STRESSES CREATED IN CERAMIC SHELLS USING QUICKCAST MODELS

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ABSTRACT

Improvements in resins and build styles, coupled with increasing experience, have meant that ever more metal parts are being produced from stereolithography (SL) models via the investment casting route. However, despite these advances, 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.

The central reason behind the inability to investment cast some SL parts' lies in the expansion of the cured resin. The thermoset plastic material of the SL model does not melt during the autoclave process and its expansion creates stresses in the ceramic wall that cause the relatively weak shell to crack.

A work programme is in progress at the University of Nottingham to show *how, why* and *when* these stresses are built up and compare them to the stresses created during the conventional autoclaving of wax parts. The eventual aim of the project is to gain a full understanding of the stresses induced in the models and to develop new build structures that will allow the successful autoclaving and subsequent casting of stereolithography models.

Details of the work programme are outlined in this paper, along with initial results obtained.

INTRODUCTION

The use of stereolithography models as thermally expendable patterns in the investment casting process is now an established method of gaining functional metal parts[1]. Many metal duplicates have already been produced from models built in the Quickcast 1.0™ and the 'new' Quickcast 1.1™ build styles. However, despite the advances in resin and build styles, the percentage of final castings produced when using SL models falls significantly short of the number achieved when using conventional wax patterns.

Also, the majority of castings that are being produced are being manufactured by specialist investment casting foundries who are willing experiment and adjust their conventional techniques to accommodate the problems encountered when casting with SL models[2]. Even when successful castings are produced, the dewaxing of the shells (still necessary because of the wax tree that the stereolithography models are mounted on) is generally achieved in the flash furnace. This is despite the fact that the steam autoclave is far and above the most popular method for the dewaxing of shells within todays investment casting industry[3]. There is also evidence to suggest that the autoclave is a more efficient dewaxer than the flash furnace[4]. However, dewaxing shells containing stereolithography models in the autoclave generally results in broken shells[5].

A work programme has begun at the University of Nottingham to investigate the stresses caused by the expansion of the SL models in the green ceramic shells as the construction is passed through the autoclave cycle. From this work, it is hoped that a clearer understanding can be obtained of what is happening to the SL / ceramic system. This should eventually lead to the development of guidelines for the design of 'successful' internal structures.

It is necessary that any new internal structure should allow the shelled models to be autoclaved rather than have the dewaxing realised in the more aggressive flash furnace environment. The reason for this is to open the opportunities for the investment casting of stereolithography models and to allow *any* investment casting foundry to take an SL part and have the ability to achieve a casting. If the shells can survive the autoclave phase, there is generally no problem encountered when the shells are subsequently fired in the flash furnace.

This paper aims to introduce the current work programme giving a general outline and direction research programme. Some initial calculations are also included.

WORK COMPLETED

HOLLOW SL MODELS

Having autoclaved, without success, a range of models built in the Quickcast™1.0 build style, an experiment was performed that was designed to determine whether it was possible to autoclave even the simplest and weakest of structures. A series of autoclaving trials were carried out on simple shapes with absolutely no internal structure at all, ie hollow parts. This experiment was performed with the rational that if it was *not* possible to autoclave these parts, then it would then be highly unlikely that *any* design of structure would facilitate autoclaving. Conversely, if it were possible to 'dewax' shells containing these hollow SL parts without cracking the ceramic, then there should exist some form of structure in between a hollow and the Quickcast™1.0 structure that will allow the successful autoclaving of the SL pattern.

Hollow spheres, cubes and cylinders were built, treed and shelled (an example of the hollow cylinders is shown in *figure 1*). The shells were then subjected to a standard autoclave at seven bar (165°C) and the dewaxing of all the shells was a complete success. Sectioning of the shells, however, uncovered some unexpected and revealing results.

The 'theory' behind how the Quickcast models are expected to perform in the autoclave states that as a model expands under the influence of heat (in the autoclave), it should then soften and collapse in on its own voids[6]. If this were the case, on sectioning the autoclaved hollow parts we would have simply noticed a buckling of the SL model away from the walls of the ceramic shell. What *actually* seems to have happened (*figure 2*) is that, far from being intact within the confines of the ceramic shell, the hollowed parts seemed to have gone through some form of thermal shock, and were - in all cases - in several pieces.

What appears to have happened is that instead of the parts expansion inducing failure in the shells, the resins own expansion has promoted the failure of the *part* before it has had time to soften and therefore buckle, as expected. This observation runs contrary to the previously explained reasoning about how the Quickcast structure should behave during autoclaving, in that it is designed to soften *and then* collapse in on its own voids. Experience from this experiment alone shows clearly that, in fact, almost the direct opposite has occurred with the models collapsing *before* the resin has had time to fully soften. As the models seemed to have shattered into several pieces within the shells this implies that the parts themselves had 'failed' before they caused failure in the ceramic shell.

