Letters

Comparison of Residual Stress Effects on the Yielding and Fracture of Metal and Glass Composites

Ease of analysis and experiment encourages the study of the effect of residual stresses on the yielding and fracture characteristics of composite cylinders [1, 2]. Recently each of us participated in such studies, one with glass-glass composites [3] and the other with metal-metal composites [4, 5]. The purpose of this note is to point out how different material characteristics, i.e. the brittle nature of the glass and the ductile nature of the metal, can result in drastically different response to axial loading of composites with similar residual stress states.

The glass composite system was fabricated to allow study of the strengthening effects resulting from cladding. The metal composite system was used in studying the mechanical interactions between two metal components during fabrication and subsequent mechanical loading. Both systems were fabricated at high temperatures, the glass by a fibre-drawing technique [3] and the metal by a diffusion bonding process [4]. Residual stresses are the unavoidable consequence of cooling from fabrication temperatures. The difference between the thermal expansion coefficients of the two components in each system gives rise to triaxial residual stresses at ambient temperatures. Both systems permitted both analytical and experimental determination of such residual stresses. In the glass system, the stresses were predicted by an elastic thermal stress analysis and the axial stress was measured photoelastically [3]. In the metal system, the stresses were predicted by an elastic-plastic thermal stress analysis [4] and all three principal stresses were measured by a modification of the Sachs boring-out method [6].

The elastic and thermal properties of the materials used in the two systems are shown in table I. The predicted residual stress distributions (which were experimentally verified) are presented in fig. 1. While the stress states are not identical, their similarity is clear. If it is assumed that the transverse stresses do not change during subsequent axial loading,* then the residual stress values can be used directly to predict yielding or fracture. Such predictions are shown in table II for two commonly used criteria of yielding or fracture. In the core of both systems, the maximum normal stress and the maximum shear stress (Tresca) criteria both predict premature yielding or fracture. In the cladding, the maximum normal stress criterion predicts an increase in the yield or fracture strength, whereas the Tresca criterion predicts a decrease.

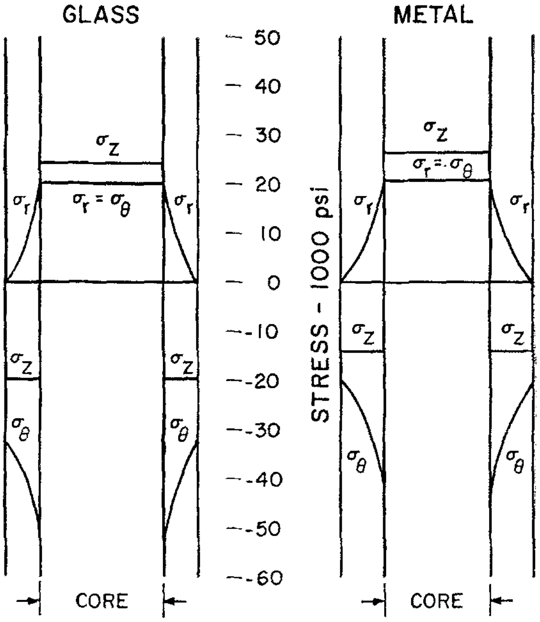

Figure 1 Composite cross-sections showing magnitudes of residual stresses.

The measured "strengthening" (stress at failure of the composite minus stress at failure of a solid cylinder of cladding material) under axial loading, as shown in table II, reveals the correspondence of the magnitude of strengthening of glass with the residual axial compressive stress. This is consistent with the maximum normal stress fracture criterion and results from the sensitivity of glasses to surface flaws [7]. The 4340 steel case component of the metal system, on the other hand, yielded in accordance with the Tresca criterion† [8], showing a decrease

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*Hecker *et al* [4] have shown that the transverse stresses do change during axial loading if plastic deformation occurs. However, such changes are not sufficient to affect the subsequent conclusions.

†The data corresponded better with the von Mises criterion [8]. The Tresco criterion was used here for the sake of mathematical convenience. The maximum difference between the two is 15%.

TABLE I Properties of individual components.

	Glass Core*	Cladding	Metal Core	Case
Material	pyrex†	vycor‡	OFHC Cu	4340 steel
Young's modulus	9.8×10^6 psi	9.7×10^6 psi	16×10^6 psi	28.5×10^6 psi
Poisson's ratio	0.2	0.18	0.34	0.285
Thermal expansion coefficient	$3.2 \times 10^{-6}/°C$	$0.8 \times 10^{-6}/°C$	$16.5 \times 10^{-6}/°C$	$11.7 \times 10^{-6}/°C$
Area fraction	0.444	0.556	0.334	0.666

*Thermal expansion value relates to glassy range, i.e. below the glass transition; in supercooled liquid range, above the glass transition, thermal expansion of pyrex is roughly three times higher than the value given [9].
†Corning Glass Co No. 7740.
‡Corning Glass Co No. 7900.

TABLE II Predicted and observed residual stress corrections to yielding and fracture criteria under axial loading.

