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FINITE ELEMENT ANALYSIS OF FUNCTIONALLY GRADED MATERIAL TO REDUCE CRAZING IN TRANSPARENT ARMOR

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14. ABSTRACT

The overall goal of this particular study was to provide proof of concept through modeling and simulation to predict the impact of a functionally graded material (FGM)-based target on the shockwaves generated from an impactor. Most armor systems are comprised of a single material or a composite layup of several materials. The intent of this study was to provide insight into the effectiveness of morphed microstructure consisting of a glass and transparent ceramic FGM.

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INTRODUCTION

Goals, Scope, Status, and Prior Work

The goal of this effort is to support the development of novel transparent armor systems based on functionally graded materials (FGM) through modeling and simulation. One requirement of transparent armor is that it must maintain its transparency after multiple projectile hits. For this to be successful, the base material must be resistant to crazing or cracking. Crazing and cracking are partially the products of the buildup of hydrostatic tensile stresses within the material (ref. 1). On impact, the material must disperse tensile stress waves created during projectile impact.

In the models developed, the FGMs are tested based on alumina and glass [calcium oxide (CaO)- zirconium dioxide (ZrO2)-silicon dioxide (SiO2)]. The FGM was developed using varying concentrations of each material from 100 to 0% end to end. The hypothesis adopted for this analysis is that varying the concentration will affect the microstructure of the FGM, such that tensile shock waves created during projectile impact will dissipate and decrease as they travel through the thickness of the FGM.

A related piece of work prior to this report is the glass ceramic FGM report. This report showed a one-dimensional model where particle distribution was introduced instead of layers. An impactor was used instead of displacing surface nodes.

BRIEF CONCLUSIONS

The FGM breaks up the reflecting pressure wave as shown in figure 1, but the highest tensile wave that was found on the impact surface was not attenuated compared to the control model. A possible solution would be to modify the impact surface zone by changing from a 100% pure material at the surface to a composite material in order to disperse the surface tensile wave.

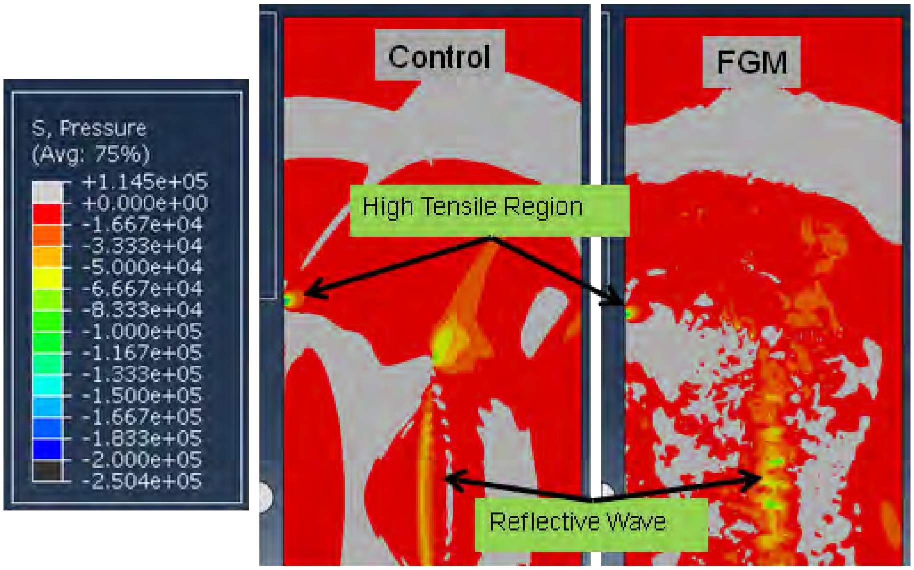


Figure 1
Pressure plot

METHOD

Model Information, Procedures, and Possible Errors

General purpose finite element software ABAQUS Explicit 6.12 (ref. 2) was used to simulate projectile impact into the FGM. The FGMs with varying distributions of alumina and CaO-ZrO2-SiO2 were developed using the Digimat composite modeling software. In Digimat, several three-dimensional (3D) FGMs were created with varying particle density to create the gradient.

The ABAQUS analyses were dynamic with nonlinear materials and nonlinear geometry. All the parts were modeled as deformable elements using S4R and S3R [quadrilateral 4-node and 3-node stress/displacement (S) plane strain shell elements with reduced (R) integration and hourglass control] plane strain elements with reduced integration and hourglass control. Friction is assumed negligible and set to 0.0. All contact surfaces as well as the particles and matrix shared nodes forming a perfect bond. Damping was set to 2% alpha, and the initial conditions consisted of giving the impactor a velocity of 24,000 in./sec.