MATERIAL PROPERTIES AS A FUNCTION OF TEMPERATURE

As with all materials, the properties of the cured stereolithography resin change with a variation in temperature. The combination of these property changes have a fundamental affect on what happens to the SL / ceramic construction under heating during the autoclave cycle. No accurate data previously existed for the material properties of the epoxy resin at elevated temperatures and a work programme was started to obtain this information.

By determining and contrasting the material properties of the cured SL5170 resin and ceramic materials, it is believed that a correlation between the thermal expansion and mechanical properties can be established that will yield the root cause behind the failure of the shells. The mechanical properties and thermal expansion results are used as the raw data for some stress analysis considered later in this paper, and will be used for the future finite element (FE) simulation of the autoclave phase.

THERMAL EXPANSION

The expansion of the thermoset SL model within the confines of the ceramic shell construction is the central reason behind the high failure rate encountered during the investment casting process. Clearly its determination is core to the understanding of what is happening under heating during the autoclave cycle. Effectively, the difference in thermal expansion of the ceramic and epoxy materials will yield the strain induced in the system and this is used for future stress calculations.

Figure 3 shows a typical linear expansion graph obtained for the SL5170 epoxy resin. The results were obtained using a linear dilatometer in accordance with *ASTM E228 - 85*. In the range from ambient to about 60°C, there is a linear expansion, α, of approximately 88 x 10^{-6}. In the range from 65 to 150°C there is a twofold increase in thermal expansion to 181 x 10^{-6}. This sharp increase occurs around the glass transition temperature of the cured resin as the secondary bonds of the thermoset plastic material melt.

TENSILE STRENGTH OF RESIN

Figure 4 gives a resume of the tensile strengths obtained for the SL5170 epoxy resin in the range from 20 to 100°C. The corresponding value for Youngs modulus obtained in the same test is shown in *Figure 5*. The tests were performed in accordance with *ISO 527*. The material was only tested up to 100°C because, as can be seen, the strength (and the corresponding value for Youngs

Modulus) is negligible at temperatures at and above 90°C.

The graph clearly shows the sharp decrease in strength of the resin as the samples are ramped through an increase in temperature. This tends to confirm the theory that most of the problems should be occurring at the lower temperatures, where the Quickcast model still has enough material strength to not collapse but enough expansion to crack the shells.

INITIAL STRESS CALCULATIONS

To aid in the design of new structures, it is envisaged that eventually the autoclave phase will be simulated using a finite element package. This will be done to predict the failure of the shells for particular structure designs. However, the next stage of the work programme was aimed at producing some results using some basic theory for *solid* stereolithography patterns. This was to help confirm why the SL models are cracking the shells and to predict at what temperature the models will fail for a particular thickness of resin.

For the purposes of this paper, and for simplification of the problem, the calculations are based on the stereolithography / ceramic construction being reduced to an *open ended thick walled cylinder*, with the ceramic 'cylinder' surrounding the resin core (see *figure 6*). When the problem is reduced to this system, it is then possible to apply Lames equations[7] to solve for the stresses in the ceramic shell and the resin core, caused by the systems heating in the autoclave.

The following assumptions are made to further simplify the system

- The material properties of the ceramic (E_C & υ_C) are considered constant.
- External pressure is atmospheric.
- The expansion of the ceramic is considered negligible in contrast to that of the resin.
- The system is open ended. ($\sigma_Z = 0$)
- Poissons ratio for the materials remains constant.

From Lames equations it can be shown that the pressure at the interface of the surface of the ceramic shell and the stereolithography model, P, can be represented as

$$P = \frac{\Delta\epsilon}{\frac{1}{E_C}(k + \upsilon_C) + \frac{1}{E_R}(1 - \upsilon_R)}$$

Where:

$\Delta\epsilon$ = Strain induced by expansion of the resin (= $\alpha\Delta T$)
E_C = Youngs modulus of the Ceramic Shell
E_R = Youngs modulus of the resin model.
υ_C = Poissons ratio of the ceramic shell

υ_R = Poissons ratio of the SL5170 resin, and

$$k = \frac{(r_C^2 + r_R^2)}{(r_C^2 - r_R^2)}$$

(r_R = Radius of resin 'core')
(r_C = Outside radius of ceramic 'Cylinder')

From the above equation it can be demonstrated that the radial and hoop stresses (σ_r & σ_θ, respectively) in the ceramic at the internal bore of the 'cylinder', (where the maximum stresses occur), are:

$$\sigma_\theta = kP$$
$$\sigma_r = -P$$

and that for the resin core,

$$\sigma_r = \sigma_\theta = -P$$

at any point in the core.

