Thermal Effects on Accuracy in the 3DKeltool^{TM} Process

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Abstract
The 3DKeltool^{TM} process has been used to produce injection moulding inserts capable of producing millions of parts with quick cycle times (1). Short lead times are possible however accuracy is reduced for dimensions over 150mm.
The use of room temperature vulcanising (RTV) silicone rubber in the 3DKeltool^{TM} process is a possible reason for the loss of accuracy in larger parts. Effects of temperature changes during the process are assessed both theoretically and experimentally.
The results show close agreement between theoretical predictions and experimental results for dimensional changes. Suggestions which could allow accurate manufacture of larger 3DKletool^{TM} parts are presented.

Background
The 3DKeltool^{TM} process uses a master, such as a stereolithography (SL) model, to make injection moulding inserts or electrode discharge machining (EDM) electrodes from powdered metal. The process uses intermediate steps which involve creating moulds from RTV silicone rubber (see Figure 1).

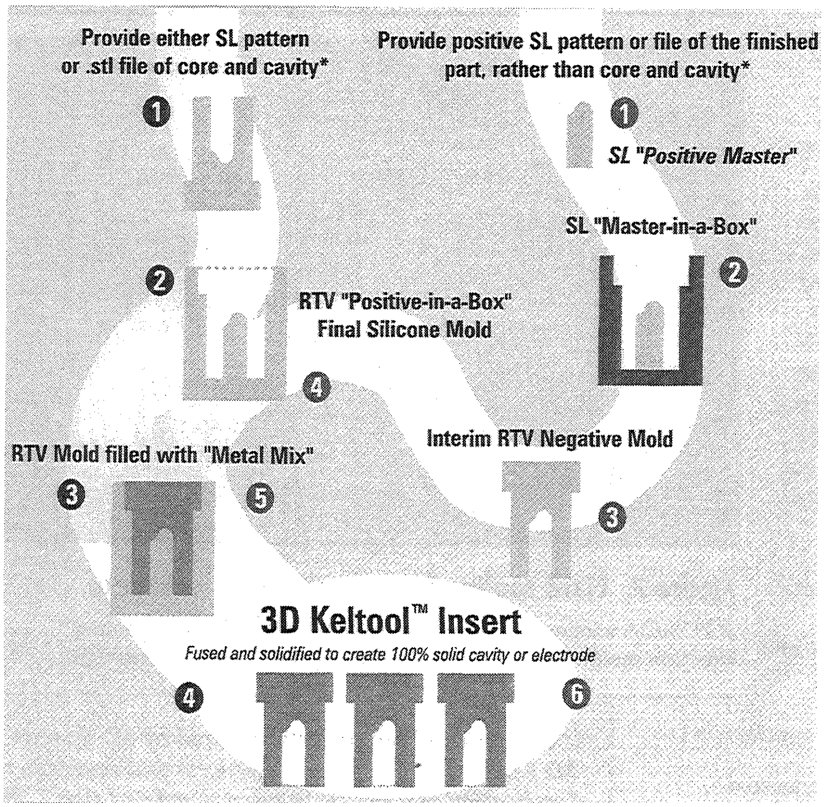

Figure 1: Outline of the 3DKeltool^{TM} Process

The work covered in this paper is concerned with producing the RTV silicone rubber moulds and not with any of the later stages of the 3DKeltool™ process. This means that the work is also relevant to other processes such as vacuum casting with RTV silicone rubber moulds.
One of the major constraints with the current 3DKeltool™ process is that its use is limited to parts with dimensions under 150mm if high accuracies are to be achieved. The high coefficient of thermal expansion (CTE) of RTV silicone rubber is thought to be a possible cause for this limitation on part size when high tolerances are required. It is important to consider tolerances required in tooling when assessing the effects of any sources of loss of accuracy. For engineering parts tolerances of +/- 50 microns are usually specified although in some cases +/- 10 microns may be required (2).

Thermal Properties of materials used in the 3DKeltoolTM Process
When using the 3DKeltool™ process to create injection moulding tooling, the materials used are SL cured epoxy (as the master), cured RTV silicone rubber (for intermediate mould(s)) and tool steel (the final injection moulding insert). The linear CTEs for these materials at around room temperature are:

SL5170	8.8×10^{-5} mm/mm/°C
RTV Silicone Rubber	30×10^{-5} mm/mm/°C
Tool Steel	1×10^{-5} mm/mm/°C

How Thermal Properties Limit Accuracy
Figures 2 - 4 show how much expansion will be caused by temperature increases in parts made from the materials used in the 3DKeltoolTM process. Note that temperature decreases will result in similar contractions in dimensions.

