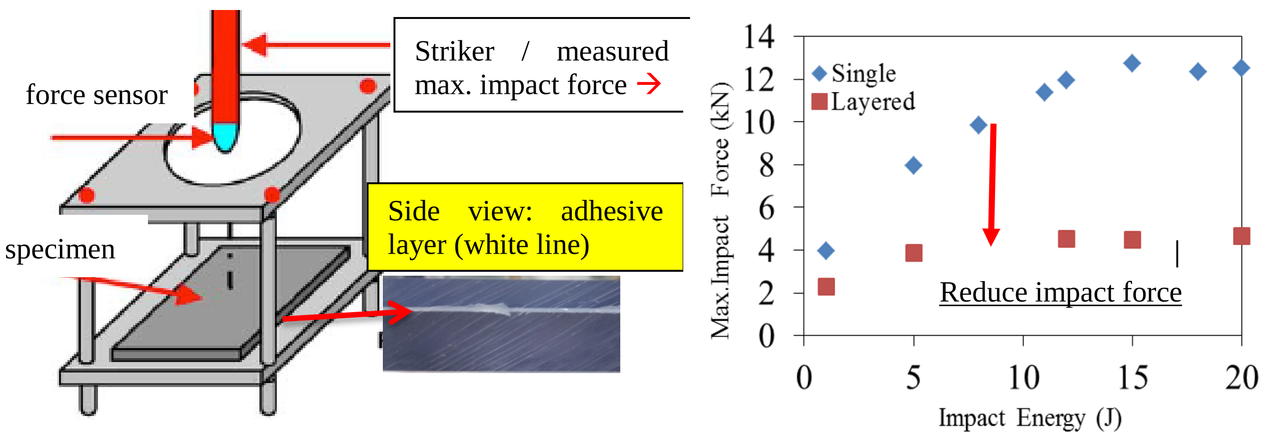

Fig. 3 (left) *Drop-weight impact experiment on layered specimens with thin 5083 interfaces.* ***(right)*** *Variation of the maximum impact force of baseline and layered Plexiglas specimens.*

The reduced modulus E_r is determined by the Young's modulus E and the Poisson's ratio v of the indenter/projectile material (subscript *i*) and the target (subscript *t*):

$$\frac{1}{E_r} \approx \frac{1-v_i^2}{E_i}(projectile\ ) + \frac{1-v_t^2}{E_t}\ (target) \tag{3}$$

Because decreasing the contact stiffness is equivalent to decreasing the reduced modulus as shown in Eq. (1), the through-thickness Young's modulus along the impact direction of the target E_t should decrease according to Eq. (3) because $E_i >> E_t$. We are not able to change the projectile, and the base materials, so the only way to decrease E_t is through the addition of the soft interface layers. After the soft layers are embedded inside the base materials, the reduced modulus will decrease based on micromechanics theory. Therefore, low Young's modulus of the interface/adhesive layer is identified as a material parameter in order to reduce the maximum impact force and damage. This conclusion would be enhanced by stress wave theory also.

Mechanism-3: High property mismatch between the interface and the base material

As shown in Figure 2(b), the stress wave patterns caused by the projectile impact were very different across thin 5083 bonding. Our preliminary modeling result using one-dimensional stress wave theory shows that a very small amount of the incident stress wave was transmitted into the top polymer layer (Figure 1(b) and its YouTube video), due to the dramatic reduction of the impedance (product of the material density ρ and the sound wave speed) of the soft 5083 adhesive layer. The ratio of the transmitted stress in the inner layer over the incident stress in the external layer after reflection at two material interfaces (between material B/A, and A/B. Here A refers to adhesive or interface, and B refers to bonded or base material next to material A) can be expressed as,

$$\lambda = \frac{4\sqrt{\rho_B E_B \ / (\rho_A E_A)}}{\left(1+\sqrt{\rho_B E_B \ / (\rho_A E_A)}\ \right)\left(1+\sqrt{\rho_B E_B \ / (\rho_A E_A)}\right)} \tag{4}$$

