FINITE ELEMENT ANALYSIS & STRAIN GAUGING OF THE STEREOLITHOGRAPHY / INVESTMENT CASTING SYSTEM

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ABSTRACT

Many metal parts have been produced from stereolithography (SL) models via the investment casting route. However, it is still not possible for every foundry to directly use SL models as thermally expendable patterns and gain the same success as achieved with wax patterns. Significant drawbacks still exist with the QuickCast™ structure that restricts its use to specialist investment casting foundries who are willing to alter their standard techniques.

As part of a continuing work programme at the University of Nottingham, the stresses that are created in the SL/ceramic construction have been determined using simple stress analysis and finite element analysis techniques. Further work has involved connecting strain gauges and thermocouples to SL parts in order to confirm the results obtained with the theoretical stress analysis. Inspection of the results obtained is aiding the generation of new build structures to enable the successful autoclaving of SL models.

Details of the work to date are outlined in this paper, along with the results obtained.

INTRODUCTION

Since 1993, with the introduction of the original QuickCast™ build structure[1], it has been possible to gain functional metal parts from stereolithography (SL) models using the investment casting process. The accuracy of the SL models lends itself well to investment casting because of the high tolerances that can be achieved when using this casting method. Thousands of metal parts have now been produced[2] using the QuickCast™ process in a variety of different metals.

However, there are significant drawbacks associated with using SL models as thermally expendable patterns. The main problem area concerns the gross mismatch between the thermal expansions of the cured SL resin and the ceramic shell[3]. Because the epoxy resins used for the models are thermoset plastic materials, they do not melt under the influence of heat but continue to expand. It is this expansion that causes the catastrophic failure of the shells. The QuickCast™ build styles - effectively thin walled hollow parts with an internal open lattice structure of closed triangles (QuickCast1.0) or squares (QuickCast1.1) - were developed to allow the expanding SL parts some room to expand into and collapse during autoclaving. Yet, experience has shown that when using conventional autoclaving techniques for dewaxing (still necessary because of the wax tree that the SL models are usually connected to), the QuickCast™ models still generally cause the shells to crack.

Due to these difficulties associated with achieving a casting from an SL model, it has generally been the more progressive foundries[4], more willing to adapt their existing techniques, who have been able to make the most of the stereolithography process for making one off or short-run metal components. However, it is desirable that all investment casting foundries should be able to take a stereolithography model and, by using their standard techniques (including the autoclave), be able to achieve a finished casting.

Work at the University of Nottingham is continuing into the investigation of the stresses caused by the expansion of the SL models in the green ceramic shells as the construction is passed through the autoclave cycle. This work is giving a much clearer understanding of what is happening to the SL / ceramic construction and is giving a clear indication of the necessary requirements for the design of 'successful' internal build structures.

This paper is a continuation and update of the work presented previously[5]. It gives details of the stress analysis performed to date and indicates the future direction of the research programme.

BACKGROUND WORK

Failure of SL Models

Due to the relatively large expansion of the cured epoxy resin, autoclaving *solid* SL models will cause the investment casting shells to crack. To overcome this, QuickCast™ models were developed to enable investment casting shells to survive the autoclave phase by allowing the models to soften and then collapse in on their own voids[1], Yet despite this, experience has shown that QuickCast™ models still generally cause the shells to fail in the autoclave phase[6].

Thus, to enable QuickCast™ parts to be used as thermally expendable patterns, it has been recommended[7] that foundries skip the steam autoclave phase and dewax shells containing these models directly in the flash-furnace. Even though this method (coupled with other significant modifications to the standard investment casting process) works, it should not be viewed as a viable solution to the problems of 'dewaxing' QuickCast™ models. What ideally required is a build structure that allows the direct substitution of the SL part for the wax, with out any variation to the standard investment casting process.

On a brighter note, trials have shown[5] that it is entirely possible, without modification, to autoclave thin walled hollow parts. This indicates that it is very likely that a structure(s) exists in between a hollow and solid that will also allow the autoclaving of parts (built in that structure) to be successful. If a stereolithography / investment casting construction can make it through the autoclaving stage there will normally be no problem in achieving the resultant casting.

Sectioning of the autoclaved shells that contain these thin walled hollow parts shows that the SL models shatter within the confines of the shell. On investigation, this appears to contradict the QuickCast™ 'theory' of the part softening and then collapsing in on itself.

If the parts were to soften *and then* collapse (as the 'theory' states), then upon sectioning of the autoclaved shells you would expect to see merely a buckling away from the walls of the SL model. The shattering of the hollow parts indicates that the stereolithography parts have indeed failed before they have time to soften. This transforms the reasoning behind the design of new structures, in that models must therefore be designed to fail (under the influence of their own expansion) before their expansion causes the ceramic shell to crack.

Material Properties as a Function of Temperature

Determining the changes in material properties as temperature increases, especially of the cured SL resin, is fundamental to understanding why investment casting shells containing SL models are failing. The key to the failure of the shells lies in the high coefficient of thermal expansion (CTE) of the resin when compared to that of the green ceramic shell.

The determination of the material properties is crucial to enable stress calculations to be performed. The relevant properties obtained are used in simple stress analysis tools (such as Lames theories[8]) and more complex finite element analysis (FEA) packages.

A summary of the graphs for thermal expansion and Youngs modulus (*Figures 1 & 2*, respectively) are repeated in this paper for reference. Key points to note are the doubling in thermal expansion (from approximately 88×10^{-6} to 181×10^{-6}) that occurs around the glass transition temperature of the material. Correspondingly, there is a significant drop in the Youngs modulus at temperatures above the glass transition.

The graphs clearly show the sharp decrease in strength of the resin as the samples are ramped through an increase in temperature. This indicates that most of the problems *should* be occurring at the lower temperatures, where the QuickCast™ models still have enough material strength not to collapse but enough expansion to crack the shells.

STRESS CALCULATIONS

Finite Element Analysis: Thick Walled Cylinder

To complement the work previously performed using Lames theories to determine the stresses created in a simple stereolithography / investment casting construction, the Thick Walled Cylinder (TWC) problem was also modelled using an FEA package. (In summary, a TWC in this instance is taken to mean an open ended 'cylinder' of ceramic shell encasing a solid epoxy resin core. See ref. 5)

Figures 3 & 4 show the results obtained using Lames theories and the FEA package, respectively for resin cores of 1mm and 50mm diameters. There is a clear correlation between the results obtained using these different theoretical methods. The profile of the curves obtained from the FEA work match closely those obtained with Lames, except that there is a slight increase of temperature at which the maximum stress occurs with the FEA results. The magnitude of the stresses obtained with the two methods are also very similar to each other.

The similarities of the results from these two theoretical methods gives some degree of confidence as to suitability of using the FEA technique to model more complex examples.