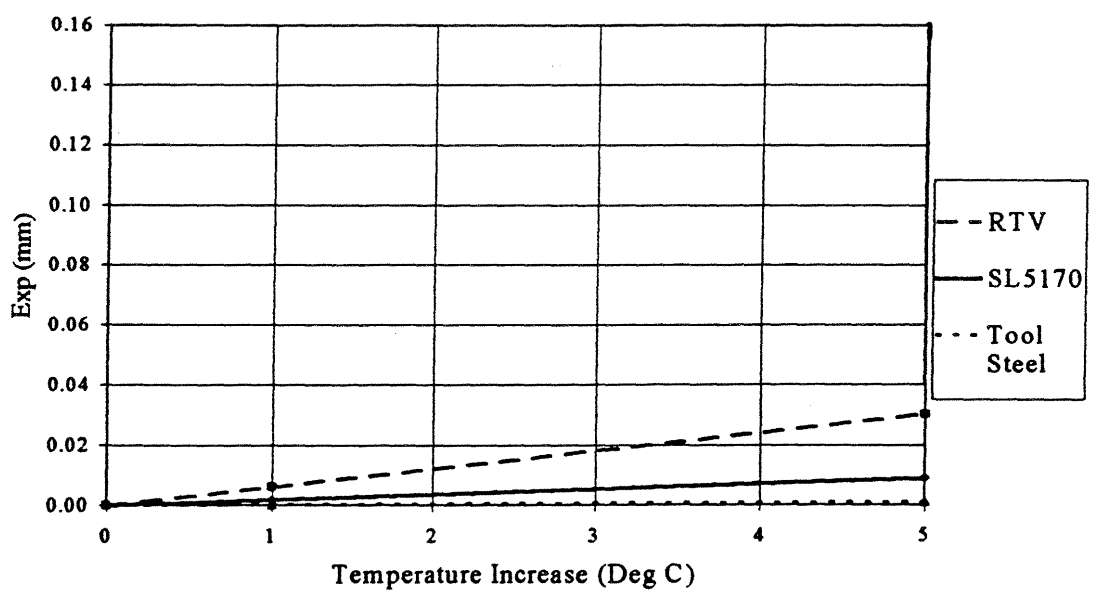

Figure 2: Effect of Increased Temperature on 20mm Dimensions

Figure 2 shows that for dimensions of 20mm or smaller, a change in temperature of up to 5°C (which is not unreasonable (3)) with either of the three materials shown should not be sufficient to cause expansion or contraction of over 50 microns through thermal expansion/contraction alone. The RTV silicone rubber is shown to change dimensions as a result of thermal expansion/contraction more than the other materials with an expansion of 30 microns caused by a temperature change of 5°C.

