Effect of Mold Temperature on High-resilience (HR) Cold-cure Flexible Polyurethane Foam Surface Texture

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ABSTRACT

Flexible polyurethane foam is often molded directly into preheated tools for foaming reaction which expands to fill the mold cavity. The foam that is directly in contact with the mold surface cures as the foam skin. Parts frequently have surface defects ranging from shrink marks, to voids, to mottling and knit lines. There are many possible causes such as applying too much or too little release agent, or mold surface not cleaned and conditioned as required before the foaming process. Uneven mold temperatures are also suspected to be a cause of surface defects, especially in high-resilience (HR) cold cure polyurethane foam systems. A specially designed mold capable of maintaining tight temperature tolerance was built to produce foam samples at varying temperatures. The effects of mold surface temperature on the foam surface texture are studied and analyzed. The effect of processing temperature on the macro and micro surface texture is examined. It is shown that the processing temperature has a significant effect on the foam surface texture. 3D topographical analysis of foam surface texture discovered a trend from samples produced at varying temperature from 30^0C to 80^0C. This research is funded by EPSRC and assisted by Collins and Aikman UK and Rojac Tooling Technologies Ltd.

Keywords: Polyurethane foam; Surface texture; Mold temperature; Surface roughness

INTRODUCTION

Flexible polyurethane (PU) foam captures the major foam market for upholstery, mattresses, automotive seats and interiors, carpet backing, packaging and padding [1]. PU foam molded products are manufactured by mixing raw materials, a polyol and an isocyanate, in a preheated tool. The heat from the tool promotes urethane polymerization and foaming which expands to fill the mold cavity.

PU foam molding tools are typically manufactured from aluminum by machining with straight heating channels drilled to take the heating fluid. In the flexible foam molding process, particularly cold-cure flexible foam molding, temperature control is a very important factor. The process requires uniform surface temperature throughout the mold. Temperature variation leads to variable foam flow and encourages foam collapse, scaling of the foam surface, cavities left void and varying foam densities [2, 3].

Proper thermal management of PU foam molding tooling is critical for increasing overall part quality and thereby reducing scrap rates [4, 5]. The objective of this research is to understand the effects of mold temperature on the surface texture of HR cold-cure flexible foam parts. The effect of processing temperature on surface roughness is presented.

Much of the work previously undertaken to reduce flexible foam molding scrap and improve quality has focused on chemical compositions, chemical reactions and materials development [6]. No detailed published work focusing on the effect of mold temperature on high-resilience cold-cure polyurethane foam molded parts has been found.

Current and past research on mold temperature control has largely focused on plastic injection molding tools rather than polyurethane foam molding tools mainly due to the larger market share attributed to the injection molding process [7]. Furthermore, most of this research has been biased towards mold cooling rather than heating due to the intrinsic problem of heat build-up in injection molds [8].

The aim of this research is to assess the effect of mold temperature on the surface texture of polyurethane foam parts in the HR cold-cure polyurethane foam molding process.

EXPERIMENTAL METHODOLOGY

Polyurethane foam specimens of standard size, complying with the Standard Test Methods for Flexible Cellular – Slab, Bonded, and Molded Urethane Foams ASTM D 3574 –95, were produced for testing the effect of mold temperature on the foam surface texture. The ASTM D 3574 – 95 stipulates that a representative specimen of regular shape measuring at least $0.1m^2$ in area by full-part thickness of 25 mm is used. A specially designed mold capable of maintaining tight temperature tolerance was built to produce foam samples at varying temperatures. A non-contact 3D laser scanning gauge was used to measure and quantify the foam surface roughness.