Finite Element Analysis: 50mm CUBE

Basic theoretical stress analysis techniques, such as Lames theories, limit the complexity of the parts that can be analysed. Having confirmed the validity of the FEA package, the FE analysis was next extended to simulating the stresses induced in a SL 50mm cube encased in a shell 5mm thick; this represents a more complex geometry containing edges and corners. Though it is envisaged that eventually cubes containing QuickCast™ structures will be modelled, the FEA was (for the purpose of this paper) restricted to cubes of varying hollows. Initially, three variation of the 50mm cube have been analysed; these include:

- 50mm Cube; Solid
- 50mm Cube; Hollow with a wall thickness of 5.0mm
- 50mm Cube; Hollow with a wall thickness of 2.5mm

A schematic of the FEA model is detailed in *Figure 5*. It is hoped that in future, thinner walls as well as 'structured' parts will be modelled.

Figure 6 shows the stress profile over a range of temperatures for a solid 50mm block, a hollow 50mm block with a wall thickness of 5mm and a hollow 50mm block with a wall thickness of 2.5mm. All of the resin blocks are covered with a shell 5mm thick.

The introduction of corners have, predictably, had a great effect on the concentration and value of the stresses induced in the ceramic. For the solid 50mm block, there is a maximum stress of about 130MPa. Comparing this to the value obtained from the 50mm diameter core in the thick walled cylinder example of about 16MPa, it is clear that the corner has had a dramatic effect.

Though these hollow parts have been modelled with relatively thick walls, the effect on the induced stresses by introducing a hollow into a solid part is striking. There is a dramatic drop in stress as the wall thickness decreases. The block with a 2.5mm thick wall produces stresses in the ceramic approaching a value that is thought to be autoclavable. Interestingly, reducing the wall thickness has the same effect as reducing the resin thickness in the TWC problem, in that it decreases the temperature at which the maximum stress occurs (see *Figure 4*). It should be noted that the maximum induced stress (in the ceramic) occurs at the mid-point of each edge of the cube.

STRAIN GAUGING

Initial Strain Gauging

One of the principal reasons for performing the FEA was to identify not only the magnitude of the maximum stress, but also its location.

Initially a *Solid 50mm* stereolithography cube was built. This cube was then strain gauged and thermocoupled at the positions identified by the FEA work. An example of the strain gauging of the solid resin block can be seen in *Figure 7*. Having applied the gauges to the surface of the model, the initial face coat of the ceramic shell was applied and allowed to dry. With care, strain gauges were also applied to this initial face coat and the part was then coated with its subsequent ceramic layers, up to the normal thickness.

This strain gauged block was then placed into an oven and the results were recorded. A sample of the results can be seen in *Figure 8*. This figure shows the values gained for one of the strain gauges attached to the resin block and the equivalent gauge attached to the ceramic shell. It seems that there is a clear break in the ceramic around 60°C. This initial result was very encouraging because it seems to confirm the observation that the majority of the problems are happening at or below the glass transition temperature of the resin. *Figure 9* shows the shelled cube after it has gone through the heating process. It can just be seen that cracks have propagated from the centre of each edge which corresponds exactly with the predictions of the FEA. However, it is surprising that even though the ceramic shell has cracked under the influence of the heat, it has still remained mainly intact.

One initial drawback that became apparent during this test is that to gain a result from the strain gauged ceramic, it seems that a crack has to propagate directly over the strain gauge.

These results appear to go some way to confirming the work performed with Lames theory and the FEA work.

Further Strain Gauging

Having achieved a reasonable result in the initial laboratory based 'dewaxing', the strain gauging was then expanded to encompass the full range of examples that were simulated using the FEA. For comparative analysis, three (3) of each type were fabricated. The types built were:

- Solid blocks (Referred to as *Solid _1/2/ or 3*)
- Hollow blocks, wall thickness 5.0mm (Referred to as *Hollow 5.0mm_1/2/ or 3*)
- Hollow blocks, wall thickness 2.5mm (Referred to as *Hollow 2.5mm_1/2/ or 3*)

and also, to repeat previous work involving the autoclaving of thin-walled hollow parts

- Hollow blocks, wall thickness 1.0mm (Referred to as *Hollow 1.0mm_1/2/ or 3*)

As before, strain gauges and thermocouples were fixed onto the surface of the SL blocks and also attached to the initial 'face-coat' of the ceramic. For the Solid models, an additional thermocouple was also placed at the centre of the block. These blocks were then subjected to a real 'dewaxing' in a commercial steam autoclave.

A representative sample of the results obtained for the Solid block can be seen in *Figure 10* and, similarly, an example of the results for a Hollow block (in this instance, Hollow5.0mm_1) is shown in *Figure 11*. As expected, all the shells failed except for the ones containing the *Hollow_1.0mm* samples.

DISCUSSION

The clear result from the initial strain gauge work has not been duplicated in the autoclaving trials. There seems to be a stark difference in the results achieved when the autoclave is used to 'dewax' the samples. The graphs are far more difficult to interpret, but one of the most obvious thing to note is the conspicuous increase of temperature at which the shells appear to fail.

This *apparent* increase can be explained if the temperatures recorded in the Solid block are referred to. *Figure 12* shows the temperatures recorded at the interface between the shell and the resin and also at the centre of *Solid_2*. The interface temperature has a very steep temperature gradient, but it can be clearly seen that the temperature at the centre of the block lags way behind this interface value. This demonstrates the insulative properties of the epoxy resin. Though the shells appear to be failing at about 120 to 130°C, it should be noted that this temperature is the *surface* temperature of the cube so, crudely speaking, the actual average temperature of the resin block at which the shells fail correlates to about 60 to 70°C. This is much more in line with the value predicted with the FEA package and demonstrated with the initial strain gauge trials.

The heat input rate is clearly much more of an issue than was previously thought. The autoclave that was used to 'dewax' these samples offered a very steep heating input, and consequently destroyed the shells (see *Figure 13*). The oven that was used to heat the solid block in the initial strain gauge work (described previously) provided a more gentle heating rate that allowed the resin cube to heat up more uniformly. The heating rate for the initial strain gauge work (again measured at the interface of the ceramic and model) is more in line with the rise in temperature recorded at the centre of the equivalent autoclaved block. (See *Figure 14*)

In order to initially simplify the problem, the theoretical work performed (Lames theory and FEA) assumed that the SL / investment casting construction reached an instant and *uniform* temperature throughout. For the initial strain gauge work, because the heat input rate was relatively slow, the temperature distribution through the resin cube was more uniform. It is for this reason that the initial strain gauge work reflects more closely the theoretical results. It should be noted that although the solid cube heated in the oven also failed, it did so far less catastrophically than the autoclaved version.

For samples that were heated in the autoclave, the resin cube can be separated into two areas: an outside 'skin' that is getting progressively hotter and an inner core that, due to the temperature lag, initially remains mainly at ambient temperature. (The outer layer, of course, eventually consumes the inner as the effects of the lag are diminished). However, whilst the inner core remains solid, it restricts the softening and expanding outer layer from deforming. So, as the outer 'skin' gets progressively hotter, its expansion increases to such a rate that it causes the shell to fail.

Summary

The relatively novel approach to using strain gauges appears to present some difficulties. There are clear problems associated with using strain gauges that are imbedded and adhered to the ceramic with an adhesive that has a thermal expansion far greater than that of the ceramic itself. The problem of the expanding adhesive simply reflects the original problem of the cured SL models causing the shells to crack due to the gross mismatch of thermal expansion.

