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Analysis of thermal stability of fused optical structure

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ABSTRACT

Large glass mirror pieces made by fusing smaller pieces together are susceptible to shape changes from glass removal in finishing operations and from temperature changes due to differences in thermal expansion within the mirror. A method of predicting the size and shape of these changes using the finite element method of computer simulation is described. The method is verified by comparison to measurements on 2 glass samples.

1. INTRODUCTION

Large optical elements made by fusing together smaller components are susceptible to small step changes in material properties at the component interfaces. These can add to the small distortions due to residual stress release when mirror components are cut or drilled for support connections. Even after annealing, glass components can contain residual stresses due to very small material inhomogeneity. The combined effects of differences within each piece of glass and differences between pieces of glass are large enough that mirror finishers may want to include adjustments for these effects in their procedures.

This paper describes an approach that enables glass manufacturers and/or mirror finishers to predict the size and shape of the distortions seen during drilling or cutting and during heating or cooling. The method works if the very small variations in the coefficient of thermal expansion (CTE) can be quantified as they are for ULE glass.

To evaluate the importance of these effects and our ability to predict and adjust for them, computer simulations were made of the thermal distortions of two samples made from pieces of Corning's ULE glass. Measured variations in CTE within pieces and from piece to piece were input and the distortions for uniform temperature changes and for drilling a large blind hole were predicted. Both axial and radial variations within each piece were included in the simulation. The finite element method (FEM) of computerized structural analysis was used to do these simulations. Studies were made to determine if using average CTE values for each piece of glass would be accurate enough or if the variability within each piece needed to be included in the model. These computer simulations were validated by comparing their results to measured distortions on the samples.

2. MEASUREMENTS

The measurements were performed by Contraves Inc.[1]. They were done by polishing one surface to a spherical radius (182 cm) and measuring surface contours using an interferometric technique. The measured surface was intended to be a $1/10^{th}$ wavelength surface (for 633 NM wavelength light) and was measured to be just slightly better than that. Several different hole drillings and thermal changes were performed on the 2 samples and the surface shapes were measured.

The geometries of the two sample pieces are shown in Figures 1 & 2. The first piece is a disk, 14" in diameter and 4" thick, made by fusing together two thinner glass disks. The second piece is a disk, 18" in diameter and 4" thick, made by fusing together 3 pieces of glass each shaped like a piece of pie. Measurements were made on sample 1 for 9 different conditions and on sample 2 for 7 different conditions.

A typical set of experimental surface contours is shown in Figure 3. The peak (0.072) and valley (-0.116) values indicate a total difference of 0.188 wavelengths or 119 nanometers (0.119 microns). For this set of contours, Figure 4 shows the surface height along four radial lines plotted against radial position. Since the surface was measured to be slightly better than a tenth wavelength, all measurements should be considered accurate to no more than this 0.0633 micron value. Experimental changes that produced changes of this amount or less were not simulated. A typical measurement sequence was as follows:

measure surface at room temperature (23.3C)

drill hole in back of sample and remeasure surface

cool to freezing (0C) and remeasure

There were differences of several degrees between the cold temperatures in different sequences.

3. FINITE ELEMENT MODELING

Finite element computer models of the 2 samples were generated and analyzed for surface distortions during six different process changes. The FEM meshes for the two samples are shown in Figures 5 and 6. The two material sample could be modeled as a body of revolution so only a radial slice needed to be modeled. The entire three material sample had to be modeled. The ANSYS[2] commercial FEM software running on a VAX 6520 was used to perform the analyses.

The CTE was measured at 8 radial and 18 axial locations for each piece of glass used to form the samples. Previous studies have shown that this material varies radially and axially but not circumferentially. The measured CTE values were used to define values for each of the individual elements in the mesh. Figure 7 shows the 2 material mesh with the CTE values indicated for each element. The models were also run with the average CTE for each piece assigned to all the elements of the piece. This makes for a simpler and faster analysis but may be less accurate.