Tool Design

A mold capable of holding tight temperature tolerance was built to produce the polyurethane foam specimens. Perstorp Components Soft Foam Tool Design Guideline and Specifications was used to design, fabricate and test the mold. The important guidelines and specifications are listed below:

- Tool must be airtight while foaming.
- Foam shut off face width = 20 ± 2 mm.
- Vertical shut off faces must be avoided at all times. Maximum angle 10^0 from vertical.
- Internal venting must be avoided.
- No porosity on tool surface.
- Nominal wall thickness = 20 mm (tolerance = 18 mm – 25 mm).
- Tools must be water tested to 100 PSI (6.5 bar) for a minimum of 1 hour.
- Water channels to be 15 mm diameter where possible (10 mm minimum diameter where it is not possible to use 15 mm).
- Pipe joints to be away from injection head.
- For all joints and fittings, each must be straight for minimum of 30 mm after any bend.
- Position of Water Inlet and Outlet connection at mold side or rear.
- Nominal thickness around water channel = 5 mm – 10 mm.

Conforming to the above guidelines and specifications, the following is a list of the mold design.

Mold cavity	: 32 cm x 32 cm
Cavity depth	: 2.5 cm
Surface area	: 32 cm x 32 cm = 1024 cm^2 (0.1024 m^2)
Volume	: 32 cm x 32 cm x 2.5 cm = 2560 cm^3 (0.00256 m^3)

Layout of Mold Heating Channels

Conventional gun-drilled holes for mold heating channels (Figure 1) were found to be unsuitable due to the tendency of water to flow the shortest and easiest route. Milled-grooves were found to ensure better water flow as compared to gun-drilled holes.

The dimension of the heating channel was 15 mm wide and 17 mm deep, thereby achieving a close 8 mm distance to mold surface. Hot water from a heater was passed through the back of the mold via the channel of flat-milled grooves (Figure 2) to achieve a uniform heat distribution throughout the mold surface. A plate was used to cover and prevent leakage from the heating channels.

Clamping Unit and Flash

During the polyurethane foam molding process, it is critical to avoid flashing of foam between the molds halves that will produce parts with a thin layer of foam material around its fringes (Figure 3). Flash occurs when the pressure inside the mold arising from polyurethane foaming reaction is greater than the clamping force holding down the mold lid. Flash will results in loss of foam mass and density.

A good clamping system was required in order to avoid foam from flashing between the lids. A rotational wedge-web was designed to quickly and firmly clamp down the mold lid (Figure 4). The angle of the wedge slope required to get the maximum clamping force is calculated from the coefficient of friction between steel wedge and steel which was between 0.1 – 0.12 (Figure 5).

<u>Calculation for maximum clamping force:</u>

The coefficient of friction for steel on steel = 0.1

Therefore, $\tan^{-1} 0.1 = 5.7^0$

5.7^0 angle used to machine slope the wedge.

Thermocouple

Thermocouples were inserted at various locations to track the mold surface temperature throughout the experiment. The thermocouples were inserted through small holes drilled up to 0.5 mm to the mold surface. The thermocouples were inserted at various locations as shown in Figure 6 to record the mold surface temperature throughout the experiment.

Finite element analysis, as shown in Figure 7, was conducted to ensure that the drilled holes do not cause mold rupture during the foaming process, which generates close to 2 bar pressure inside the mold.

The selection of a particular thermocouple type ideal for the mold multi-point temperature measurement required in this experiment is based on the following criteria: sensing application; physical conditions; accuracy; sensitivity and compatibility with the existing data-logging equipment, CR10X data-logger.

T-type thermocouples, Copper-Constantan (BS EN 60584.1 Part 5), were used since the mold temperature range for this experiment is limited between 30^0C to 80^0C. At low temperature range, the T-type thermocouple has a very close tolerance of ± 30 μV (± 0.50^0C) and can perform even when moisture may be present. Repeatability is in the range up to 200^0C (±0.1^0C). To ensure correct temperature readings were recorded, two thermocouples were calibrated at UKAS certified facilities. The calibrated thermocouples were used as benchmarks to gauge the accuracy of the rest of the thermocouples. Tests were performed using steam and freezing water, and the output for all thermocouple were confirmed to be within ±0.3^0C range. The thermocouples were linked to the data-logger and a laptop computer to record the mold temperature across the mold (Figure 8).