SL parts that do not crack the shells during the autoclave phase (not published) show that the strain gauges are appearing to register a negative strain. This *apparent* compression of the ceramic runs entirely contrary to what actually happens. However, a logical explanation of this phenomena is that as the adhesive coating the strain gauge tries to expand under the influence of heat, it is unable to because it is itself encapsulated by the ceramic shell. As the ceramic is (relatively) not expanding, the strain gauge is forced into *compression*, and thus registers a negative strain.

CONCLUSIONS

There are clear similarities between stress values obtained for the thick walled cylinder using Lames equations and the results obtained with the FEA package.

Though these results are preliminary and simplified, they clearly show a general trend, and support the idea that the majority of the problems are occurring before or about the beginning of the glass transition temperature of the cured resin.

The initial strain gauge results that were performed in the low heat input oven offer good substantiation of the theoretical work performed. The results obtained from the more aggressive autoclave trials are more confusing and seem to highlight the difficulties of using strain gauges in such an environment.

ACKNOWLEDGEMENTS

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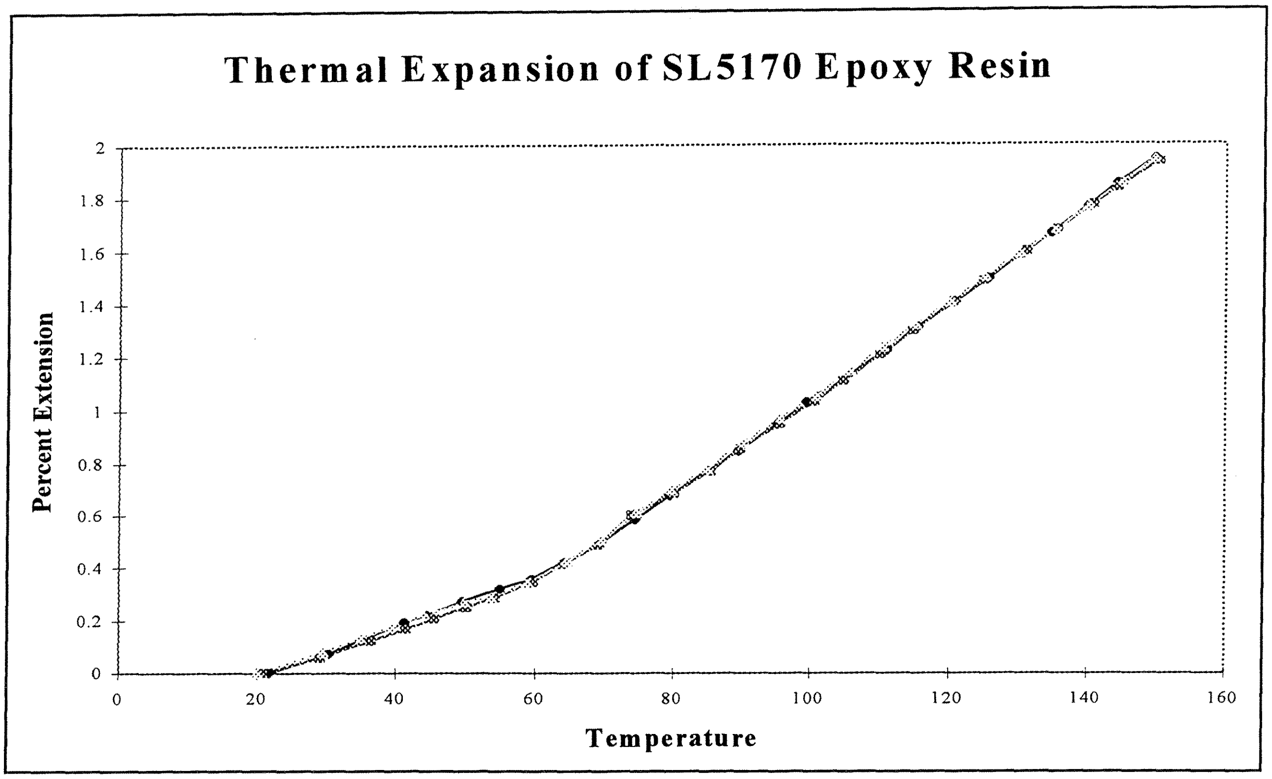
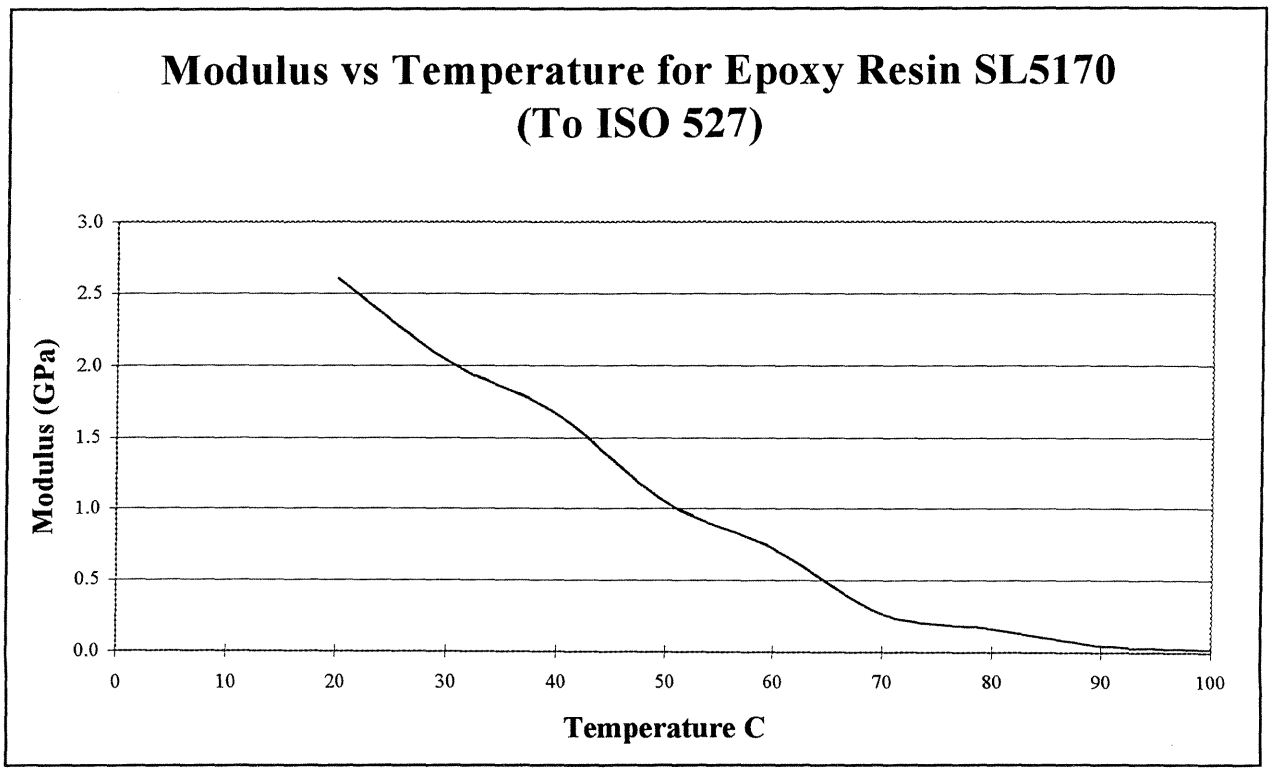


