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HEAT TRANSFER AND THERMAL STRESS ANALYSES OF A GLASS BEAM DUMP*

INTRODUCTION

Today's new generation lasers require durable beam dumps which can absorb large amounts of energy while remaining structurally sound. This report analyzes a full scale model of one particular laser glass beam dump which tends to fail in small scale experiments. In these small scale experiments, the laser causes plasma formation on the front face of the beam dump, material spalling off of the back face, and cracking and cloudiness within the glass. This damage is more prevalent when the beam dump has been shot a number of times with the laser. While many phenomena are taking place within this beam dump, this report focuses solely on thermal effects - whether the thermal effects of laser deposition on the full-scale glass beam dump will cause failure within the glass.

PROBLEM SPECIFICATIONS

A schematic representation of the glass beam dump is shown in Figure 1. The laser is incident on the front face of the glass beam dump with the energy of 20 KJ for a time length of 5 nsec. It is assumed that the area of the front face exposed to the laser is 9 cm by 9 cm square and that the laser intensity is uniform along the front face except at the 1 cm border where the energy drops linearly to zero. Thus, the laser intensity is approximately 250 J/cm^2 at the front face, ignoring the linear decline in energy at the border. It is also assumed that the laser attenuates from full intensity at the front face to 1% of full intensity at the back face by the formula:

$$I = I_0 e^{-\alpha y} \quad (1)$$

where I equals the intensity, I_0 is the maximum intensity at the front face (250 J/cm^2), y is the distance from the front face and α is the absorption coefficient. At the front face of the glass beam dump, three of the four sides of the laser-exposed area are surrounded by a border of unexposed glass. Dimensions of the block are variable with the constraint that the block should be as small as possible and provided all of the above specifications are met. For the first case, the dimensions of 10 cm by 11 cm by 10 cm were chosen such that the border of unexposed glass mentioned above is 1 cm wide. This implies that α , the absorption coefficient, is equal to 0.4605 cm^{-1} by solving equation 1. The dimensions of 10 cm by 11 cm by 100 cm were chosen for the second case, keeping the border of unexposed glass at 1 cm wide and varying only the length of the block (the dimension which is parallel to the direction of the laser). For case 2, α equals 0.046 cm^{-1} .

HEAT TRANSFER ANALYSIS

The heat transfer of this glass beam dump was calculated using TOPAZ3D (Ref. 1), a three dimensional finite element heat transfer code. Table 1 lists the thermal material properties used for the TOPAZ3D analysis. Because the range of temperatures is small, constant properties were assumed. Figure 2 shows the mesh model of the glass beam dump created using the program, INGRID (Ref. 2) - a three dimensional mesh generator. Only half of the block was modeled, taking advantage of the plane of symmetry (see Figure 2). The zoning of the mesh was carefully chosen to mimic the linear decline in energy along the 1 cm border and thus the mesh was finer in the regions of the glass block which experienced the highest gradient in temperature due to the laser. It was assumed that the glass block was in a vacuum with the boundary condition of thermal radiation to the ambient (at a temperature of 300 K) from all outer surfaces of the block. The laser was represented as a variable volumetric internal heat generation rate within the glass block, a rate which began instantaneously at 0 seconds and ended instantaneously at 5 nsec. 2178 nodes and 1700 elements were used and the total problem time was set at 1 hour.

For case 1, the resultant temperature fields calculated by TOPAZ3D at 5 nsec. are shown in Figure 3. At the front face, there is a uniform rise in temperature of 54 K (for a total temperature of 354 K) in the area exposed to the laser except at the 1 cm border. The temperature at this border drops linearly from 354 K to 300 K (or no temperature rise). The area of unexposed glass at the front face sees no rise in temperature. At the side face cross-section (the block is sliced down the middle revealing the central side plane - the laser is incident to the right edge), the temperature rise declines exponentially from right to left (from the front face to the back face) as expected.

The resultant temperature fields at 5 nsec for case 2 are shown in Figure 4. The trends of temperature rise in case 2 follow the same trends as in case 1, the only difference being that the magnitude of temperature rise is reduced by a factor of 10.