Using the results previously obtained from the mechanical testing of the epoxy resin, values for Youngs modulus and thermal expansion (E_R & α_R, respectively) can be entered in the formula. Poissons ratio for the resin has been approximated from data supplied from Ciba Geigy and is considered to be constant through out the temperature range. Material properties for the shell (E_C & υ_C) have been estimated from data supplied from the National Engineering Laboratory. The values used are:

E_C = 3.5 GPa
υ_C = 0.1
υ_R = 0.4

The thickness of the shell wall (r_C - r_R) is constant and is set at an 'average' value of 6mm. Values of hoop stress obtained for resin cores of 0.5mm & 4mm diameter are shown in *figure 7*. Assuming a maximum principle stress criteria, failure of the ceramic shell will occur when $\sigma_{\theta(bore)}$ (hoop stress at the bore of the ceramic 'cylinder') reaches the MOR (modulus of rupture) value of the ceramic shell.

Figure 7 shows that, despite the various assumptions made, the basic profile of the stresses induced seems to confirm what was previously suspected. The stresses in the shell increase and reach a peak as the resin retains some material strength and then rapidly decrease as the material properties of the resin change. The decrease in stress occurs at, or around, the start of the glass transition temperature, T_g, of the resin where the material turns from being a true solid to a 'leathery', flexible material with a very low modulus. As the resin core increases in diameter, it is clearly demonstrated that there is rise in hoop stress in the ceramic shell. If the hoop stress equals or exceeds the MOR value of the ceramic, the shell will fail.

Figure 8 shows schematically how present Quickcast™ structure behaves in the autoclave contrasted with what we are aiming for in any future structure design. Also schematically detailed are a range of shell strengths that broadly represent the present situation. Any future design of structure must be designed to 'fail' before its expansion causes the failure of the minimum strength shell.

FUTURE WORK

STRESS ANALYSIS: PRACTICAL

Having performed the simple stress analysis, as detailed above, confirmation will be obtained by attaching strain gauges and thermocouples to a range of systems and have them shelled and subjected to the autoclave cycle. Initially these trials will be performed using simple shapes to confirm (or otherwise) the results obtained by calculation.

It is planned that initially 50mm blocks will be produced and tested in the following styles in order to reflect all the possible scenarios of investment casting with stereolithography models:

- Solid blocks (built in ACES build style)
- Hollow blocks (ie, no internal structure)
- Quickcast blocks
- Wax blocks

The solid and hollow blocks should give 'datum' results, as they represent the two extremes of the structure scenario, ie, maximum and minimum expansion induced stress. Testing of the wax blocks will allow a comparison to what is happening during the standard investment casting process.

FINITE ELEMENT SIMULATION

Having gained a clearer picture of the failure characteristics of the process from the stress analysis, a finite element analysis (FEA) programme will be started to initially simulate the results achieved from the stress analysis. As the results are confirmed with the FEA package, and as a greater understanding of the failure modes of the SL / ceramic construction is achieved, a set of guidelines should emerge that will facilitate the design of new structures that incorporate the failure characteristics observed.

ITERATION OF STRUCTURE DESIGNS

Having confirmed the validity of the FEA model, new structure designs will be simulated to predict the failure characteristics of those structures.

CASTING TRIALS OF DIFFERENT STRUCTURES

One of the main aims of the current work programme is to produce a stereolithography model in a structure that *any* investment casting foundry can use as a direct substitute for their conventional wax pattern, without the need for any special attention. As the design of internal structures progresses, a series of casting trials will be performed to determine the 'autoclavability' of the parts.

CONCLUSIONS

Despite reservations about the actual values obtained from the stress analysis equation, due to the uncertainty of the values used for the mechanical properties of the ceramic and the simplified model, it is believed that the trend in stress concentration, seen in *figure 7*, is broadly correct. The peak in hoop stress created by the expansion of the resin at around 60-65°C is consistent with the observations of the author.

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 SL5170 epoxy resin.

ACKNOWLEDGEMENTS

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Hollow Stereolithography cylinder mounted on a wax tree prior to shelling.