Figure 1



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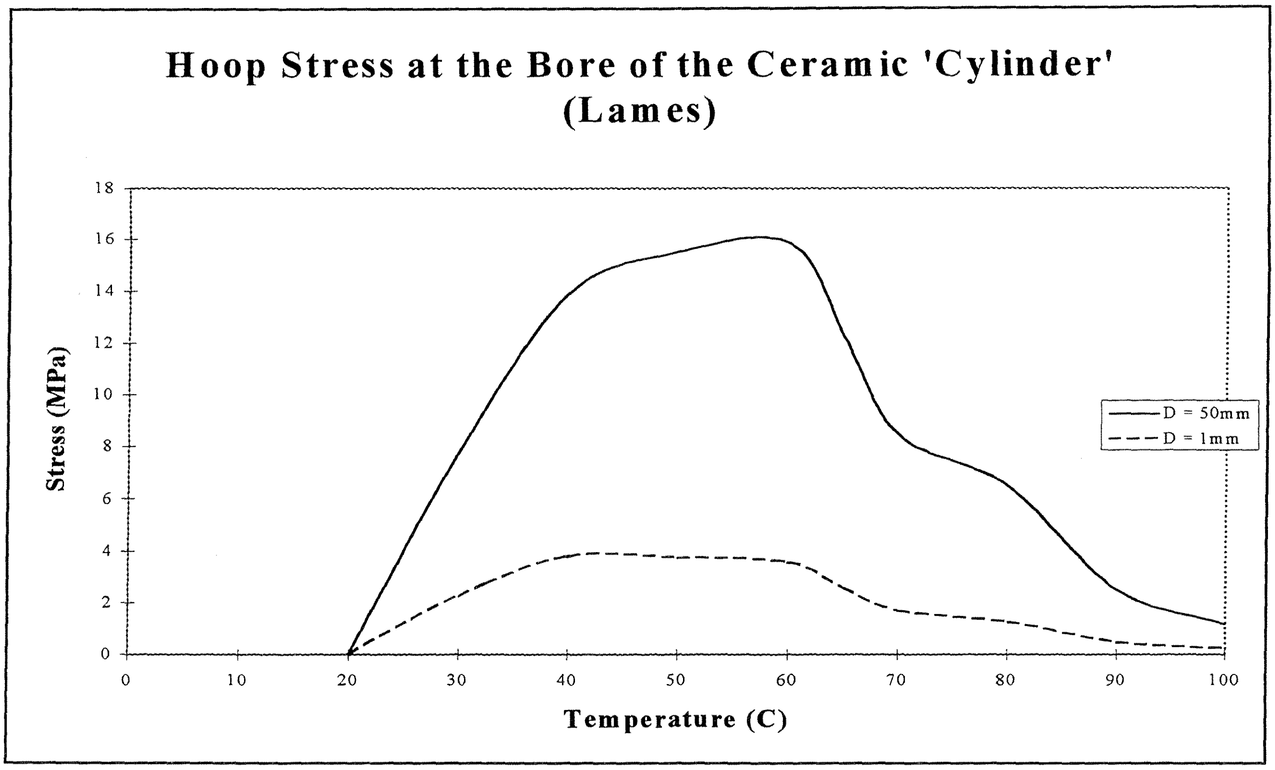

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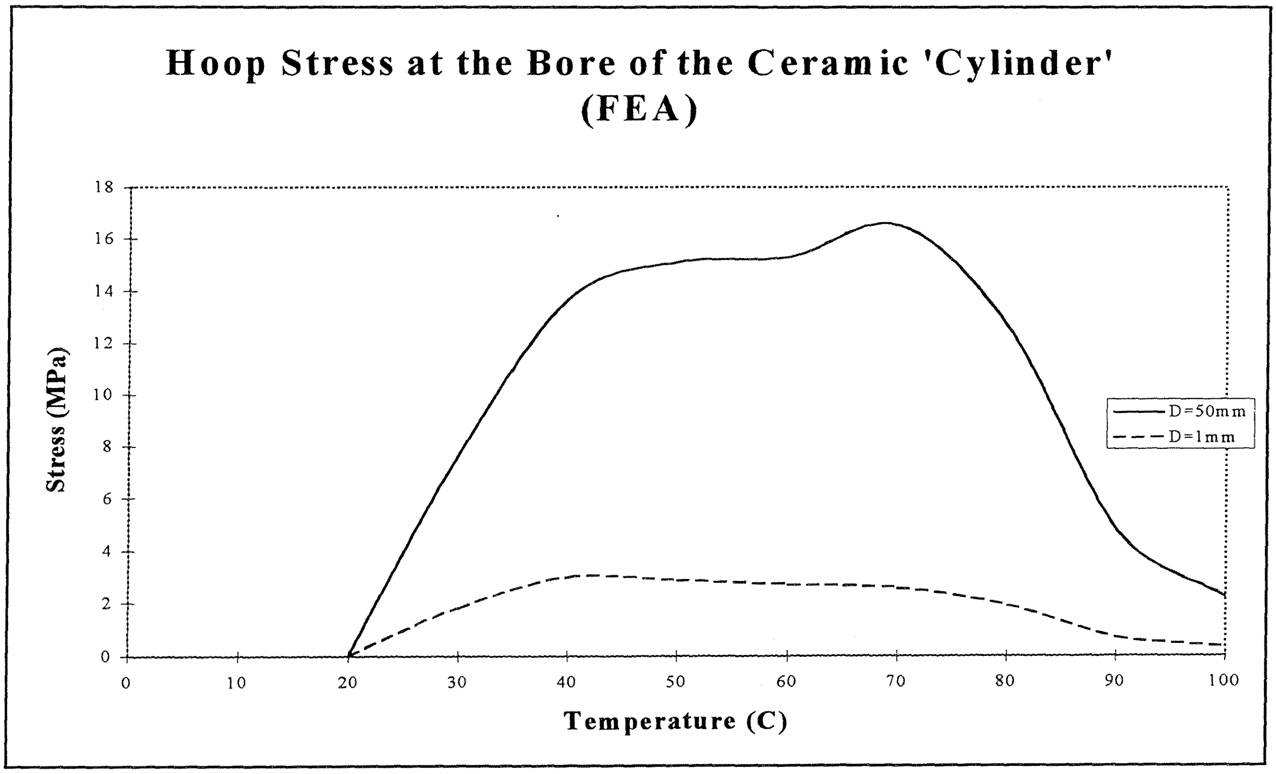