The finite element software used does not permit removing elements in the middle of an analysis. Therefore drilling out glass was simulated by having the elements being removed undergo a material phase change that lowered the elastic modulus from 10 million psi to 10 psi. Figure 8 shows this change. These elements remain in the model but become 1 million times more flexible. Therefore, any stresses in them disappear and any constraints they were applying to the rest of the model are removed. The temperature sequence for a typical simulation is as follows:

1000C	stress free at annealing point
23.31C	cooled to room temperature to create residual stresses
23.29C	cooled extra 0.02C for phase change simulating drilling
0C	cooled to near freezing to simulate temperature change

To see the effects of a particular change, the distortion values before the change were subtracted from the values after the change. Figures 9 and 10 show typical FEM results for the two samples.

4. RESULTS

Table I lists the measured and two predicted distortion values (peak to valley) for 6 different conditions. The error values are [(predicted - measured)/measured]x100%. Because of differences in defining the reference surface, there is no direct comparison between individual FEM and measured contours. However, they both should predict the same total distortion values and show the same general shape. A comparison of Figures 4 and 9 indicates that, for this condition, both the measurements and the FEM predict a slightly concave surface with a dimple over the top of the hole. The methods agree in shape as well as amplitude.

FEM accuracy depends on several factors including having an accurate model geometry, an accurate description of the material properties, a fine enough mesh density and an accurate representation of the loads and constraints. The geometry modeled has one main difference from the measured geometry: the spherical surface was not included in the model. This results in the model having more material left above the holes than the actual samples did and should make the model stiffer. The elastic modulus value used is accurate to only 1%; the temperatures used to simulate the measurements are accurate to only a few percent. Representing a continuously varying CTE by a set of discrete values, see Figure 11, also introduces errors. More detailed measurements of CTE and finer meshes would improve the model.

In 5 of the 6 conditions studied, using the average CTE values for each piece gave less accurate FEM results. For some conditions the difference is small, but for others it is quite large.

In addition to distortions, the FEM predicts stresses within the samples. The residual stress levels for these two samples are less than 200 psi. The residual stresses are about the same for all conditions predicted indicating that they are created during the cooling from annealing to room temperature and not during any subsequent finishing operation.

5. CONCLUSIONS

Given the mesh size based on the amount of CTE data, the simplification of the geometry, the temperature variability, and the small size of the changes being modeled; the FEM predictions generally agree with the measured values. While an average error of 14% may not sound very good, for a FEM simulation with the material details involved it is quite good.

These simulations indicate that using the average CTE value for each piece of glass can lead to significantly less accurate results. This is true because the drilling operations modeled leave thin layers of glass that may have properties significantly different from the average.

This study indicates that FEM simulations can be used to predict the performance of mirrors and components made from several smaller pieces of ULE. For glass manufacturers this technique holds more value than just a tool to predict performance of existing glass samples. It can be used to predict performance before pieces of glass are fused together and lead to better matching of pieces for creating mirrors. It is another step toward better mirrors and improved material utilization.

6. REFERENCES

1. Contraves Report TR-27820, Aug., 1990 (proprietary)

2. ANSYS User's Manual, Swanson Analysis Systems Inc., 1991

TABLE I

Measured and Predicted Glass Surface Distortions

Condition	Measured (NM)	Predicted by FEM: Average CTE (NM)	Average CTE (% ERR)	Detailed CTE (NM)	Detailed CTE (% ERR)
Two material sample					
smaller hole; warm	70	45	-36	87	24
smaller hole; cold	87	151	74	188	116
Two material sample					
larger hole; warm	60	52	-13	55	-8
larger hole; cold	119	121	2	119	0
Three material sample					
smaller hole; warm	169	2068	1124	139	-18
smaller hole; cold	220	2095	852	154	-30