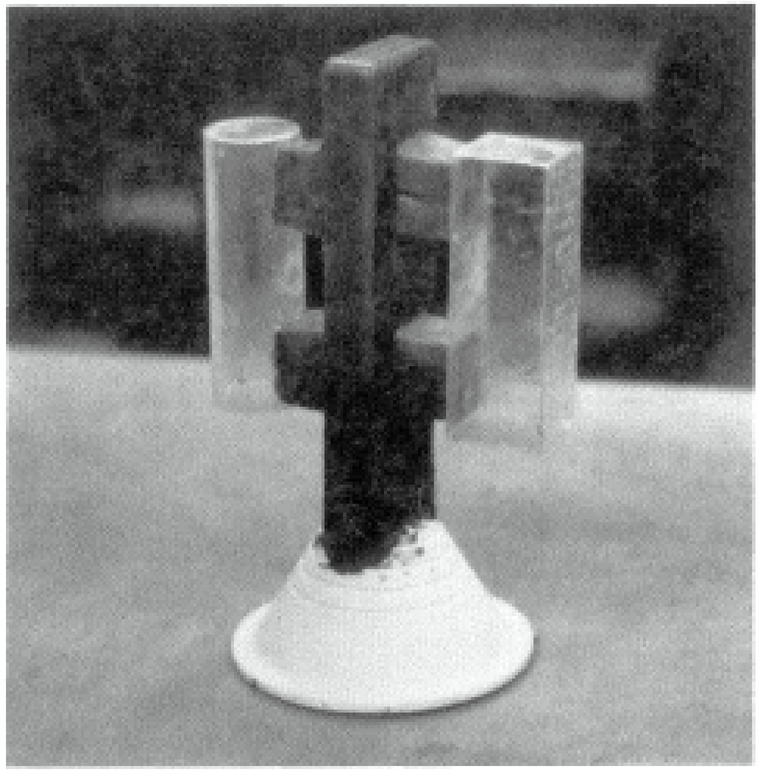
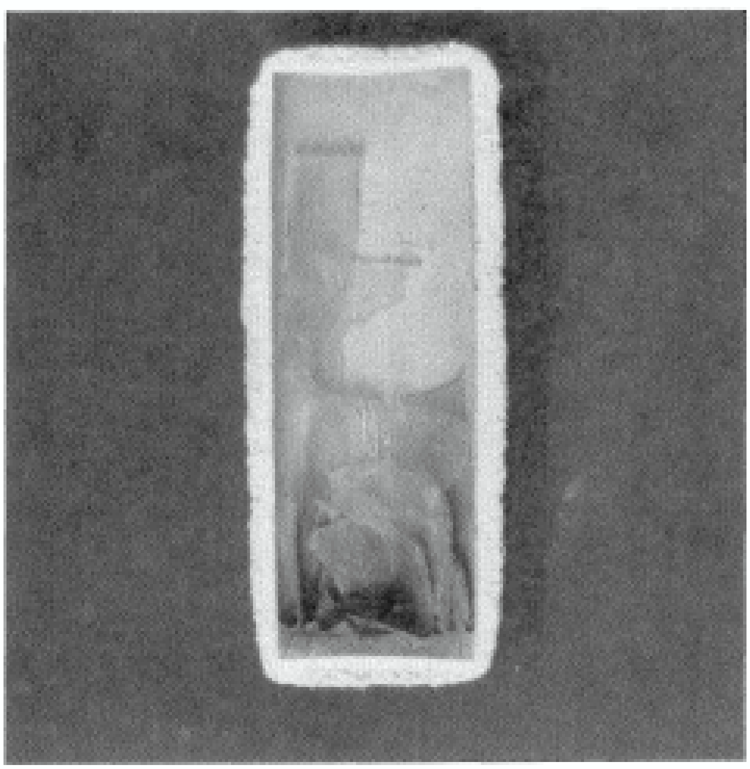


Figure 1



Section through the hollow cylinder after the shell has been through the autoclave.