Temperature time history plots for selected nodes on the front and back faces (case 1) are shown in Figure 5. Node A is located at the center of the area exposed to the laser on the front face. The node sees a temperature rise of 54 K within 5 nsec, then that temperature rise falls with time as the effects of conduction and radiation dissipate the heat. Nodes B and D are located at two different midpoints on the 1 cm border of the front face where the laser energy drops off linearly. These two nodes see a temperature rise of about 27 K within 5 nsec which is half of the temperature rise of node A, revealing that temperature rise, too, drops off linearly along the 1 cm border.

The overall temperature rise of the front face as calculated by TOPAZ3D is significantly close to the predicted temperature rise of 53 K, calculated by assuming conservation of energy on the glass block.

THERMAL STRESS ANALYSIS

The thermal stress of the glass beam dump was calculated using NIKE3D (Ref. 3), a three-dimensional finite element code for solid and structural mechanics. Table 2 lists the material properties used for the NIKE3D analysis. Constant properties were

assumed. The same mesh model as in the TOPAZ3D analysis was used including the same zoning of the mesh (see Figure 2). The temperatures calculated by TOPAZ3D were used as input for NIKE3D.

The resultant principal stresses at 5 nsec for case 1 are shown in Figure 6. On the front face, the maximum thermal stresses lie on the outer edge of the 1 cm border and range from 9.1 MPa to 22 MPa (1300 psi to 3200 psi). The contours on the left side face reveal that this high range of stress extends to about 2 cm below the surface of the front face. The principal stresses at 5 nsec for case 2 are significantly less (see Figure 7), ranging from 1.4 MPa to 3.8 MPa (200 psi to 550 psi). This lower range of stress extends to about 20 cm below the surface of the front face (see Figure 7 - Left Side Face).

Figures 8 and 9 show the deformation of the glass block due to thermal effects for cases 1 and 2, respectively. A two-dimensional view of the deformation of the front face is to the left (in both figures), and a three-dimensional view of the total deformation is on the right. Although these deformations are scaled up by a factor of 1000, case 1 clearly undergoes much more deformation than case 2 where the deformations are barely noticeable. These deformations qualitatively reveal the large amount of stress that the beam dump undergoes for case 1 as compared to case 2.

The stresses and displacements calculated by NIKE3D are reasonably close to predicted values, calculated by assuming that the glass beam dump was constrained. Of course, it was assumed that the beam dump was unconstrained for the NIKE3D analysis.

CONCLUSION

The thermal effects of laser deposition on a glass beam dump were analyzed, and temperatures and thermal stresses were calculated using the finite element analysis codes, TOPZ3D and NIKE3D. But the question remains, do these thermal effects cause failure within the glass beam dump?

Many types of glass can usually withstand a maximum principal stress of around 10 MPa or 1500 psi (Ref. 5). The maximum principal stress in case 1 is about twice this figure signifying that the laser glass beam dump probably cannot withstand this high amount of thermal stress. Fractures and cracks within the glass will possibly occur. However, case 2 reveals that by lengthening the beam dump by a factor of 10, thermal stress is significantly reduced. Even though this laser glass has a lower fracture toughness than other types of glass¹, it can probably withstand the maximum principal stress of 3.8 MPa (550 psi) as seen in case 2. Thus the longer the length of the beam dump, the more likely the beam dump will withstand thermal stress (keeping in mind the assumption that the absorptivity coefficient, α , also varies with length),² and the less likely that the glass will fail due to thermal effects.

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1. The fracture toughness of this glass beam dump (laser glass - 750 phosphate) is $0.4 \text{ MPa} \cdot \text{m}^{1/2}$ (Ref. 4), while the fracture toughness of many other types of glass is around $1 \text{ MPa} \cdot \text{m}^{1/2}$ (Ref. 5). Since the fracture toughness of this laser glass is less than 1, the maximum principal stress for the laser glass will most likely be less than 10 MPa (1500 psi) - the ball park figure for the maximum principal stress of many other types of glass.
 2. Note that varying the height or the width of the beam dump has very little effect on the temperature gradients and thermal stresses within the glass. This is because the laser shot lasts for only 5 nsec - too short of a period of time for the heat to be effectively dissipated throughout the unexposed area of the glass.