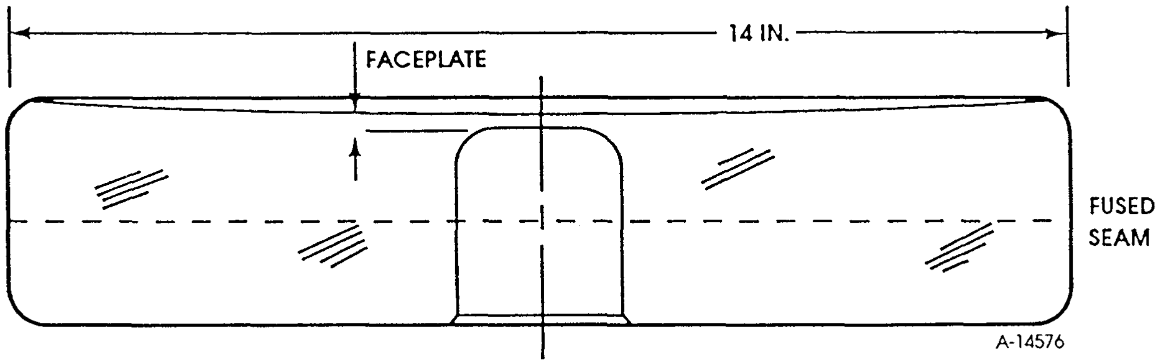

FIGURE 1. Geometry of the two material sample

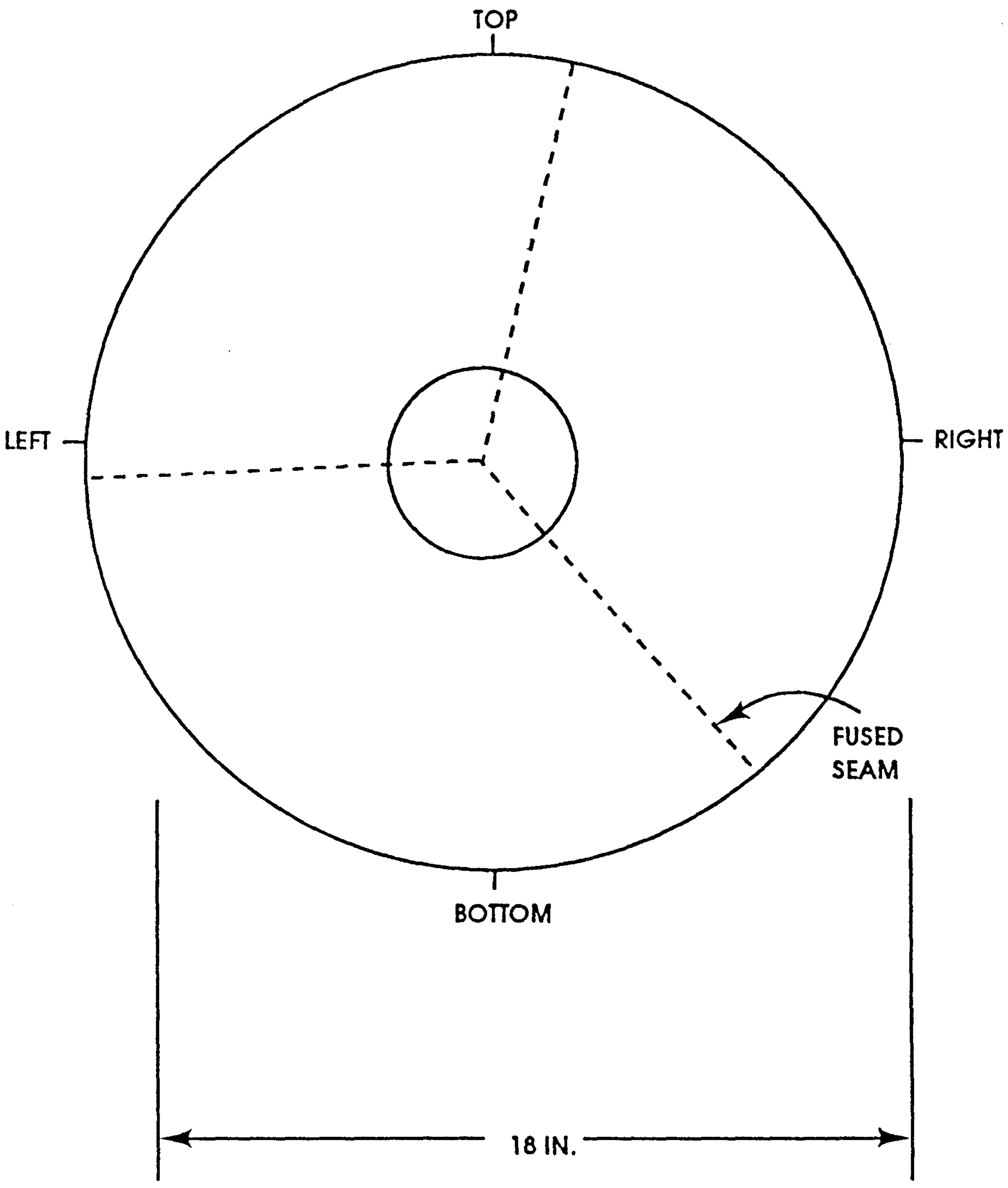

FIGURE 2. Geometry of the three material sample