Figure 2

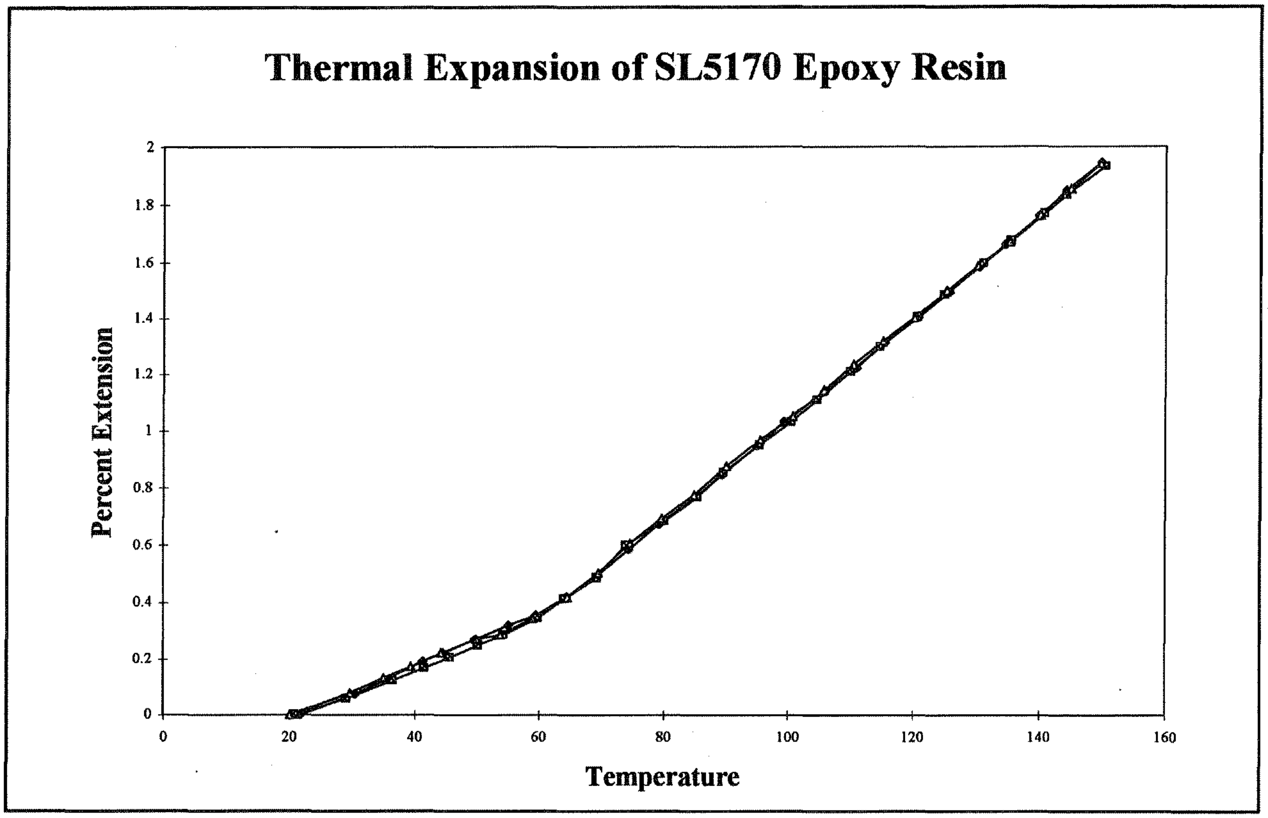


Figure 3