Manufacture of Test Specimens

The foam-molded specimens were manufactured by mixing polyol and diisocyanate diphenylmethane (MDI) using micro cell mixing and metering equipment. The mold was preheated to the required test temperature. The heat from the tool helped to initiate the reaction and cure the material, which expanded to fill the mold cavity.

The mixed material was dispensed into the open mold through the mixing head, and the lid was quickly closed to avoid foam from flashing. It was important to ensure that the tool was airtight to avoid decompression faults on foam parts.

The initial experiment was conducted at a mold temperature of 70^0C then followed by 80^0C, 60^0C, 50^0C, 40^0C and finally at 30^0C, with the same procedure repeated for each molding cycle. Five specimens were molded at each mold temperature with the same amount of shot injected at the exact location in the mold, while release agent was sprayed after every three shots. The molding time was 90 seconds, after which specimens were demolded (Figure 9), rolled, weighed and labeled. A cast iron bar was used to roll over the specimen to break the closed-cell structure. Immediately after the foam specimen was demolded and rolled, each sample was weighed on a precision balance (Figure 10), and the length, width and thickness were measured to calculate the initial densities. The samples were again weighed after 14 days, and the length, width and thickness were measured again to calculate the densities.

SURFACE TEXTURE INSPECTION

Every surface has some form of texture whether it is smooth or otherwise. The easiest and most common method for assessing a surface texture is through visual inspection or sensual touch (Figure 11). Both these techniques are limited to qualitative assessment and very subjective to evaluator preferences.

As recommended by the ASTM D 3574, all tests were performed more than 14 days after the foam had been manufactured. The foam specimens were kept undeflected and undistorted at the temperature and humidity of test for more than 12 hours before tested at a temperature of 23 ± 2^{o}C and in an atmosphere of 50 ± 5% relative humidity.

Considering that the foam surface is very soft and porous, the method adopted for surface measurements was a non-contact gauging technique provided by the Talysurf CLI system. This system uses a 10 mm laser triangulation gauge to deduce the height of a surface point by sensing the position of a laser spot on the surface using a CCD detector placed at an angle away from the incoming laser beam (Figure 12).

The main requirement was to measure the surface texture produced at varying mold temperatures. The two main elements of surface texture are roughness and waviness. Micro surface analysis was conducted to quantify the surface roughness and macro surface analysis to quantify the surface waviness. Micro and macro analyses were conducted for top and bottom surfaces of the foam specimens.

Micro Surface Roughness Inspection

A spacing of 50 x 50 microns (X and Y-axis) was used to scan a 10 mm x 10 mm area in the middle section of the specimen (Figure 13). A grid of 201 x 201 points or scan traces in both X-axis and Y-axis was used to measure the micro surface data.

Macro Surface Roughness Inspection

The specimens were next measured over an area of 150 mm x 150 mm in the middle section (Figure 14) with a spacing of 5000 x 5000 microns for macro surface texture analysis. A grid of 31 x 31 scan traces in X and Y-axis was used to measure the macro surface data. Both the macro and micro surface data were then post-processed for 3D topography and 3D surface roughness (Sa) using Talymap Universal software.

The recorded Sa values for micro and macro for both top and bottom foam surfaces are tabulated for comparative analysis between different mold temperatures.

RESULTS AND DISCUSSIONS

Surface roughness average, Sa, as defined in EUR 15178EN is the average absolute deviation of the measured surface. Surface roughness average, Sa, is very much similar to Roughness average, Ra. In measuring the Ra value, sampling length and assessment length is used, while in measuring Sa, sampling area and assessment area is used instead. Ra and Sa are the most commonly used parameters in surface texture analysis [9]. Sa units are length, typically microns.

Using the Talysurf 3D laser scanner, each foam sample surface roughness was measured, and the average surface roughness at each mold temperature was calculated and tabulated. Table 1 tabulates the macro surface roughness of the top surface.

Figure 15 shows the surface roughness, Sa, obtained from the macro analysis of the foam top surface. Foam samples produced at 50^0C gave the smoothest surface roughness. As mold temperature deviates away from 50^0C the Sa values measured were higher.

