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Dynamic Behavior of a Shock-Loaded Glass-Ceramic Based on the $\text{Li}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2$ System

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Abstract: The dynamic behavior of the Robax glass-ceramic based on the $\text{Li}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2$ system has been investigated. The experiments were performed using the planar impact technique in combination with a VISAR interferometer. From the velocity-time profiles the Hugoniot elastic limit σ_{HEL} , spall strength σ_{sp} and strains ε have been calculated. The results are plotted in U_1 - u_p , σ_{max} - ε and σ_{sp} - σ_{max} diagrams and fitted with linear relations. At stresses above 9 GPa the existence of a failure wave in the glass-ceramic is observed.

Résumé: Le comportement dynamique de la céramique de verre Robax basé sur le système $\text{Li}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2$ a été examiné. Les expériences ont été effectuées en utilisant la technique d'impact planaire en combinaison avec un interféromètre VISAR. A partir des profils de vitesse, on a calculé la limite élastique d'Hugoniot σ_{HEL} , la force d'écaillage σ_{sp} , et les contraintes de déformation ε . Les résultats sont contenus dans des diagrammes U_1 - u_p , σ_{max} - ε et des diagrammes σ_{sp} - σ_{max} assortis de relations linéaires. A des niveaux de contrainte supérieurs à 9 GPa l'existence d'une onde d'échec est observée dans la céramique de verre.

1. INTRODUCTION

Glass-ceramics are polycrystalline materials formed by a controlled crystallization of a suitable base glass [1]. The materials based on the $\text{Li}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2$ system have found a wide-spread application and achieved a great economic importance due to the very low thermal expansion coefficient (CTE) and other excellent mechanical properties [2]. Because only very little is known about the dynamic behavior under shock-loading, the glass-ceramic Robax made by the Schott Glaswerke Mainz/Germany has been investigated under shock conditions. Robax is a highly transparent substance with a minimal amount of coloration, depending on the production conditions. The crystallite size is approximately 50 nm. The material has a high mechanical strength and heat resistance [3]. Some technical data are given in Table 1.

Density (ρ_0)	2,56 g/cm ³
Porosity	0%
Young's modulus (E)	92 GPa
Longitudinal sound velocity (c_l)	6570 m/s
Thermal expansion coefficient (CTE)	20-700°C: $0,1 \cdot 10^{-6}/\text{K}$

Table 1: Some technical data of Robax

2. EXPERIMENTAL SETUP

The planar impact technique in combination with a VISAR interferometer [4] have been used to investigate the dynamic behavior of the Robax glass-ceramic under shock-loading. These experiments are frequently used to achieve high pressures, high stresses and high strain rates under well characterized conditions [5]. The 58 mm in diameter and 3 mm thick C45-steel projectile plates have been accelerated to velocities up to 1058 m/s using a single stage gun with 70 mm bore diameter. A thin layer of Aluminum was sputtered on the rear surface of the transparent 50 mm square and 4.82 mm thick Robax target plates to obtain diffuse reflected laser light from the surface. The experimental setup immediately before planar impact is schematically shown in Figure 1. The impact of the projectile plate on the fixed target plate causes elastic and plastic waves. The waves are reflected at the free surfaces back into the materials as pressure release waves. The superposition of the waves inside the target produces tensile stresses, which damages the material. The free surface velocity of the target rear side was measured with a VISAR interferometer.

Figure 1: Schematic experimental setup

From the velocity-time records the Hugoniot Elastic Limit σ_{HEL} was determined according to

$$(1) \quad \sigma_{HEL} = \frac{\rho_0 c_l u_{HEL}}{2}$$

with the density of the Robax material ρ_0 , the longitudinal sound velocity c_l and the amplitude of the elastic precursor u_{HEL} . The spall strength σ_{sp} is determined from the relation

$$(2) \quad \sigma_{sp} = \frac{\rho_0 c_l \Delta u_{sp}}{2}$$

with the pull back signal Δu_{sp} . The maximum stress σ_{max} was calculated using

$$(3) \quad U_s = \frac{c_l}{\left(\frac{1 + c_l \Delta t}{d_T} \right)}$$

$$(4) \quad \sigma_{max} = \frac{\rho_0 (c_l u_{HEL} + U_s (u_{max} - u_{HEL}))}{2}$$

where U_s is the shock velocity, d_T the target thickness, Δt the time interval between elastic and plastic wave and $u_{\max}$ the maximum velocity. The maximum strain $\epsilon_{\max}$ and strainrate $\dot{\epsilon}$ are calculated using

$$(5) \quad \epsilon_{\max} = \left(\frac{u_{\text{HEL}}}{2c_1} \right) + \left(\frac{u_{\max} - u_{\text{HEL}}}{2U_s} \right)$$

$$(6) \quad \dot{\epsilon} = \left(\frac{u_{\max} - u_{\text{HEL}}}{2U_s \Delta t_1} \right)$$

with the time interval between the elastic and plastic wave Δt_1 .