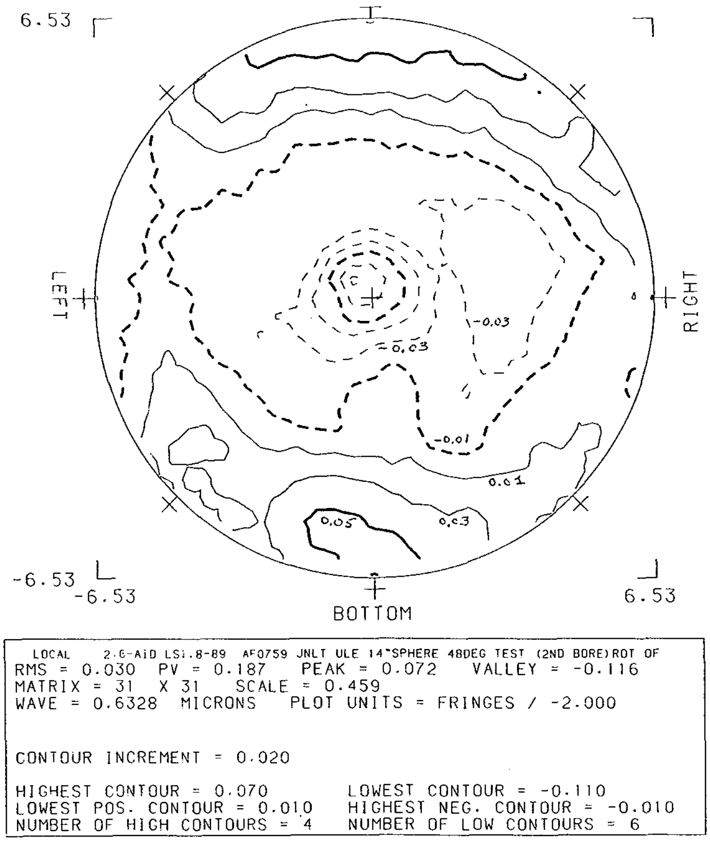

FIGURE 3. Measured surface contours; two material sample with 1.625" radius hole 3.5" deep and cooled to freezing.