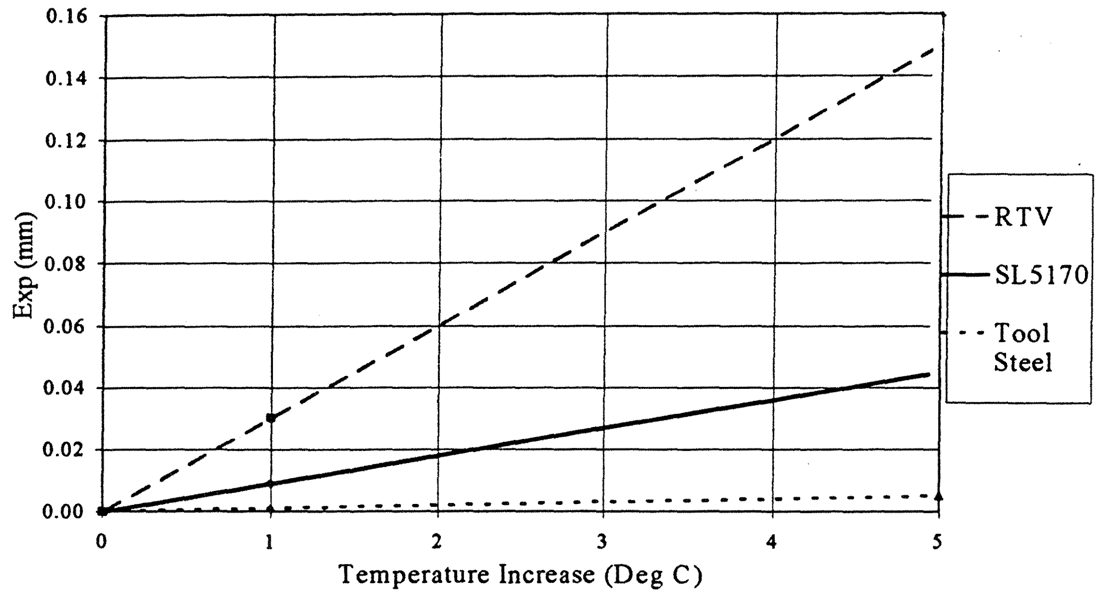

Figure 3: Effect of Increased Temperature on 100mm Dimensions

Figure 3 shows the amount of thermal expansion which may be expected in dimensions of 100mm which approaches the maximum size to which parts can be accurately made using the 3DKeltool™ process. The steep slope of the graph representing RTV silicone rubber thermal expansion indicates that a temperature change of only 2°C is sufficient to breach the 50 micron tolerance threshold with dimensions of 100mm. This suggests that the temperature control during the RTV silicone rubber stages of the3DKeltool™ process must be tight (around +/- 1.5°C) in order to produce parts with tolerances of +/- 50 microns. Such temperature control is unrealistic in most factory situations however under controlled conditions such as in a metrology laboratory tighter control (+/- 1°C) is possible. The graphs for SL resin and tool steel, however, indicate that thermal expansion alone will not cause 100mm dimensions to be outside a 50 micron tolerance if a +/- 5°C temperature can be maintained.

Figure 4 shows the thermal expansion caused in 200mm dimensions which is greater than the maximum size with which 3DKeltool™ parts can be produced to high tolerances. A temperature change of only 1°C will cause a dimensional change of 60 microns in RTV silicone rubber parts of this size. For SL parts, thermal expansion with a temperature change of 3°C will cause a dimension of 200mm to be outside a 50 micron tolerance, whereas the thermal expansion of tool steel remains negligible with regard to accuracy for parts of these sizes.