Table 1.
Material Properties used in the TOPAZ3D analysis.

Laser Glass - 750 Phosphate (Ref. 3)

Specific Heat at Constant Pressure	C_p	685	$J / (kg \cdot K)$
Thermal Conductivity	k	0.647	$W / (m \cdot K)$
density	ρ	2861	kg / m^3

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Table 2.
Material Properties used in the NIKE3D analysis.

Laser Glass - 750 Phosphate (Ref. 3)

Young's modulus	E	4.78×10^{10}	Pa
Poisson ratio	σ	0.268	
Thermal expansion coefficient	α	1.30×10^{-5}	K^{-1}
density	ρ	2861	kg / m^3

- Laser is incident to the front face.
- The entire hatched area represents the area exposed to the laser.
- The cross-hatched area represents the 1 cm border where the laser energy drops linearly to 0.

Figure 1.

Schematic representation of the glass beam dump and laser.

For case 1, the block dimensions are: width = 10 cm, height = 11 cm, length = 10 cm.
 For case 2, the block dimensions are: width = 10 cm, height = 11 cm, length = 100 cm.

Figure 2.

Mesh model of the glass beam dump.

The top mesh model shows the part of the beam dump exposed to the laser (on the left) exploded from the unexposed part (on the right).

Front Face:

Contour Values

A = 300
B = 318
C = 327
D = 337
E = 346

Side Face Cross-Section:

Contour Values

A = 305
B = 310
C = 316
D = 322
E = 327
F = 333
G = 344
I = 350

← Laser

Figure 3.

Contours of Temperature (Kelvin) at 5 nsec for case 1.

Block Dimensions: 10 X 11 X 10 cm.

Maximum Temperature = 354 K & Minimum Temperature = 300 K (ambient).

Front Face:

Contour Values

A = 301
B = 302
C = 303
D = 304
E = 305

Side Face Cross-Section:

Contour Values

A = 301
B = 302
C = 303
D = 304
E = 305

Figure 4.

Contours of Temperature (Kelvin) for case 2.

Block Dimensions: 10 X 11 X 100 cm.

(Note that the length of the block in the y-direction is scaled down by a factor of 5).

Maximum Temperature = 305 K & Minimum Temperature = 300 K (ambient).

Figure 5.
Temperature time history plots for selected nodes - case 1.

Front Face:

Contour Values

A	=	-1.81
B	=	0.923
C	=	3.66
D	=	6.39
E	=	9.13
F	=	11.9
G	=	14.6
H	=	17.3
I	=	20.1

Left Side Face:

Contour Values

A	=	-1.81
B	=	0.923
C	=	3.66
D	=	6.39
E	=	9.13
F	=	11.9
G	=	14.6
H	=	17.3
I	=	20.1

← Laser

Figure 6.
Contours of Maximum Principal Stress (Megapascals) for case 1.
Block Dimensions: 10 X 11 X 10 cm.
Overall Maximum Principal Stress = 22 MPa. (3200 psi)

Front Face:

Contour Values

A	=	-0.529
B	=	-0.037
C	=	0.454
D	=	0.946
E	=	1.44
F	=	1.93
G	=	2.42
H	=	2.91
I	=	3.40

Left Side Face:

Contour Values

A	=	-0.529
B	=	-0.037
C	=	0.454
D	=	0.946
E	=	1.44
F	=	1.93
G	=	2.42
H	=	2.91
I	=	3.40

Figure 7.

Contours of Maximum Principal Stress (Megapascals) for case 2.

Block Dimensions: 10 X 11 X 100 cm.

Overall Maximum Principal Stress = 3.8 MPa (550 psi).

$t = 0$ sec:

$t = 5$ nsec:

Figure 8.
Glass beam dump deformation due to thermal effects for case 1.
The displacements are scaled up by a factor of 1000.

$t = 0$ sec:

$t = 5$ nsec:

Figure 9.

Glass beam dump deformation due to thermal effects for case 2.

The displacements are scaled up by a factor of 1000.

(Note that the length of the block in the y-direction is scaled down by a factor of 5).

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