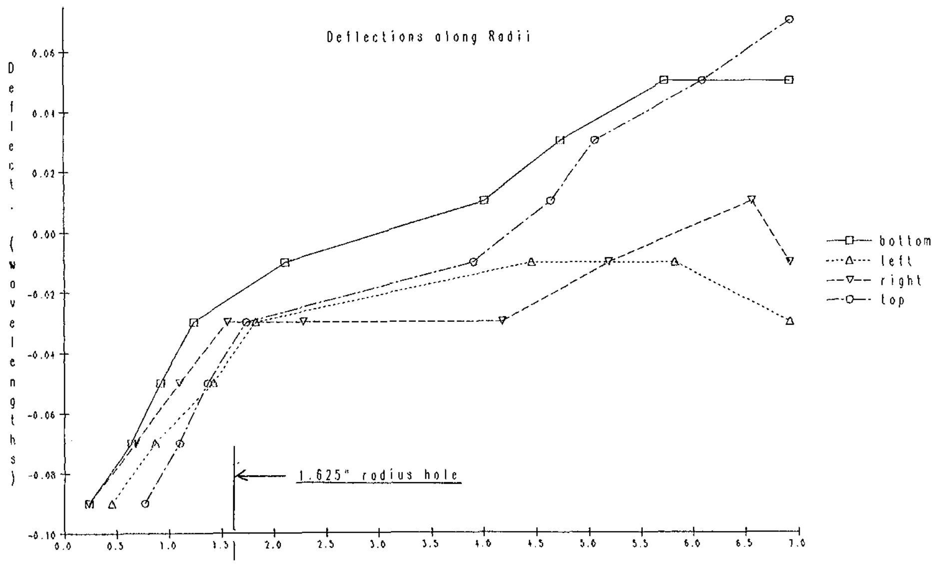

FIGURE 4. Surface distortion values along 4 different radial lines for the contours shown in Figure 3.

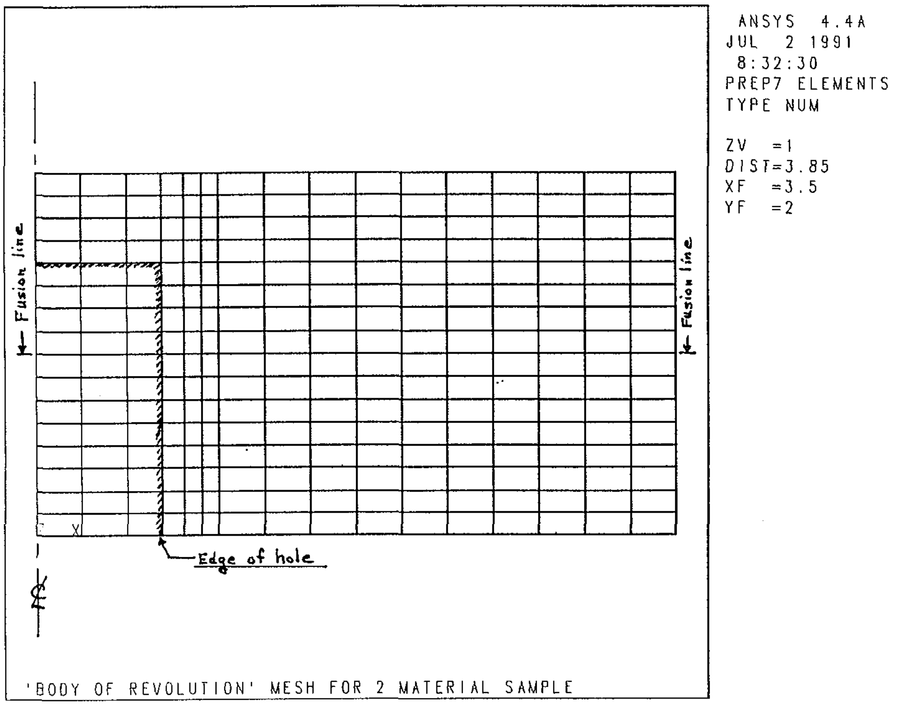

FIGURE 5. FEM mesh for the two material sample; the mesh is a radially slice from the center line to the edge for this body of revolution