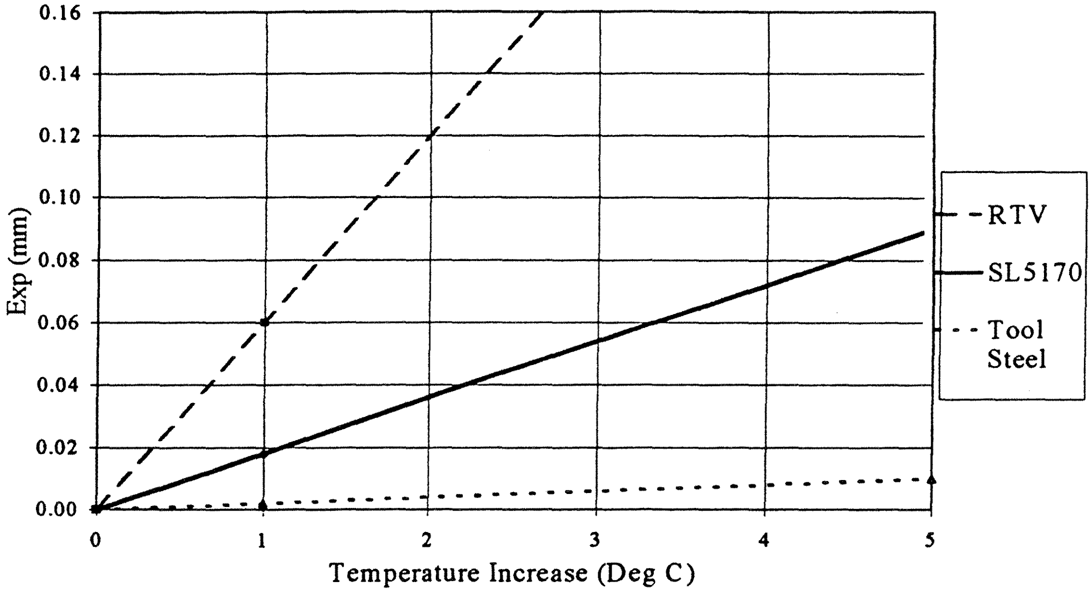

Figure 4: Effect of Increased Temperature on 250mm Dimensions

Practical Assessment of Effects of Heat on Accuracy

Method

The effects of heat on mould geometry were measured in a simple test using one SL mould built in the ACES build style and another mould made from RTV silicone rubber which had be cast around an SL master. The moulds used were based on a typewriter part with a largest dimension of 180mm (see Figure 5).
A thermocouple was inserted into the centre of each of the moulds which were then slowly heated on a lagged hot plate. When the mould temperature had risen to 45°C the mould was removed from the hot plate, placed on a co-ordinate measuring machine (CMM) and allowed to cool while measurements were taken. Ideally measurements would have been made using a non-contact method as softening of RTV silicone rubber during heating could affect the CMM results. It was assumed, however that such effects would be negligible.

Results

Figure 6 shows a clear shrinkage as the RTV silicone rubber mould was allowed to cool. The measured CTE for the RTV silicone rubber mould was 49×10^{-5} mm/mm/°C which is slightly higher than had been predicted. The reason for this being slightly higher than expected may be due to softening of the rubber at higher temperatures as mentioned above.

The slope of the graph in Figure 7 is less steep than that in Figure 6 indicating a lower CTE as expected. The CTE for the SL mould was calculated as 9.2×10^{-5} mm/mm/°C, which again is slightly higher than that which had been expected.