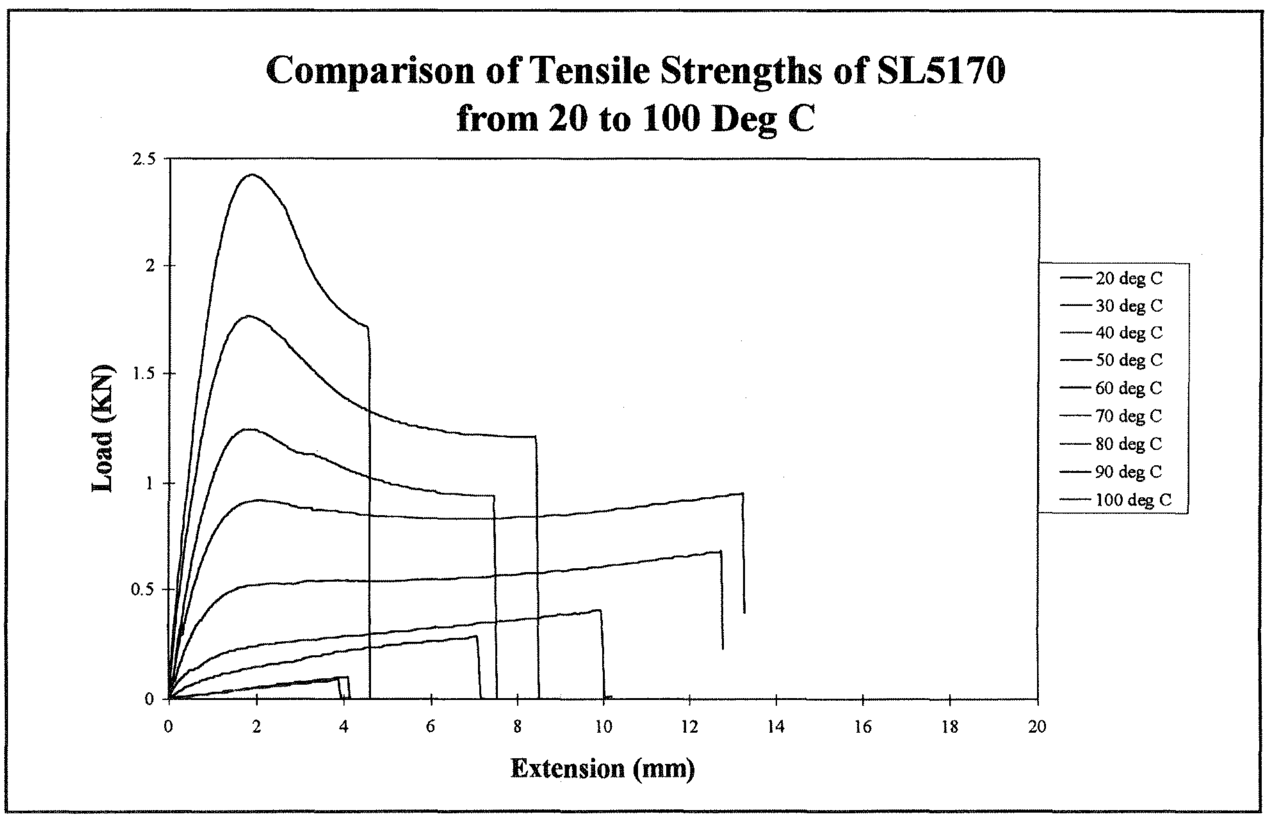


Figure 4

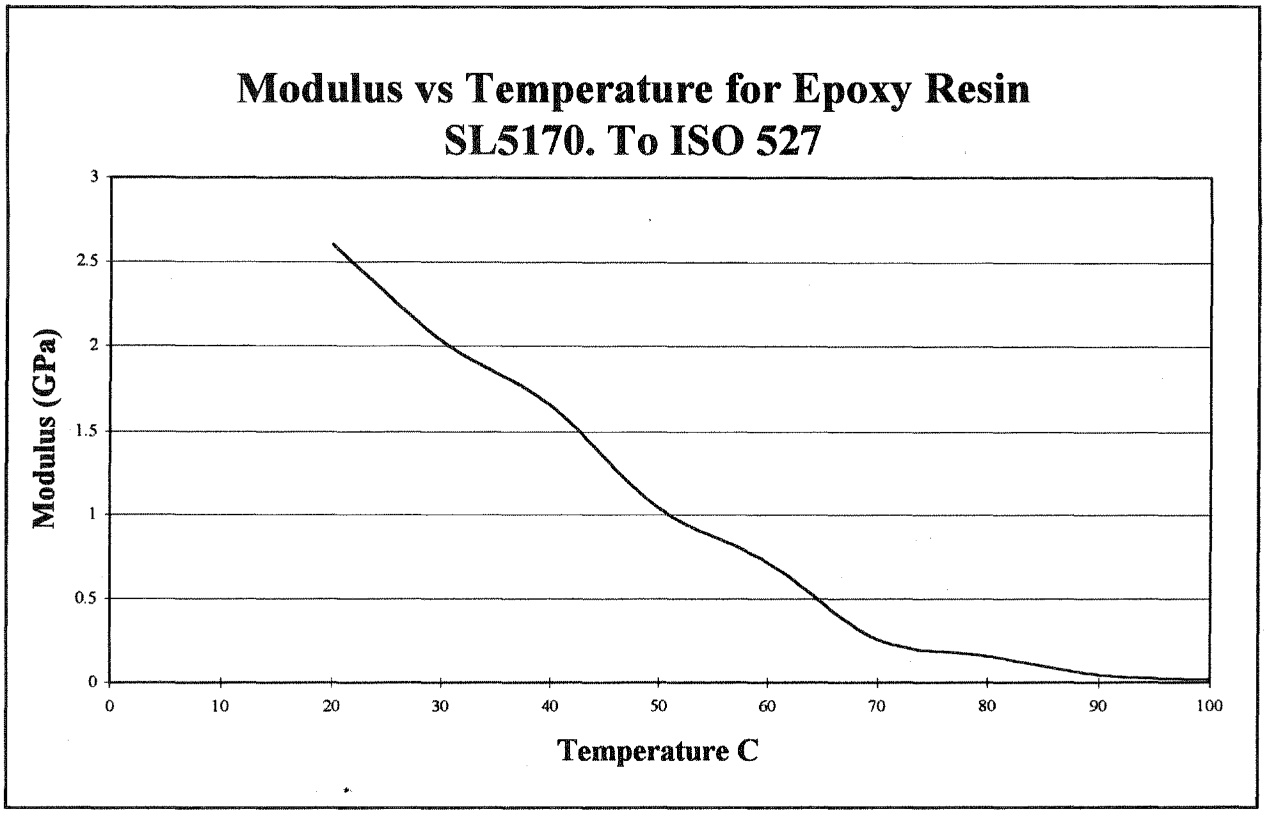