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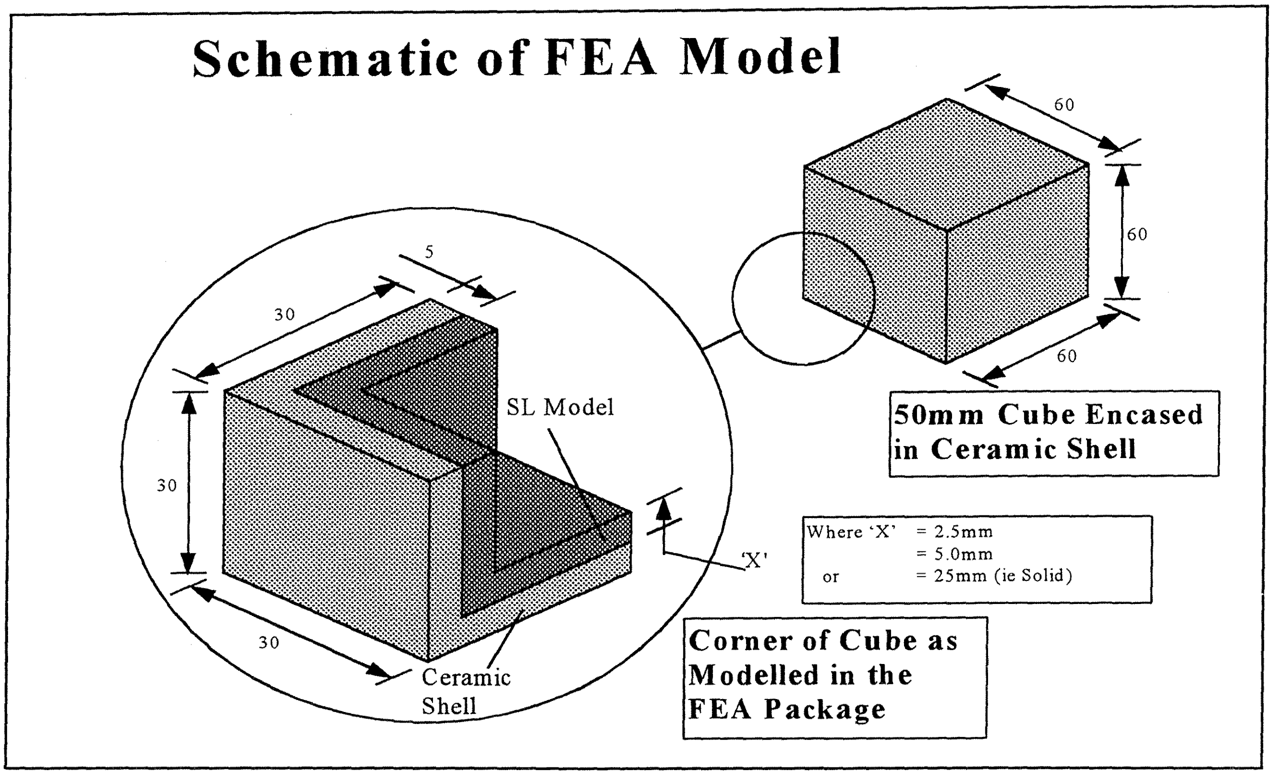