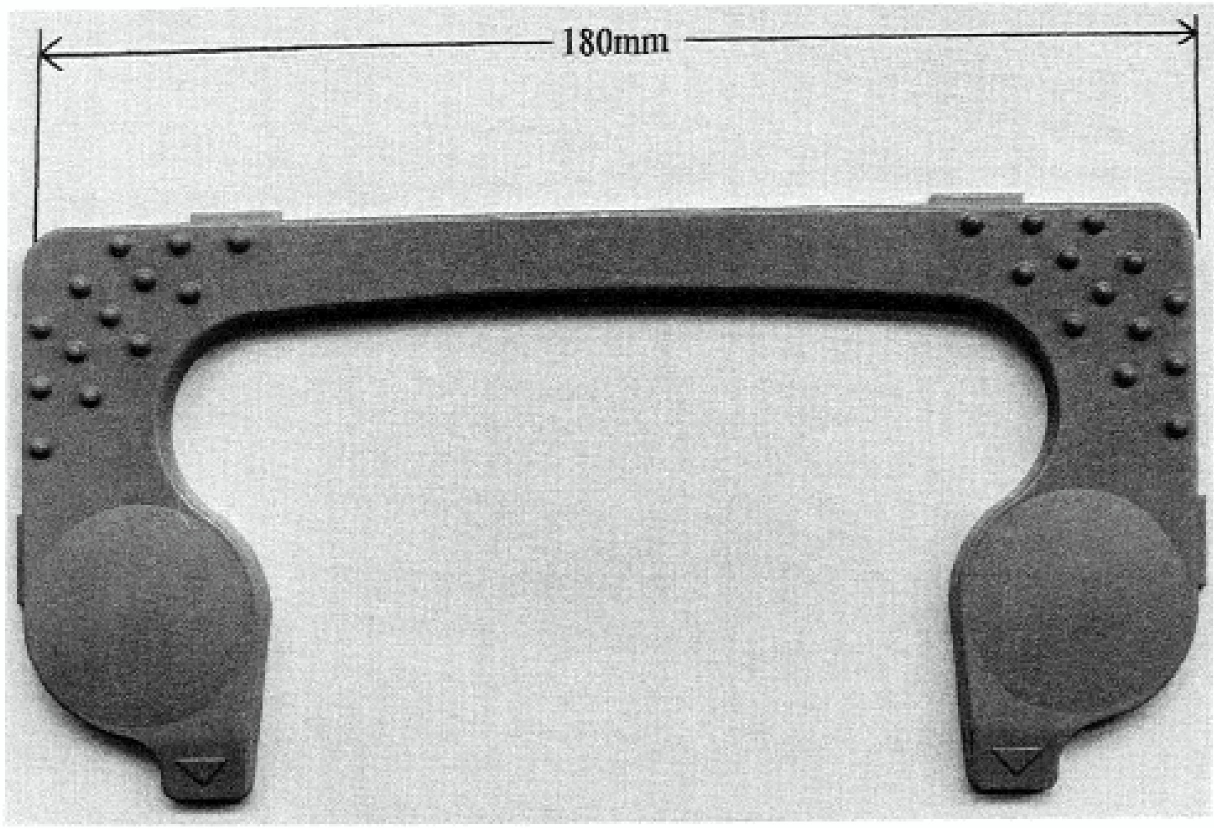

Figure 5: Typewriter part which mould shape was based on

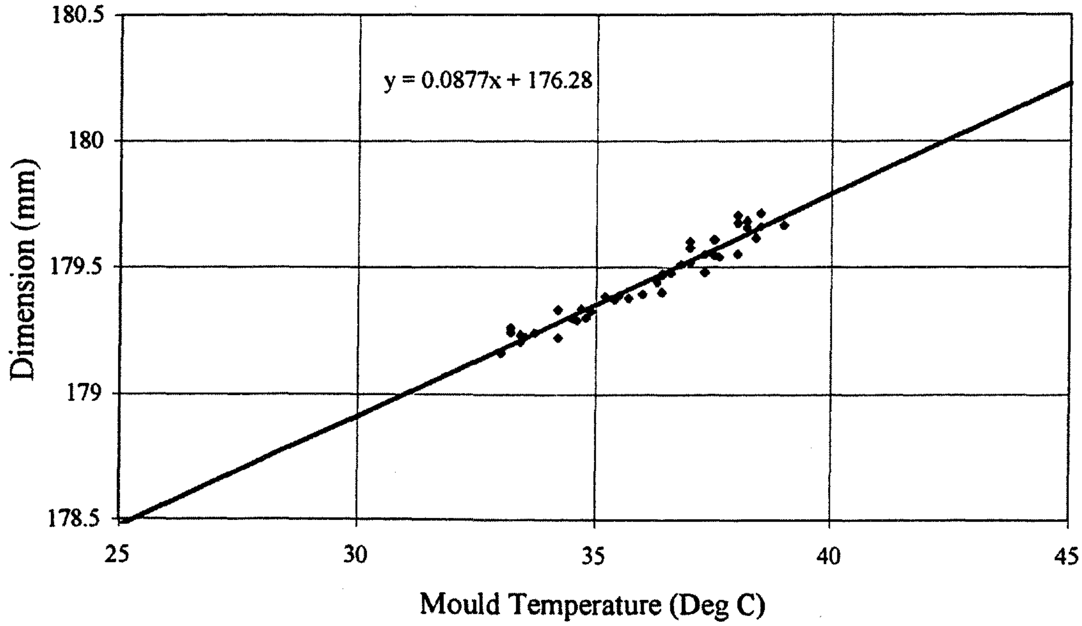

Figure 6: Graph showing relationship between RTV silicone rubber mould temperature and size

The measured CTEs for the RTV silicone rubber and SL moulds are similar to the expected values with the CTE of RTV silicone rubber being five times greater than that for SL5170. This would suggest that eliminating RTV silicone rubber from the 3DKeltool™ process could allow larger parts to be produced more accurately or with less temperature control.