Assumptions

A two-dimensional (2D) plane strain assumption was used in the ABAQUS analyses to reduce computational cost. The 3D unit cell with varying particle concentrations through the thickness of the part were imported from Digimat and converted to 2D. The sides of the unit cell were used to create the 2D model. These sides were repeated to widen the amount of glass simulated. This distance was increased to reduce the effect of shock waves reflected from the sides, such that they would not interfere in the results. Figure 2 depicts the 3D and 2D unit cells.

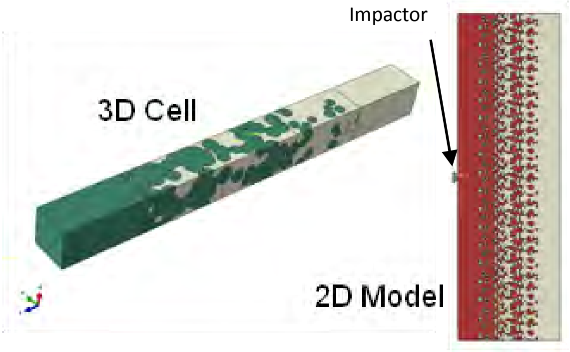


Figure 2
3D Digimat unit cell and 2D plane strain model for ABAQUS

The material properties for alumina and CaO-ZrO2-SiO2 were taken from reference 3. The particles created with Digimat are assumed to be ellipsoids with aspect ratios of 1, they were randomly oriented in the matrix, and they can interpenetrate each other. The graded material is as follows: 100%/0% glass/alumina, 80%/20% glass/alumina, 50%/50% glass/alumina, 20%/8% glass/alumina, and 0%/100% glass/alumina. There are no voids in the model and there is perfect bonding between the matrix and the particles. Material alpha damping was assumed to be 2%.

A rigid impactor was used to create the stress waves. The impactor shape, size, and velocity were selected to create clear stress waves, which are also shown in figure 2.

Parts and Instances

The impactor in figure 2 shown in green was modeled as a hemisphere with a radius of 0.5 in. The FGM target was 5 in. thick and 16 in. tall. A control system consisting of 50%/50% glass/alumina was also modeled with the same dimensions to show impact of varying the internal microstructure with the FGM. Both the control and functionally graded assemblies are one part with two materials assigned [(fig. 3) CaO- ZrO2-SiO2 shown in red, alumina shown in tan].

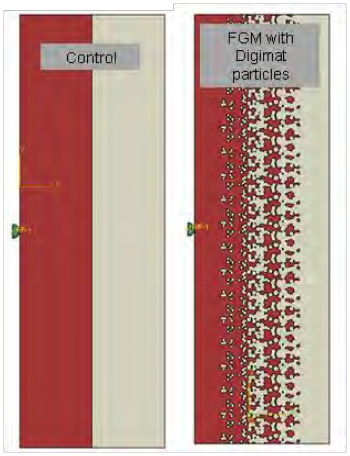
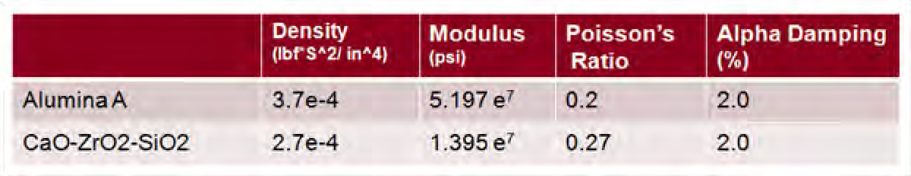


Figure 3
Control and FGM models

Material Properties

In order to capture acoustic wave movement correctly, linear elastic constants were used (table 1). A damping of 2% was applied in order to capture the natural damping of the material. The properties were recorded (ref. 2).

Table 1
Material properties



	Density (lbf*S^2/ in^4)	Modulus (psi)	Poisson's Ratio	Alpha Damping (%)
Alumina A	3.7e-4	$5.197\ e^{7}$	0.2	2.0
CaO-ZrO2-SiO2	2.7e-4	$1.395\ e^{7}$	0.27	2.0

Interactions and Constraints

Contact friction between the impactor and FGM target was assumed to be 0.0. Initial velocity of the impactor was 24,000 in./sec; this value was chosen to create strong acoustic waves. Symmetry boundary conditions (fig. 4) were applied to the top and bottom of the FGM target to capture a fixed boundary.

Figure 4
Boundary conditions

RESULTS

Tensile Pressure (psi)

The field output that most readily shows the difference between the control and FGM target is tensile pressure. Both materials in the target being ceramic based, the micro-cracking and spall of the target will be very sensitive to the material as it undergoes tension loading. The highest tensile region observed appears to be the same in both the FGM and the control targets as shown in figure 5. Light gray represents pressures from internal compressive waves generated. Figures 6 and 7 show the progression of the stress wave through the target. The wave reflected from the back surface is dispersed in the FGM material, but the surface tensile wave is not attenuated.