System	Core σ_R† MNS*	 Tresca	Cladding σ_R MNS	 Tresca‡	Observed strengthening
Glass	− 24400 psi	− 4200 psi	19500 psi	− 33000 psi	20000 psi
Metal	− 26500	− 5500	14000	− 30000	− 30000

*MNS—maximum normal stress (axial stress under axial loading).
† σ_R represents the correction term to the yield criteria
MNS: $\sigma_1 = \sigma_0 - \sigma_1^r$ where r denotes residual stress and σ_0 is the uniaxial yield or fracture stress.
$\sigma_R = -\sigma_1^r$
Tresca: $\sigma_1 - \sigma_3 = \sigma_0 + (\sigma_3^r - \sigma_1^r)$
$\sigma_R = (\sigma_3^r - \sigma_1^r) = (\sigma\theta^r - \sigma_z^r)$ because at the onset of yielding (after axial load has been applied) $\sigma_{zr} > \sigma > \sigma_\theta$.
‡Taken at the inside diameter.

over the yield strength of the 4340 steel tested by itself. This is a consequence of the fact that yielding of metals is controlled by dislocation motion which is influenced by transverse as well as axial stresses.

Failure of the core of the glass system was unaffected by the residual stresses. It did not fracture until the cladding failed and, hence, increased its fracture strength. This increase was achieved simply because the surface flaws that markedly diminish glass strength were eliminated by the cladding process. The core component of the metal system did yield prematurely in approximate accordance with the Tresca criterion.

In summary, a comparison of our previous results reveals the contrasting effects that similar residual stress states can have on the subsequent yield or fracture behaviour of glass and metal composite cylinders under axial tension. Glass composites were strengthened against brittle fracture by the axial residual stress. On the other hand, the existing residual stress state reduced the resistance of the metal composite to plastic deformation.

Acknowledgements

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Non-Basal Dislocations in GaS Crystals

A detailed study of the nature of non-basal dislocations in GaSe crystals has recently been reported [1, 2] and it is therefore of interest to compare the properties of dislocations and fracture in the crystallographically similar material GaS. GaS is composed of four-fold layers, each layer consisting of two sheets of gallium atoms sandwiched between sheets of sulphur atoms [3]. In view of its layered structure non-basal dislocations may have a significant influence on the anisotropy of the physical and chemical properties of the material [4].

Large single crystals of GaS were grown from the melt by the gradient freeze technique, and thin platelets were also grown from the vapour phase using the iodine transport method [5]. Non-basal dislocations were revealed by etching, for some minutes, in a solution consisting of approximately 5 % bromine dissolved in methanol at room temperature. The good one to one correspondence of etch pits on matching cleaved surfaces is taken as evidence that the pits are of dislocation origin. On vapour grown crystals, pits are also formed at the apex of growth spirals, where screw dislocations are known to be present.

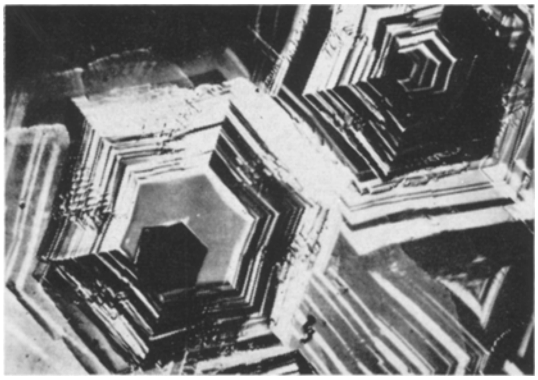

Figure 1 Etch pits in a GaS crystal.

Optical microscopy of etched surfaces reveal well defined hexagonal etch pits (fig. 1). These pits are always bounded by [11$\bar{2}$0] directions, and are to be contrasted with the triangular pits observed in GaSe [1, 2]. This difference is caused by the fact that the etch pit shapes reflect the stacking sequence of the layers in the two materials. In the ϵ and γ modifications of GaSe a layer may be transformed into its neighbouring layer by translational movements alone, while for GaS a rotation of 60° as well as a translation is required. If oxidation produces triangular depressions in each layer (fig. 2), then triangular etch pits are to be expected in GaSe and hexagonal pits in GaS. The situation is analogous to that in the hexagonal and rhombohedral modifications of MoS_2 [6, 7]. It is also apparent that most of the pits are composed of closed hexagonal terraces, and in fact some pits become flat bottomed on prolonged etching. This situation is fairly common in layered structures [2, 8] and may be taken as evidence of the bending of non-basal dislocations within the solid.

The existence of non-basal screw dislocations, of large Burgers vectors, is revealed on cleaved

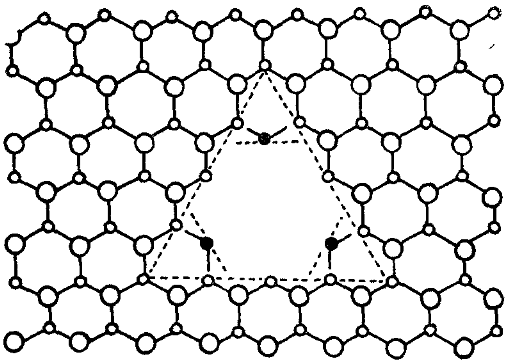

Figure 2 Schematic illustration of the production of hexagonal etch pits in GaS, by the formation of triangular depressions in successive layers. The small circles represent gallium atoms, the large ones denote sulphur. Open circles represent atoms in the top layer and the closed ones atoms in the second year.