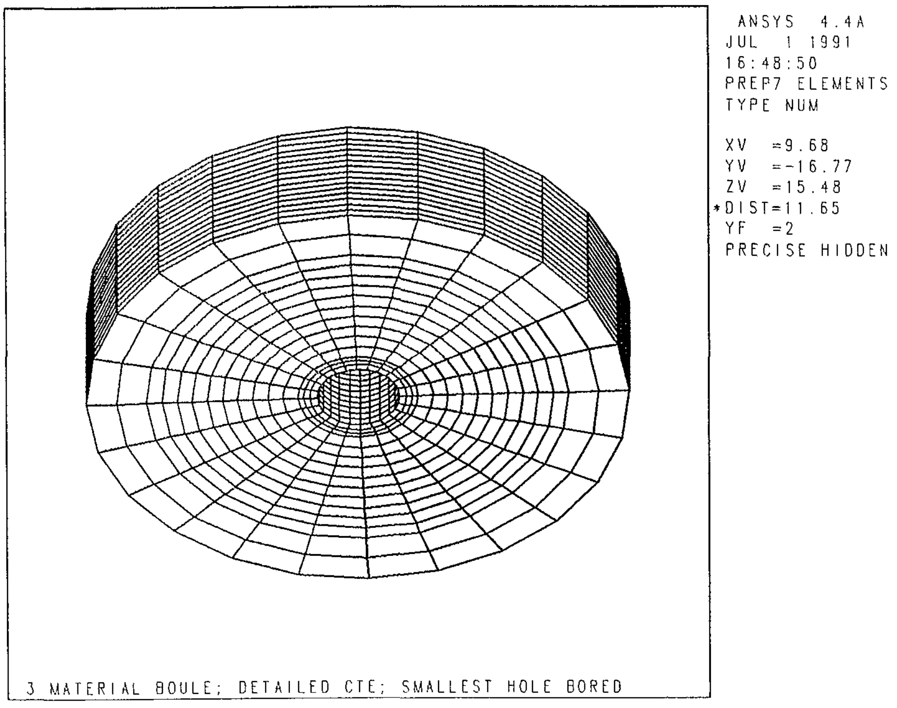

FIGURE 6. FEM mesh for the three material sample; the elements in the volume of the hole have been deleted to show the drilling

Same for all 6 elements

-8	-8	-7	-7	-7	-7	-7	-7	-4	-4	-4	-4	
-5	-5	-4	-4	-4	-4	-4	-4	-1	-1	-1	-1	
-9	-9	-8	-8	-8	-8	-8	-8	-5	-5	-5	-5	
-13	-13	-12	-12	-12	-12	-12	-12	-9	-9	-9	-9	
-13	-13	-12	-12	-12	-12	-12	-12	-9	-9	-9	-9	
-7	-7	-6	-6	-6	-6	-6	-6	-3	-3	-3	-3	
-3	-3	-2	-2	-2	-2	-2	-2	1	1	1	1	
-2	-2	-1	-1	-1	-1	-1	-1	2	2	-2	-2	
-26	-26	-29	-29	-30	-30	-30	-30	-31	-31	-31	-31	
-26	-26	-29	-29	-30	-30	-30	-30	-31	-31	-31	-31	
-26	-26	-29	-29	-30	-30	-30	-30	-31	-31	-31	-31	
-21	-21	-24	-24	-25	-25	-25	-25	-26	-26	-26	-26	
-21	-21	-24	-24	-25	-25	-25	-25	-26	-26	-26	-26	
-21	-21	-24	-24	-25	-25	-25	-25	-26	-26	-26	-26	
-18	-18	-21	-21	-22	-22	-22	-22	-23	-23	-23	-23	
-25	-25	-28	-28	-29	-29	-29	-29	-30	-30	-30	-30	