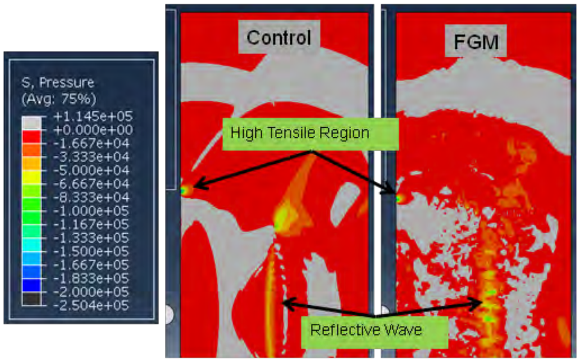
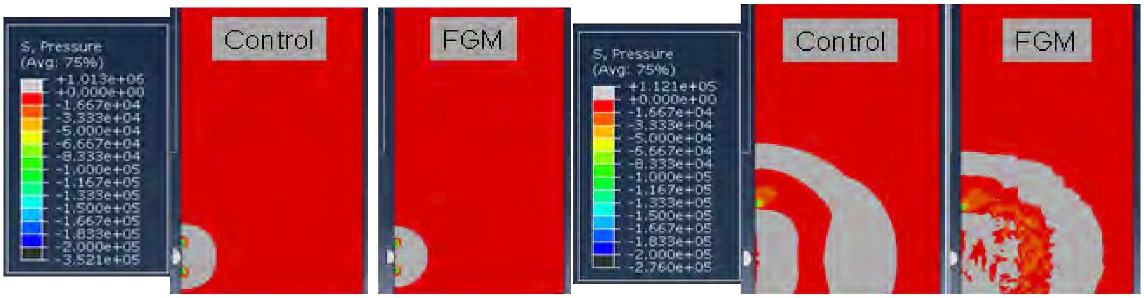


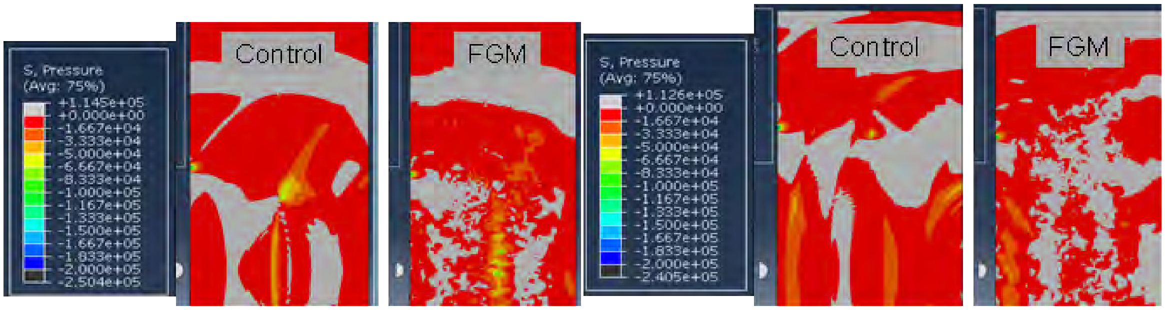
Figure 5
Pressure results (time = 23.47 µs)



(a)
3.21 µs

(b)
12.27 µs

Figure 6
Pressure results 1



(a)
23.47 µs

(b)
31.47 µs

Figure 7
Pressure results 2

CONCLUSIONS AND PATH FORWARD

The overall goal of this particular study was to provide proof of concept through modeling and simulation to predict the impact of a functionally graded material (FGM)-based target on the shockwaves generated from an impactor. Most armor systems are comprised of a single material or a composite layup of several materials. The intent of this study was to provide insight into the effectiveness of morphed microstructure.

Qualitatively, results suggest that a target with varying microstructure and particle density breaks up a shockwave more effectively than a homogenous target. The particles appear to effectively break up and minimize pressure build up from reflecting waves created in the structure as well. However, there appears to be little or no effect on the surface tensile wave. This is likely because at the surface both targets are identical. The potential impact of high tensile stresses on the surface is crazing. One potential solution would be to vary the composition at the impact surface as well rather than start off with 100% of a single material. The particles and microstructure may help disperse the surface wave and reduce the tensile stresses at the impact surface.

Future work proposed includes modifying the surface layers to have some particles at the impact surface and varying the particle distributions, shapes, and sizes. Other potential studies will include adding voids, validating models against actual penetration tests, and defining failure criteria for the FGM matrix.

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