An impedance ratio could be defined by P= $\sqrt{\rho_B E_B \ / (\rho_A E_A)}$, and an impedance mismatch of two kinds of bonded materials could be defined by IM= (P-1) / (P+1). If we assume the densities of material B and the adhesive are the same, the stress wave inside the inner layer would be smaller than the stress wave inside the external layer, if the Young's modulus of material B is more than 34 times (for λ <50%) to 1,444 times (for λ <10 %) that of material A (adhesive). For typical bonded hard polymer layers using acetoxy silicon, the stress wave transmission rate λ could be less than 11%. As a result, Figure 1(b) shows that the external layer has impact damage, but the inner layer (top) has no damage due to very few stress wave transmitted and other mechanisms such as the shear modulus mismatch. The above stress wave transmission analysis is applicable to stress waves caused by both projectile impact and crack initiation (Figures 2(b) and (c)). Now we identify another material parameter, the impedance mismatch of the bonded material and the adhesive, which also plays an important role in crack arrest. The strain rate effect is not a factor since in our experiments showing crack arrest, the strain rates were very small and neglected.

In addition to the impedance mismatch, a new parameter for interface dynamics, the shear modulus mismatch of materials A and B is proposed as follows,

$$SM = \frac{\mu_B - \mu_A}{\mu_B + \mu_A} = \frac{E_B(1+\nu_A) - E_A(1+\nu_B)}{E_B(1+\nu_A) + E_A(1+\nu_B)} \tag{5}$$

Compared to the Young's modulus mismatch, the shear modulus μ mismatch includes the Poisson's ratio ν, so it could be used to characterize more complicated phenomena. In most cases, the projectile hits the target at an inclined angle, therefore, the impact force component along the target surface will increase shear deformation of the target and dissipate some impact energy. If the shear moduli of the adhesive layer and the bonded material layers are very different, the projectile will dissipate more energy along the target surface direction, rather than the perpendicular direction to the target for penetration. This mechanism is analogous to a static boat's potential movement in a pond, when it is hit by a stone with an inclined angle above water. The stone tends to sink the boat, and also push it away along the water surface due to two impact force components. If water was replaced by mud with a high shear modulus, the boat would be hard to be pushed away and sink quickly. Therefore, materials under the boat will lead to very different shear deformation to contribute energy dissipation. Both the shear modulus and impedance mismatches of some material combinations are listed in Table 1.

Table 1. Performance comparisons and property mismatches of selected adhesives

Adhesive material A	Bonded material B	transmitted stress ratio λ	impedance mismatch IM	Shear modulus mismatch	Protection to the inner layer
Loctite 384	Homalite-100	100%	0 %	9.57%	No
Loctite 330	Homalite-100	88.9%	34.3%	56.5%	No
Loctite 5083	Homalite-100	8.8%	95.5%	98.9%	**Yes**
Loctite 5083	Plexiglas	8.6%	95.6%	99.9%	**Yes**
Loctite 5083	Polycarbonate	10.6%	94.6%	98.9%	**Yes**

If the mismatch levels were low, no protection of the adhesive layers (Loctite 330 and 384) to the inner layers was found in the impact experiments (Xu and Rosakis, 2003). For other three material combinations listed in Table 1, both mismatch levels were very high, so protection of the interface/adhesive to the inner layers existed. Both shear modulus and impedance mismatches of the adhesive and the base material should be as high as possible in order to increase impact resistance. For interface dynamics, obviously these two mismatch parameters are more important than two Dundurs' parameters α and β (1969), i.e., mismatches of the Young's moduli and bulk moduli of materials A and B.