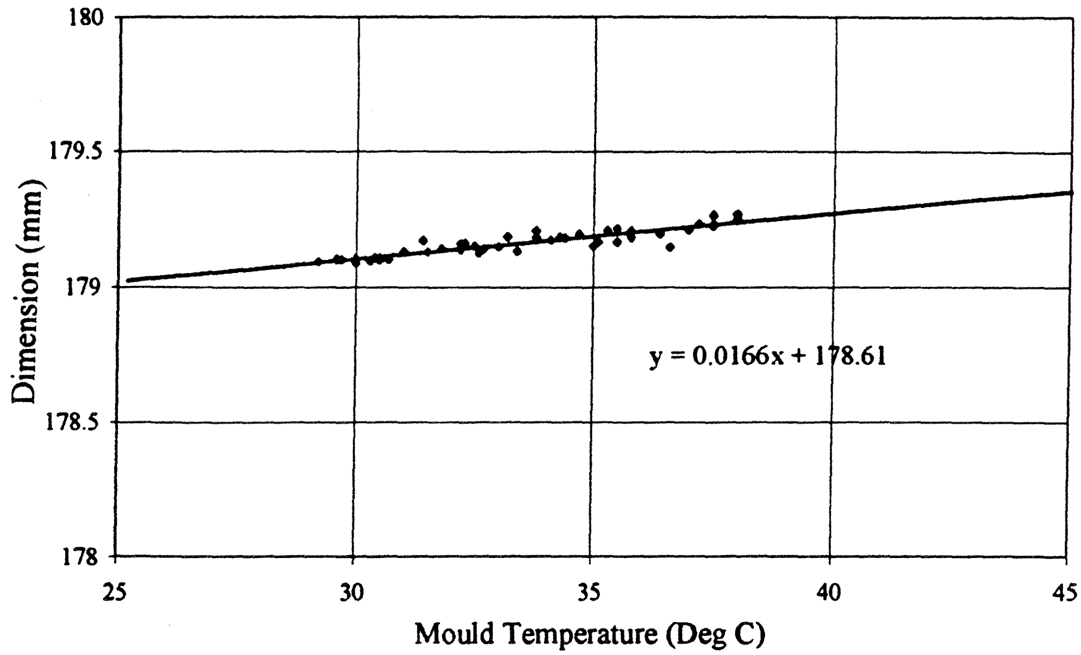

Figure 7: Graph showing relationship between SL mould temperature and size

Alternative Method

A number of possible alternatives to RTV silicone rubber have been considered by the authors including the use of low melt point alloys, wax, plaster of paris and direct SL use. However RTV silicone rubber has the advantages of good release, avoiding damage of the original SL model and green insert, and faithful reproduction of original features. For this reason, a composite mould consisting of an SL body with an RTV silicone rubber membrane was used. The idea behind the RTV silicone rubber membrane mould was to keep the advantages of good release and reproduction while minimising the effect of its high CTE.

Figure 8 shows how an RTV silicone rubber membrane mould is made, the injected RTV silicone rubber is allowed to cure at room temperature and then the core is removed. By allowing the RTV silicone rubber to key into the open Quickcast structure of the cavity part, the membrane remains fixed to the cavity with a surface that directly reflects the surface of the core part.

Practical Assessment of RTV Membrane Mould

An RTV silicone rubber membrane mould was made for the typewriter part mentioned above and this was subjected to the same test as the RTV and SL moulds had been in order to establish the effects of temperature on dimensions. Figure 9 shows the graph of temperature against mould dimensions. As expected the slope is between those for the solid RTV silicone rubber mould and the SL mould but much closer to the SL mould. The equivalent CTE was calculated to be 12 x 10^{-5} mm/mm/°C which is under 25% of that for the solid RTV silicone rubber mould.

The effects of temperature on accuracy when using RTV silicone rubber moulds could be dramatically reduced allowing larger parts to be made with higher tolerances while still having the same variations in room temperature.

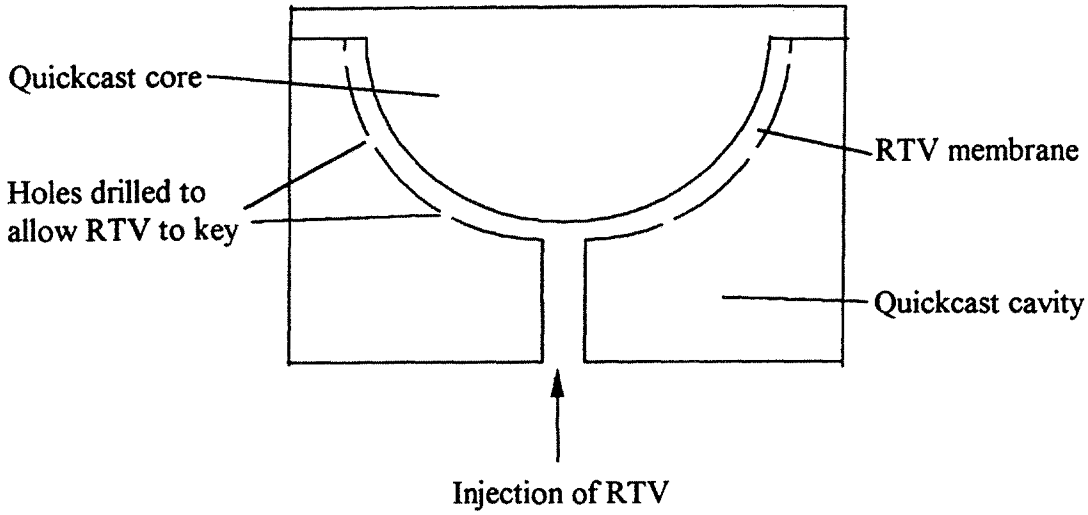

Figure 8: Cross section diagram showing how an RTV silicone rubber membrane mould is made