Fusion Line

Fusion Line

Edge of hole

CTE values in 10^{-9} in/in C

FIGURE 7. Mesh for two material sample with CTE values for each element

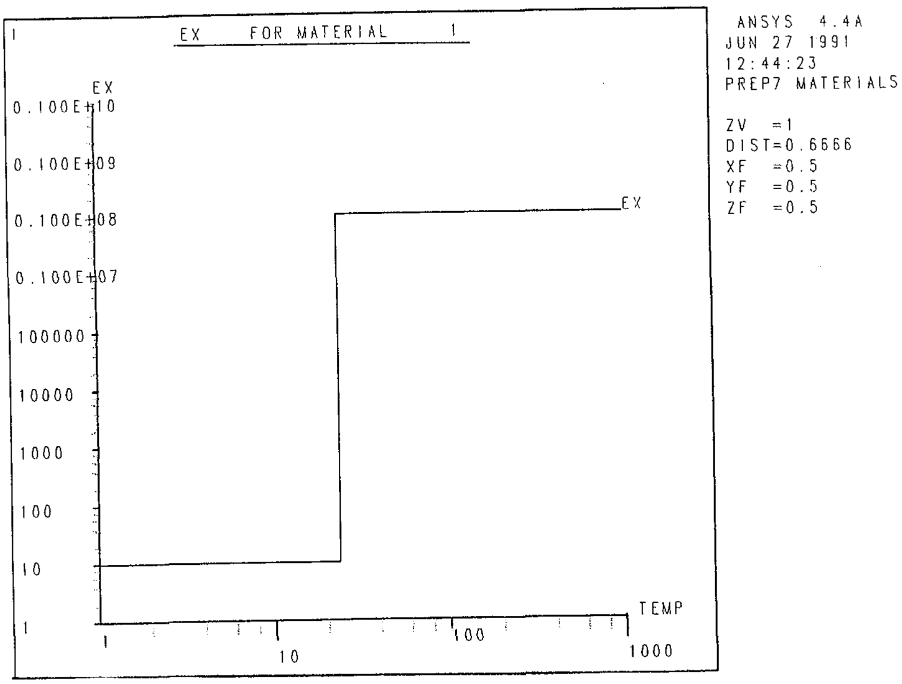

FIGURE 8. Elastic modulus vs. temperature for elements that are drilled out at 23.3C

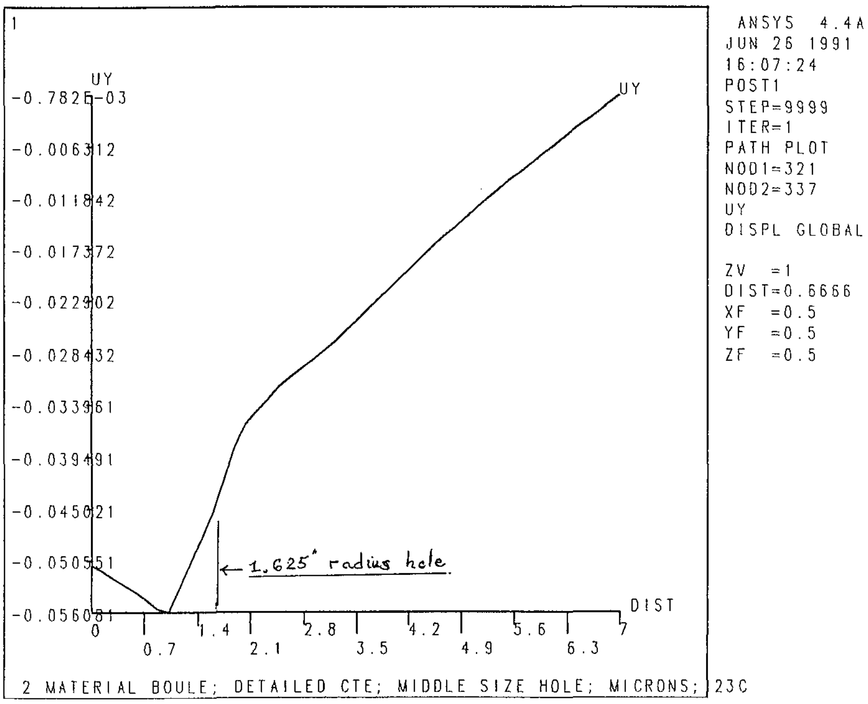

FIGURE 9. FEM distortions for the two material sample; this condition matches the one measured in Figures 3 & 4