Figure 5

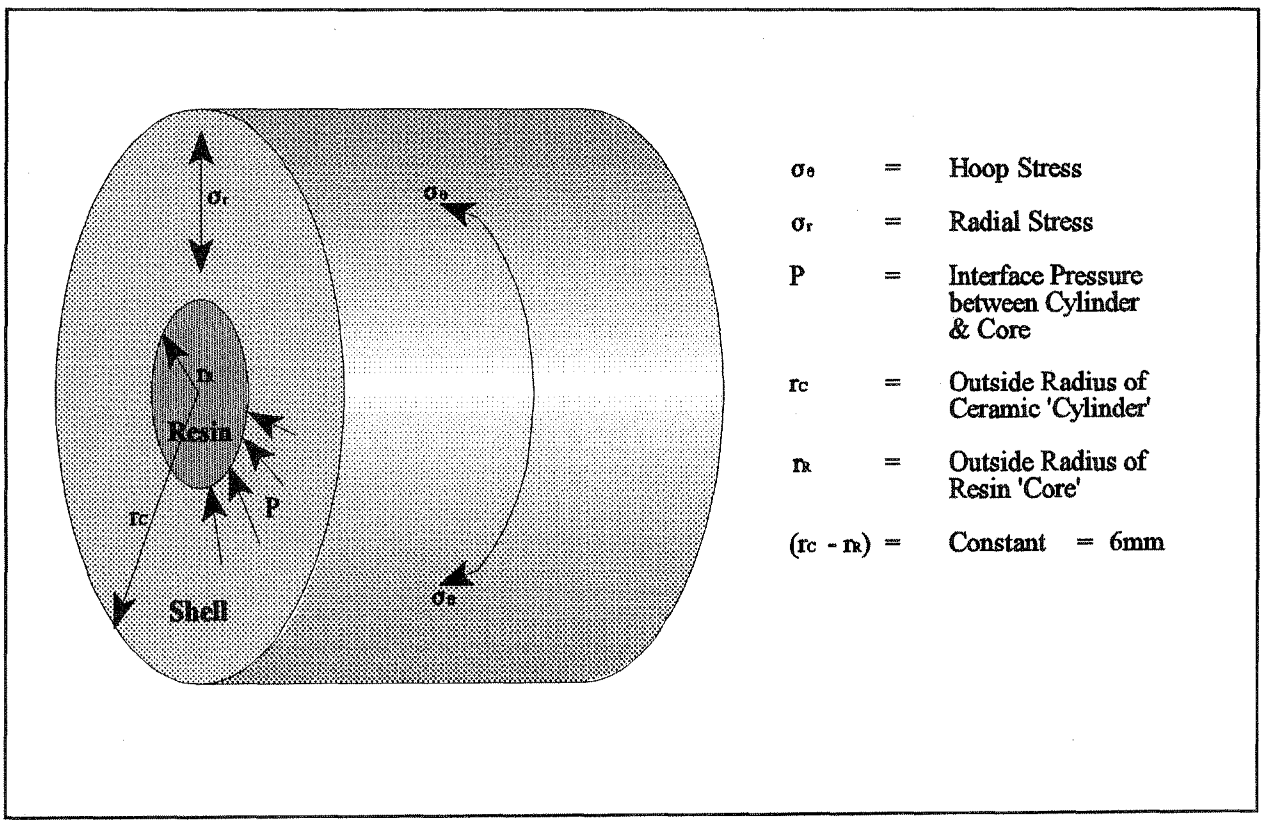


Figure 6

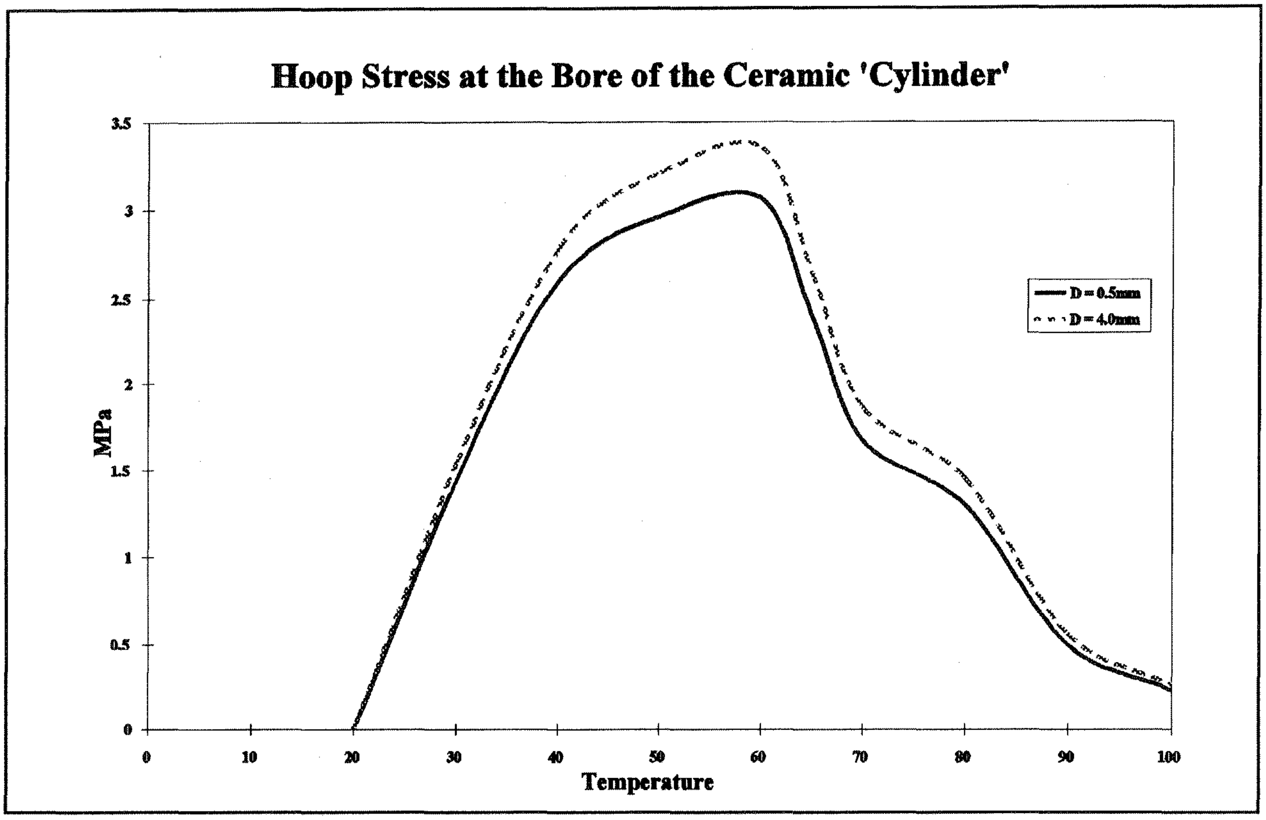