Similar results was obtained for the macro analysis of bottom surface, with foam samples produced at 50^0C having the smoothest surface roughness. Surface roughness deteriorates as mold temperature deviates away from 50^0C as shown in Figure 16. Very small Sa standard deviations were recorded at 50^0C and 70^0C while the largest standard deviation were recorded at 60^0C.

The scanned surface data fed to the Talymap Universal software was used to generate 3D topographical illustrations of the macro foam surface texture at various mold temperatures as shown in Figure 17. The topography indicates a very much smoother surface produced at 50^0C as compared to those at 40^0C and 60^0C, with undulating peak and valleys attributed to scaling and shrink marks.

The micro analysis of the foam surface roughness for both top and bottom surfaces have a similar results as in macro analysis with average Sa values lowest at 50^0C with a slight increase of Sa as the mold temperature deviates from 50^0C. Figure 18 and Figure 19 shows the surface roughness, Sa, obtained from the micro analysis of the foam top surface and bottom surface, respectively.

The effect of mold temperature on foam micro surface roughness can be qualitatively analyzed by inspecting the scan photo simulation shown in Figure 20. It can be seen that the foam produced at 50^0C had the finest surface texture free from scaling and mottling, as compared with specimens produced at other temperatures.

Micro

The micro surface roughness for top and bottom surface is best at 50^0C at 53 microns and 48 microns, respectively, with uniform surface texture. As the mold temperature increases above 50^0C, the surface roughness for both top and bottom surface get coarser at almost the same value, with visible mottling forming on the surface. Meanwhile, when the mold temperature decreases below 50^0C, the measure of surface roughness for top surface is slightly coarser than the bottom surface with more visible scaling marks comparatively.

Macro

Similarly, results shows that the macro surface roughness for top and bottom surface is best at 50^0C. As the mold temperature decreases below 50^0C, the surface roughness for both top and bottom surface get coarser. The surface texture is rougher at 30^0C with high Sa value due to void marks. Sa value decreases at 40^0C with some scaling marks and is lowest at 50^0C with fine and uniform texture. The roughness rapidly increases, attributed to shrink mark, knit lines and mottling as the mold temperature increases towards 80^0C. The variations in Sa value at 60^0C is attributed to noise after running a statistical Multiple Range Tests which shows that the variation is not significant (Table 2).

The top and bottom surface roughness at 50^0C drop to 57 microns and 77 microns, respectively, from about 140 microns at 40^0C. Similarly the top and bottom surface roughness starts getting coarser rapidly from 57 microns and 77 microns to 160 microns and 215 microns, respectively, as mold temperature increases from 50^0C to 60^0C.

This indicates that the macro surface texture is greatly affected by mold temperature varying away from 50^0C. High Sa at low temperature is attributed to incomplete curing, and high Sa at high temperature was due to evaporation of release agent wax.

CONCLUSIONS

A study of the effects of processing temperature on the foam surface texture was presented. It was shown that the mold temperature had significant and repeatable effect especially on the macro surface texture. Variations in surface roughness were observed at varying mold temperatures due to voids, shrink marks, scaling, knit lines and mottling. These variations are large enough to warrant careful considerations of mold temperature management when forming foams in the mold. It can be suggested from these findings that temperature of a production mold should be held at close tolerance to maintain a uniform surface texture. Temperature variations across the surface of foam tools, especially larger tools, is most likely one of the main reasons why foam parts have varying surface texture which often leads to scrap.

ACKNOWLEDGEMENT

We gratefully acknowledge Collins & Aikmans for helpful discussions and cooperation in allowing usage of their foam materials, foaming facilities and technical expertise. Rojac for their helpful inputs for mold design and fabrication. Taylor-Hobson for their expertise and surface measuring equipment. We would also like to acknowledge the EPSRC research grant, which funded this research activity.

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VITAE

The Rapid Manufacturing Research Group is renowned in Rapid Prototyping, Rapid Tooling and Rapid Manufacturing are currently expanding research into polyurethane molds, investigating the effects of mold temperature, effects of thermal gradients and potential to use release agent free molds. This research is funded by EPSRC and assisted by Collins and Aikman UK and Rojac Tooling Technologies Ltd.