Figure 5

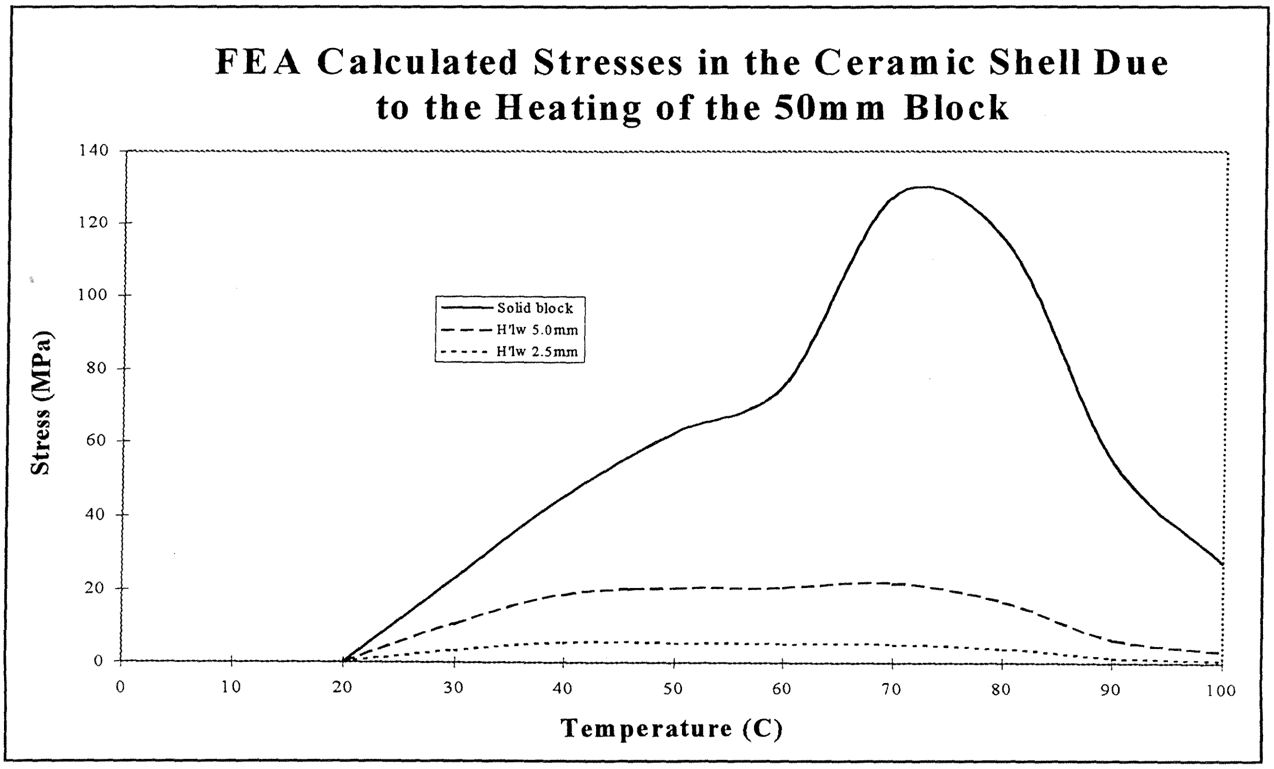


Figure 6

Example of Strain Gauging

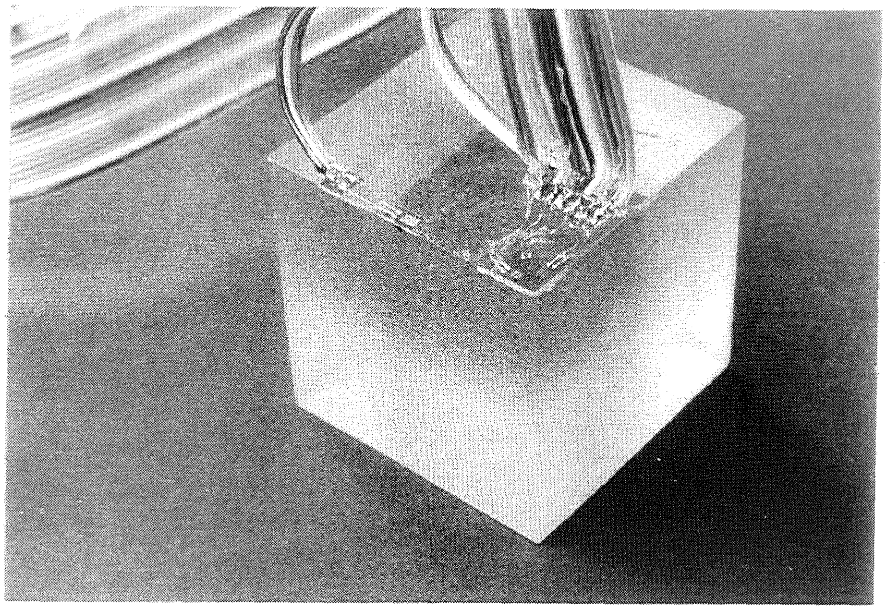


Figure 7

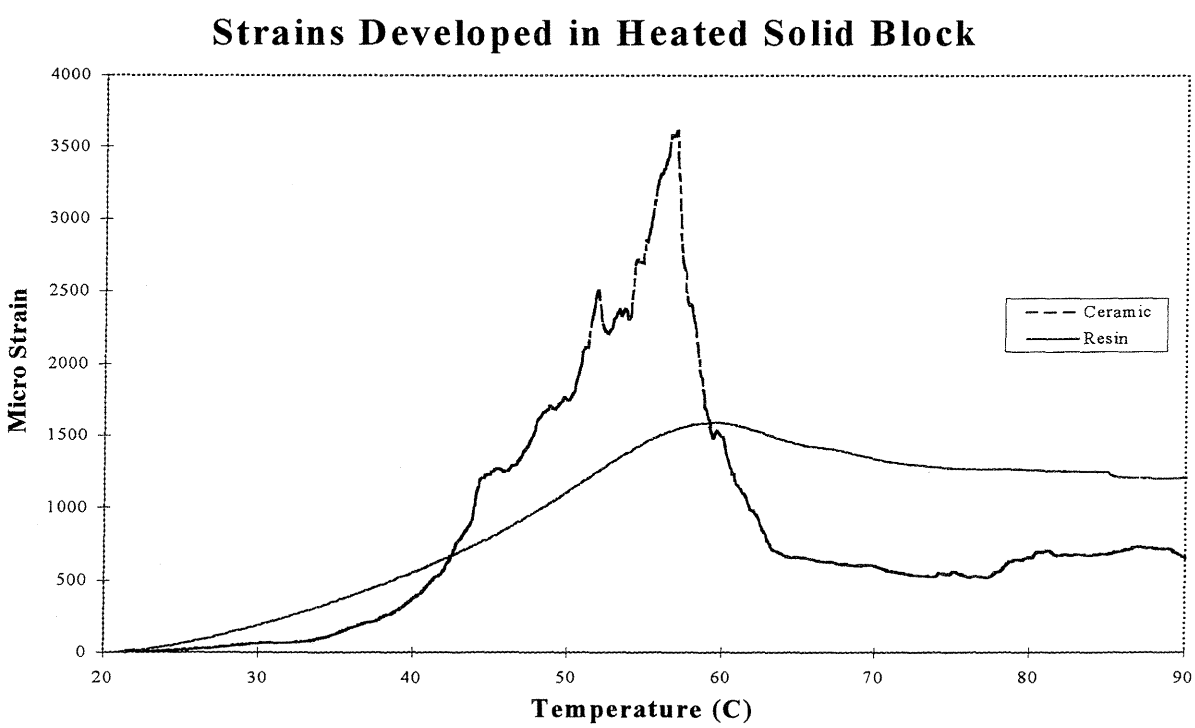