3. EXPERIMENTAL RESULTS AND DISCUSSION

A total of 22 impact experiments with impact velocities $103 \text{ m/s} < v_0 < 1058 \text{ m/s}$ were carried out with the Robax glass-ceramic material. Typical free surface velocity-time histories measured with the VISAR interferometer at different impact velocities are given in Figure 2.

Figure 2: Velocity-time histories for Robax

The curves show an elastic precursor yielding a low Hugoniot elastic limit σ_{HEL} of $900 \pm 150 \text{ MPa}$ which is followed by a further increase due to the plastic wave. Robax shows clear spall signals and in some cases

the so called ringing in spall occurred. Figure 3 shows the spall strength (σ_{sp}) versus stress (σ_{max}) diagram. A linear least square fit yields

(7)
$$\sigma_{sp} = -0.45 \pm 0.24 + 0.65 \pm 0.06 \sigma_{max}$$

Figure 3: Spall strength-stress diagram

The relationship between the shock velocity (U_s) and the particle velocity (u_p) is graphically shown in Figure 4. The data set can be described by a linear regression

(8)
$$U_s = C_0 + Su_p$$

where C_0 is 5377 ± 70 m/s and S is -0.52 ± 0.15 m/s.

Figure 4: Shock velocity vs. particle velocity diagram

The maximum stress -strain loading behavior of the Robax glass-ceramic is depicted in Figure 5 and the relation is fitted with a linear regression by

(9)
$$\sigma_{max} = 0.65 \pm 0.11 + 0.62 \pm 0.01 \epsilon$$

Figure 5: Stress-strain diagram

From the velocity time histories (Figure 2) it can be seen that at pressures above 9 GPa no spallation was observed. Instead two significant steps appear in the velocity history of test rob773 at 500ns and 600ns respectively. The nature of the small velocity decrease that accompanies the second step is not understood at present. The two steps in the velocity profile can be interpreted as a failure wave propagation in the Robax glass-ceramic. The existence of failure waves in glass under uniaxial conditions is reported by Kanel et al. [6], Raiser and Clifton [7] and Brar et al. [8]. Nahme et al. [9] assume a failure wave in porous Si_3N_4 . Kanel et al. presume that the failure wave is a network of cracks initiated by the compression.

Figure 6: Lagrangian X-t diagram and velocity-time curve of shot rob773 showing elastic, plastic and failure waves

Figure 6 shows the Lagrangian X-t diagram for test rob773. It can be seen that first the elastic wave arrives at the rear surface of the material and produces an increase in the velocity. The elastic wave is reflected back from the surface as a release wave. Immediately after the elastic wave is reflected, the slower plastic waves appear and cause a rapid jump in the velocity profile. The elastic release wave is reflected at the failure wave effecting the increase in the velocity around 500 ns. The failure wave damages the material before tensile stresses due to the superposition of release waves can occur. Because of this, no spall signal can be observed in the velocity profiles at the experiments above a stress of 9 GPa.

4. CONCLUSION

Using the planar impact technique in combination with a VISAR interferometer, the shock wave propagation in the transparent Robax glass-ceramic based on the $\text{Li}_2\text{O-Al}_2\text{O}_3\text{-SiO}_2$ system was studied. The Hugoniot Elastic Limit σ_{HEL} was determined to be 900 ± 150 MPa. From the velocity-time histories of the VISAR measurements $U_s - u_p$, $\sigma_{\text{max}} - \varepsilon$ and $\sigma_{\text{sp}} - \sigma_{\text{max}}$ diagrams have been plotted. Above a stress level of 9 GPa a failure wave occurs in the Robax glass-ceramic and therefore no spall signals can be observed in the velocity history profiles.

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