Caption below Figures

Figure 1. Gun-drilled holes heating channels.

Figure 2. Milled grooves heating channels.

Figure 3. Flash around foam parts.

Figure 4. Wedge clamping system.

Figure 5. Wedge slope for maximum clamping.

Figure 6. Location of thermocouples 0.5 mm below mold surface.

Figure 7. Stress analysis for thermocouple holes.

Figure 8. Thermocouples inside the mold linked to data logger and laptop to record mold temperature.

Figure 9. Foam ready to demold.

Figure 10. Precision balance to weigh foam.

Figure 11. Visual inspection of foam specimens. Top row from left: 30^{o}C, 40^{o}C, 50^{o}C. Bottom row from left: 60^{o}C, 70^{o}C and 80^{o}C.

Figure 12. Illustrations of laser system with CCD sensor.

Figure 13. Scanning a 10 x 10 mm area in the middle section.

Figure 14. Scanning area of 150 x 150 mm for macro analysis.

Figure 15. Macro top surface roughness for specimens produced at varying mold temperature.

Figure 16. Macro analysis of specimens bottom surface.

Figure 17. 3D topography of the scanned foam surfaces.

Figure 18. Micro top surface roughness for specimens produced at varying mold temperature.

Figure 19. Micro bottom surface roughness for specimens produced at varying mold temperature.

Figure 20. Scan photo simulation and the Sa values of micro foam surface texture at different mold temperatures.

Table

Table 1 Surface roughness average, Sa, for macro analysis of the foam top surface.

Temp. (^{O}C)	**30**	**40**	**50**	**60**	**70**	**80**
Sa (microns) Sample #1	296.0	142.0	83.3	118.0	90.5	85.7
Sa (microns) Sample #2	445.0	203.0	48.9	297.0	74.1	121.0
Sa (microns) Sample #3	339.0	110.0	64.6	169.0	78.2	119.0
Sa (microns) Sample #4	378.0	76.2	45.2	98.6	63.3	126.0
Sa (microns) Sample #5	242.0	164.0	44.2	131.0	86.1	133.0
Average Sa (microns)	340.1	139.1	57.3	162.8	78.5	117.0
Std. Dev.	77.5	48.8	16.7	79.4	10.6	18.3

Table 2 Statistical multiple comparison table using Statgraphics Plus shows only data at 30^{0}C are significant (indicated with an asterisk) ; those covering the temperature range from 40 – 80^{0}C are the same. The jump in Sa value at 60^{0}C is attributed to noise.

Method: 95% Scheffe	**Count**	**Mean**	**Homogeneous Group**
T_50	5	57.24	X
T_70	5	78.44	X
T_80	5	116.94	X
T_40	5	139.04	X
T_60	5	162.72	X
T_30	5	340.0	X
Contrast	**Difference**		**+/- Limits**
T_30 – T_40	*200.96		116.0
T_30 – T_50	*282.76		116.0
T_30 – T_60	*177.28		116.0
T_30 – T_70	*261.56		116.0
T_30 – T_80	*223.06		116.0
T_40 – T_50	81.8		116.0
T_40 – T_60	-23.68		116.0
T_40 – T_70	60.6		116.0
T_40 – T_80	22.1		116.0
T_50 – T_60	-105.48		116.0
T_50 – T_70	-21.2		116.0
T_50 – T_80	-59.7		116.0
T_60 – T_70	84.28		116.0
T_60 – T_80	45.78		116.0
T_70 – T_80	-38.5		116.0

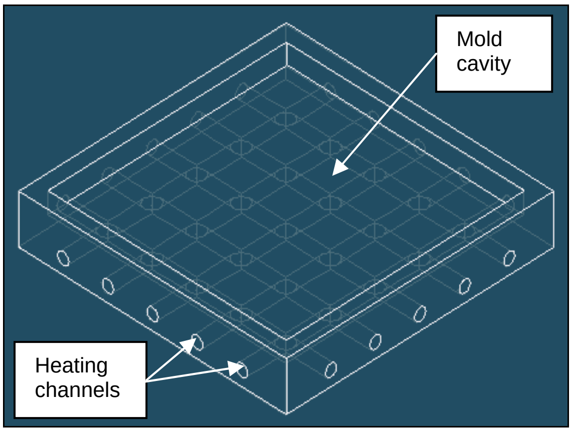


Figure 1.