Figure 8

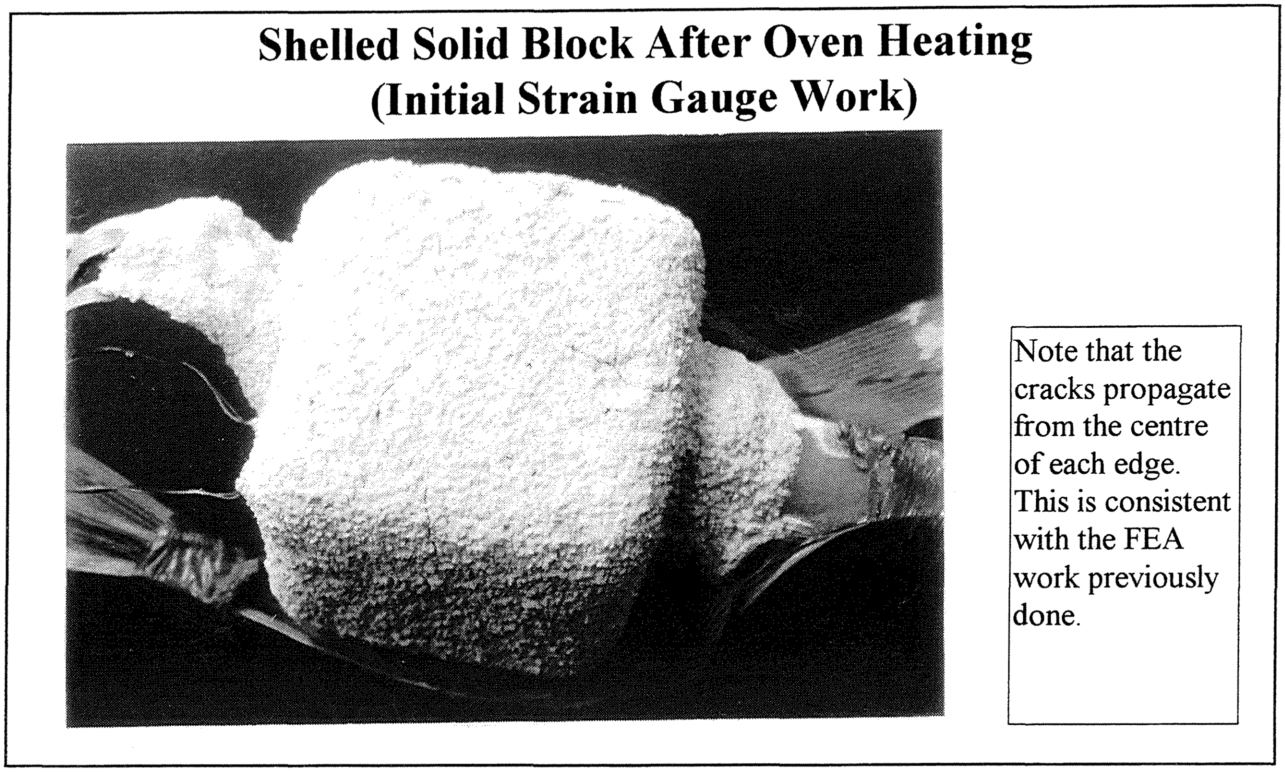


Figure 9

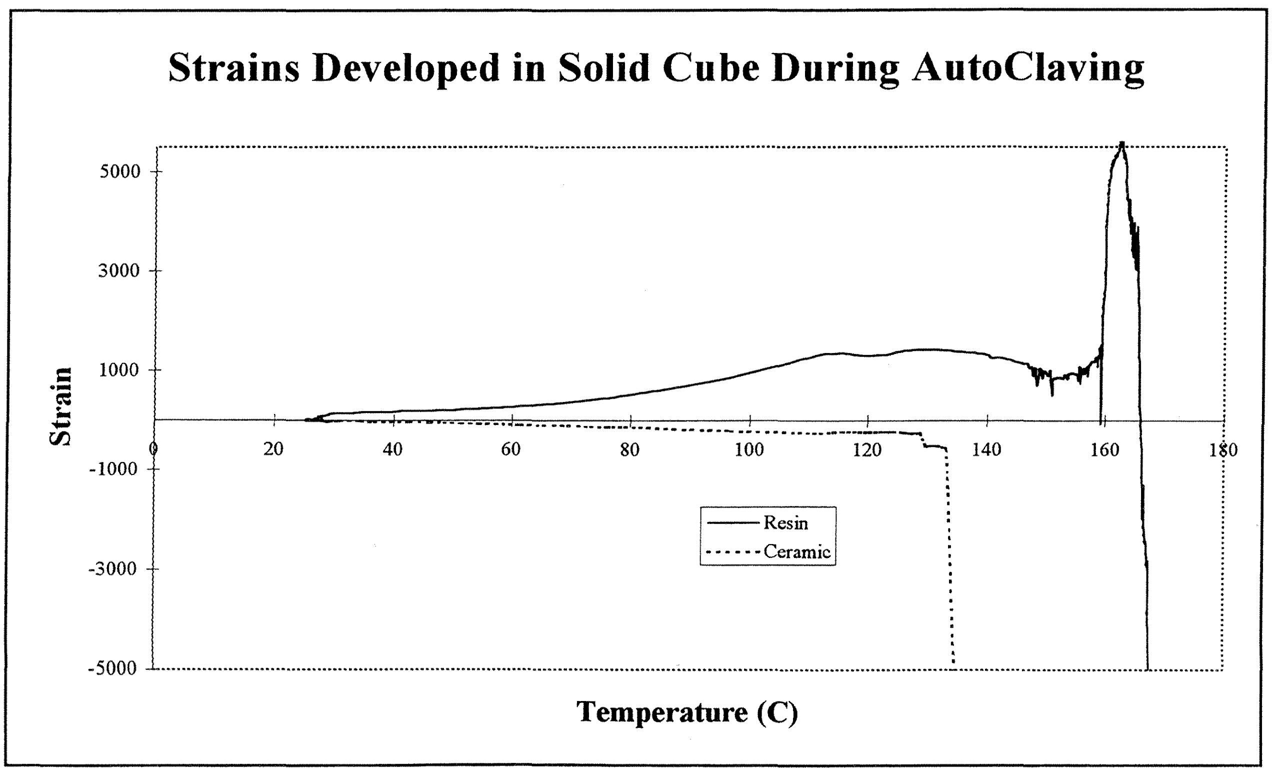
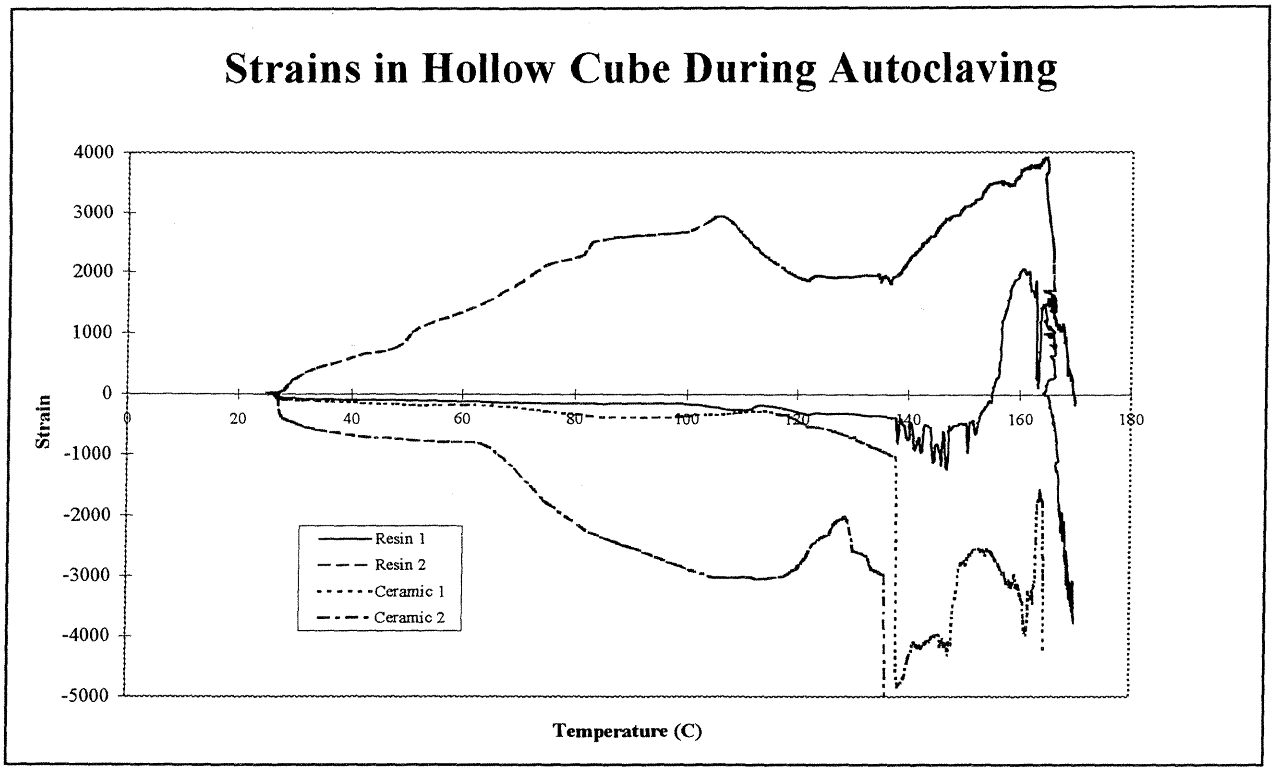