Figure 7

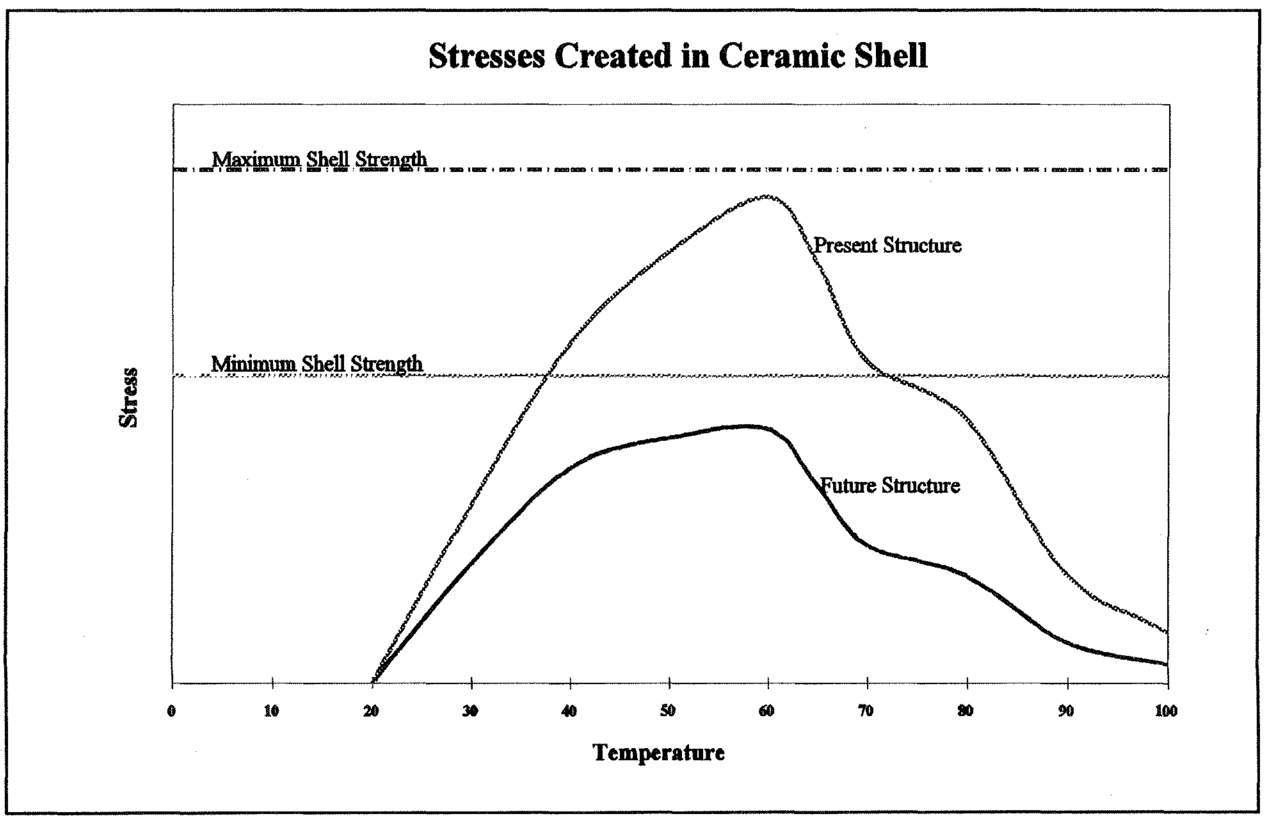


Figure 8