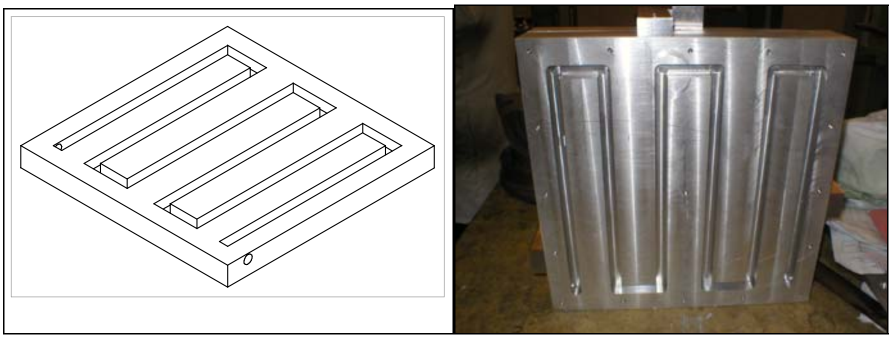
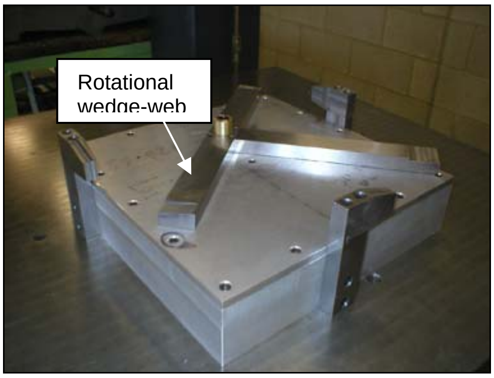


Figure 2.

Figure 3.



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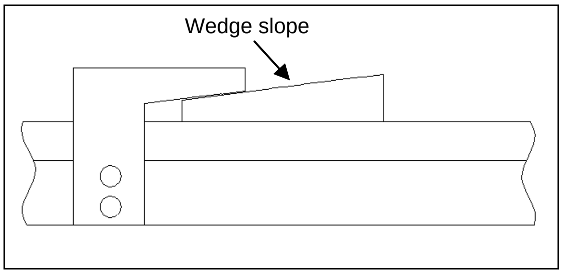

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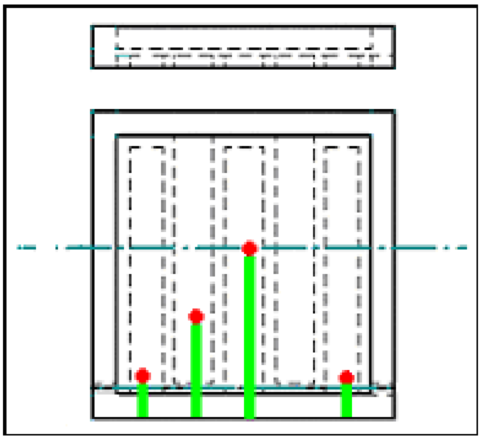