Mechanism-4: Stress wave reflection to cause dynamic crack arrest

Dynamic crack arrest is strongly related to stress wave propagation. As illustrated in Figure 4, right after impact, the initial contact between the projectile and the specimen leads to stress waves as seen in Figure 2(b). After the impact force reached a critical value, mode-I opening cracks initiated from the impact site (Figure 2(c)). Strong stress waves stemmed from these tensile cracks and propagated toward the interface. The fastest wave speed was the longitudinal wave speed C_L and the tensile stress wave magnitude was σ_I (+) as shown in Figure 4(a). Behind the stress wave, dynamic cracks propagated with a crack tip speed V_C. Since the mode-I crack speed is lower than the Rayleigh wave speed C_R (Freund 1990), and $C_R < C_L$, then V_C (max. 400 m/s for the crack in Figure 2(c)) < C_L (around 2,000 m/s for polymers used in this investigation), i.e., the crack speed in our experiments was always lower than the stress wave speed (see Figure 4(b)). Even the projectile/crack/damage speed is around the bullet speed (400-800 m/s), the above relation still holds. After the tensile stress wave reflected from the interface due to the high impedance mismatch, it became a compressive stress wave with a magnitude σ_R (-), which acted ahead of the mode-I crack as shown in Figure 4(c). It immediately reduced the crack driven force, because moving "pins" existed ahead of the crack path. This scenario is supported by Figure 2(c) because the reflected compressive stress wave was downwards, while the cracks propagated upwards. Also, the dynamic stress intensity factor K_I (t) of a dynamic mode-I crack is a linear function of the incident stress wave with a magnitude σ_L:

$$K_I(t) = \sigma_L\, f(k,\alpha,\beta,\, t,\, C_L\ldots.) \qquad (6)$$

where the complicated function f (k,….) was reported by Broberg (1999). If $\sigma_L < 0$ (here compressive stress σ_R (-)) , $K_I = 0$ or cracks arrested. Therefore, the above four mechanisms all make the contributions to cracks arrest, and we believe mechanisms-3 and 4 are dominated factors.

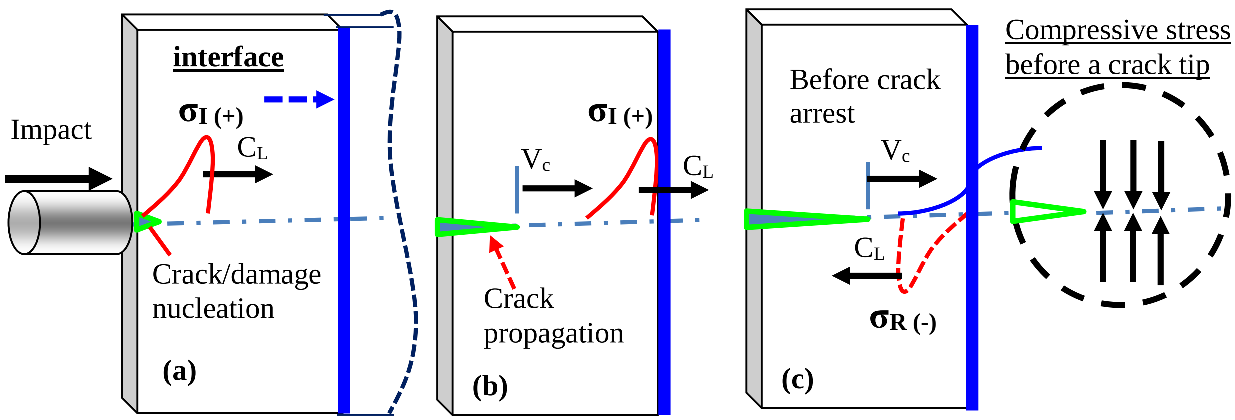

Fig. 4. *Proposed failure mechanism (a) tensile stress wave stemming from crack initiation propagates towards the interface, (b) dynamic crack propagates behind the stress wave, (c) reflected compressive stress wave from the interface reduces the crack drive force and leads to crack arrest*

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