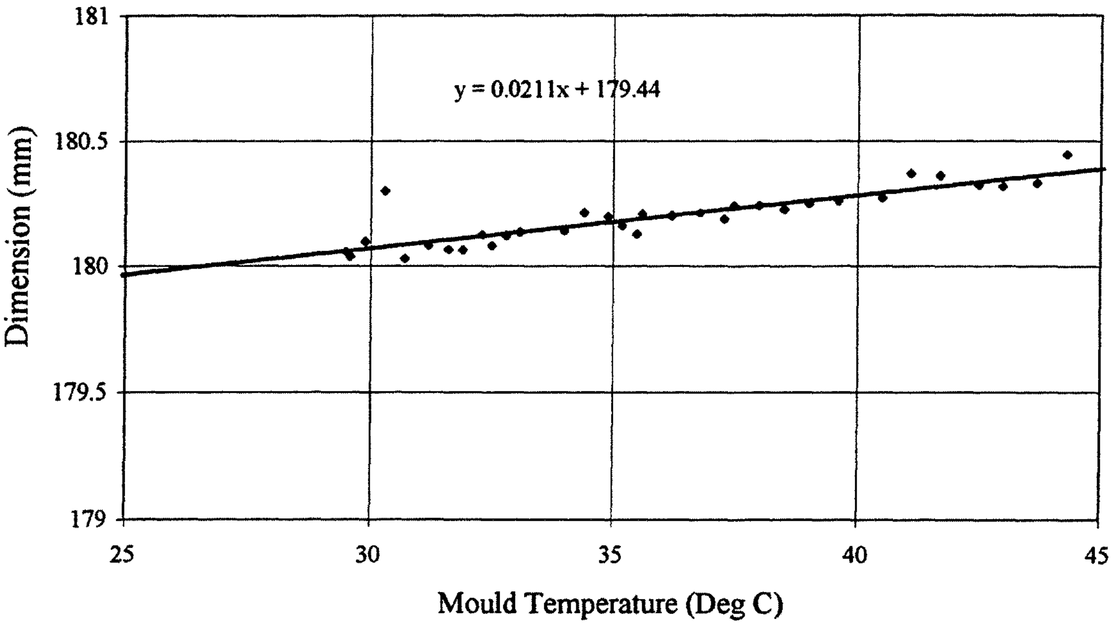

Figure 9: Graph showing relationship between RTV silicone rubber membrane mould temperature and size

Based on the measurements taken, assuming that a tolerance of +/- 50 um is required and temperature control of +/- 1°C can be maintained, the maximum part dimensions are :

RTV mould:	100mm
RTV membrane mould:	425mm

In fact for larger parts the effect of the CTE of the RTV silicone rubber membrane becomes less as a percentage of all thermal expansion and larger dimensions should be possible with the same temperature control.
Alternatively, using the RTV silicone membrane mould would allow production of a 100mm part with far looser temperature control. The temperature control required for such a part would only be +/- 4.25 °C as opposed to +/- 1°C.
The quality of the surface using an RTV silicone rubber membrane was as good as any conventional RTV silicone rubber mould.

Conclusions

The use of RTV silicone rubber in the 3DKeltool™ process has been shown as a possible reason for the limits on part sizes when producing high accuracy tooling. The alternative method of using an RTV silicone rubber membrane keyed into a QuickCast structure was successful in terms of its reduced thermal expansion and the quality of reproduction from the original SL model. This method should be particularly applicable to accurate vacuum casting of large parts.
The RTV silicone membrane method does, however involve extra time and cost especially due to the fact that an extra SL part is required. Alternatives methods to allow an RTV silicone rubber membrane to key into a base have been considered. The most promising of these is to used plaster of paris. By vibrating the SL model in curing plaster of paris with an amplitude equal to the required membrane thickness a sub mould is created. RTV silicone rubber is then poured into the plaster of paris sub mould, the SL model is pressed into the mould and the membrane is allowed to cure. The membrane which is achieved is not as uniform as that produced with a QuickCast sub mould however the cost will be less. Also, the CTE of plaster of paris is less than that of SL resin which suggests that even larger parts may be made to the same tolerances and with the same temperature control.

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