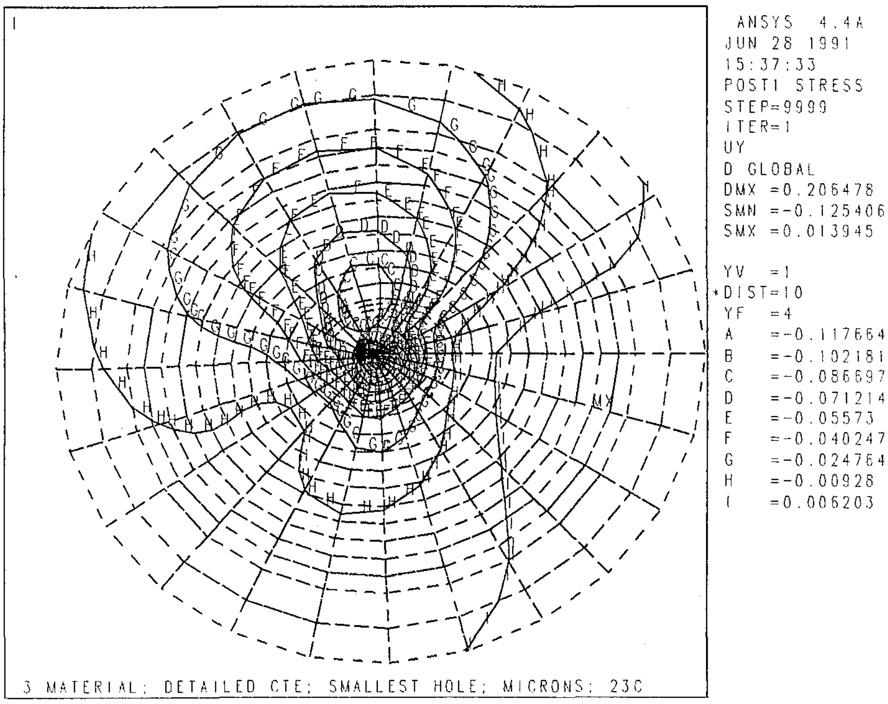

FIGURE 10. FEM distortions for three material sample; this is the hole drilled condition

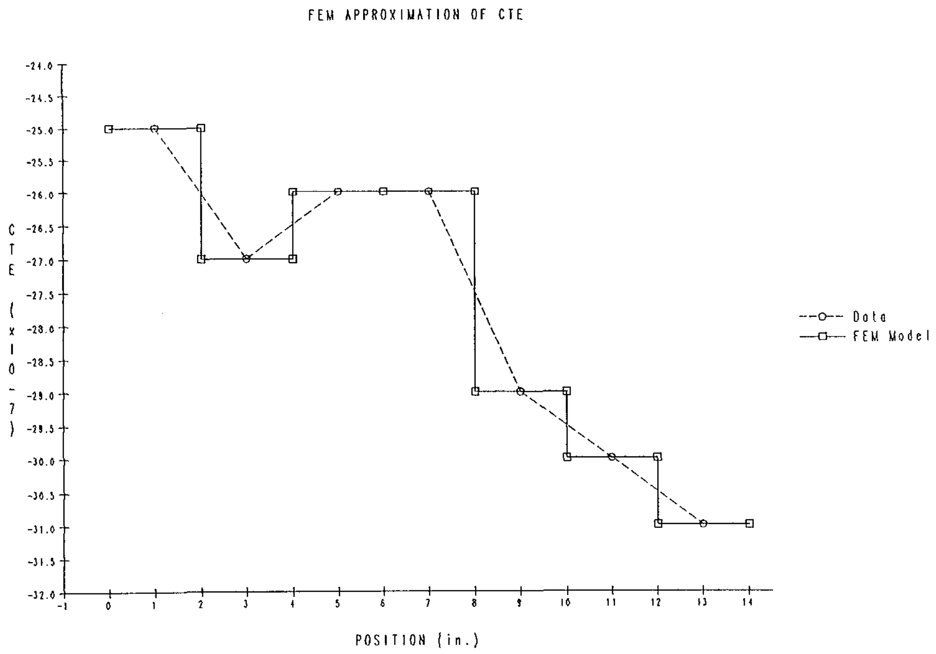

FIGURE 11. CTE vs. radius for one layer of the two material sample; the FEM represents the continuously varying curve as a series of steps