Figure 10



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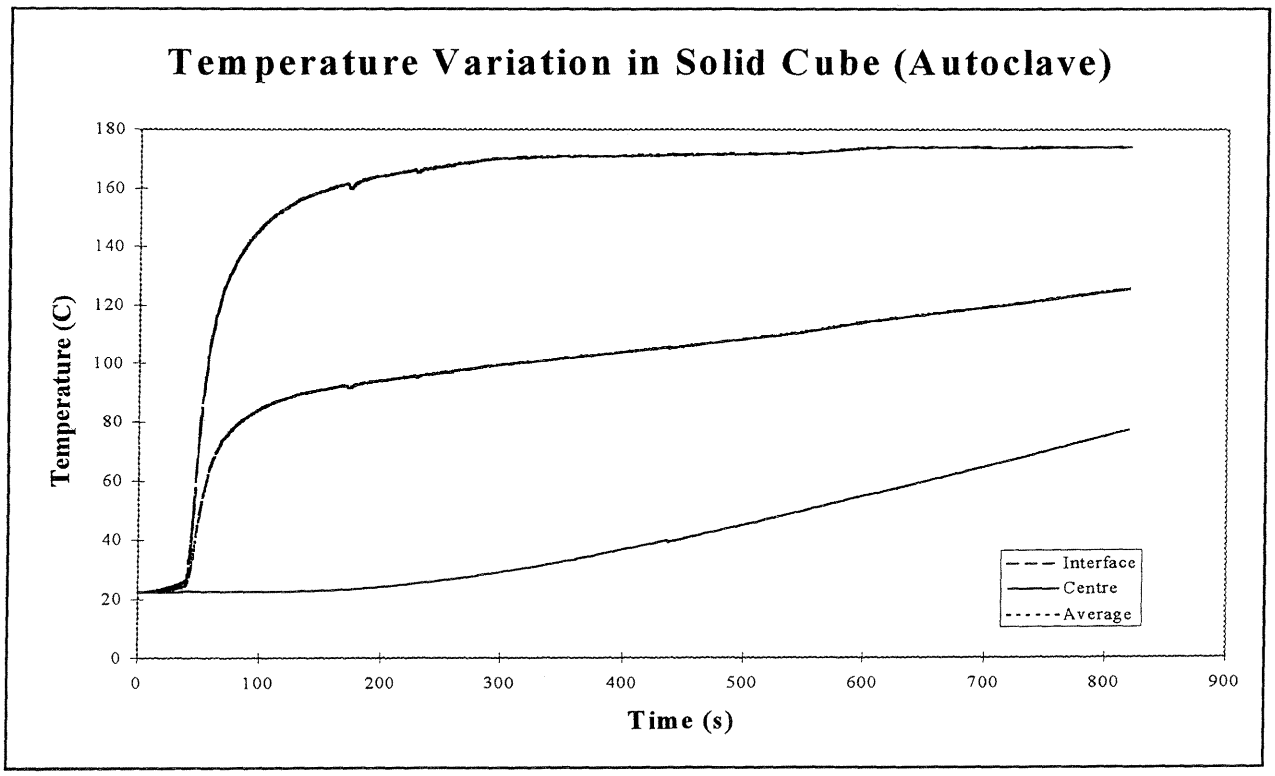

Figure 12

Shelled Cube after Autoclaving

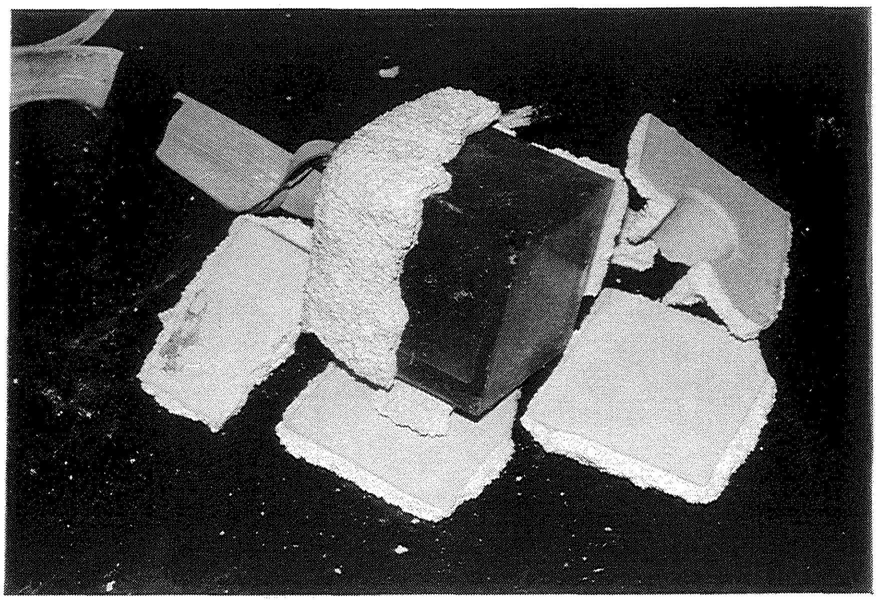

Figure 13

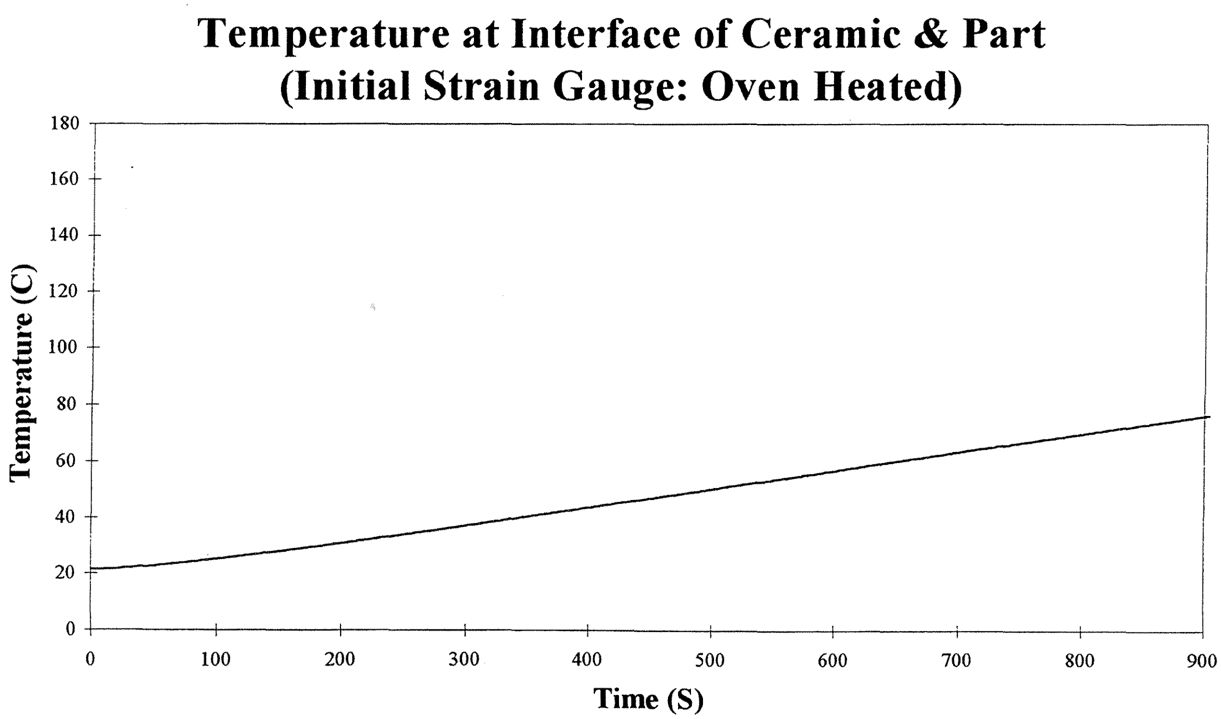

Figure 14