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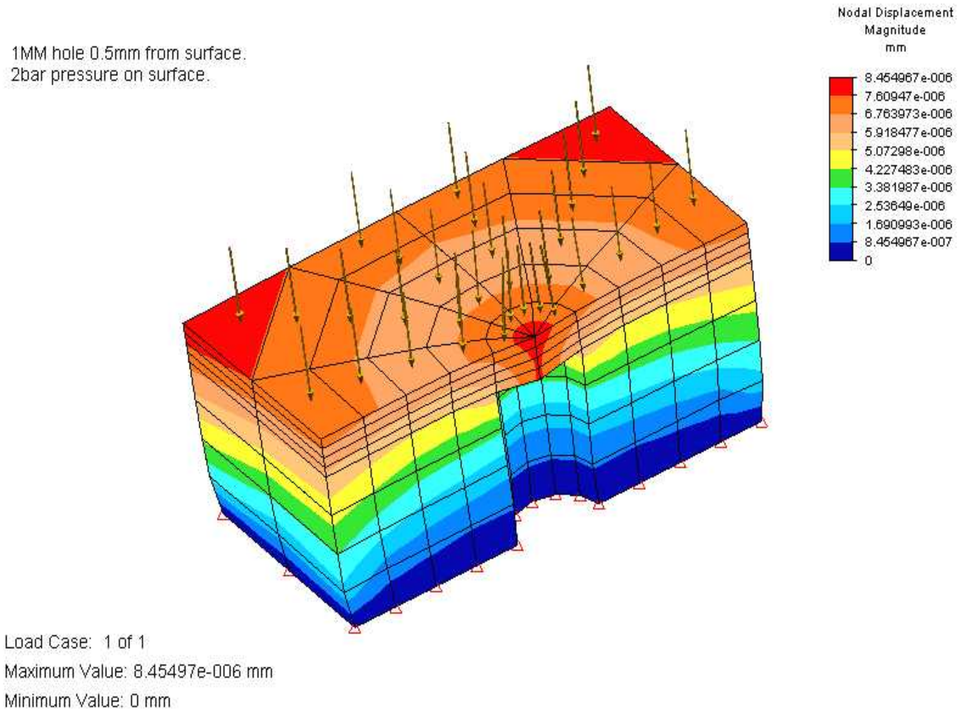

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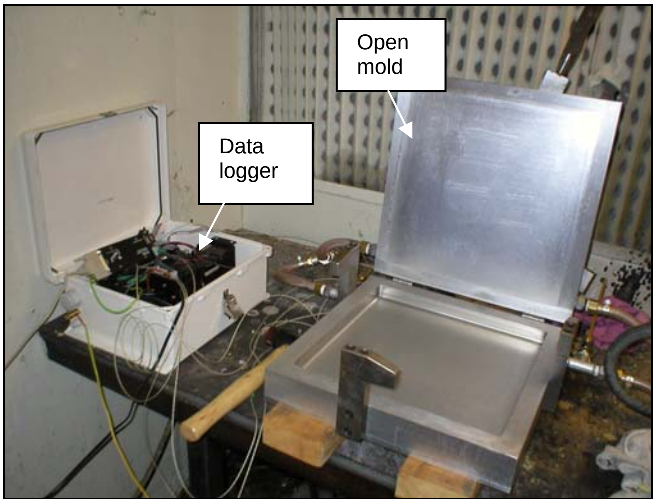

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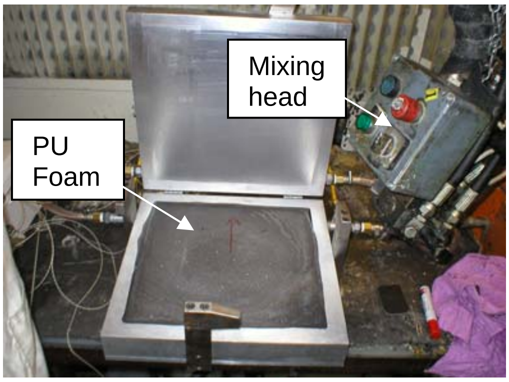

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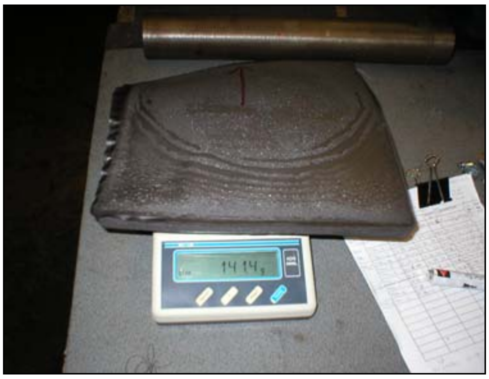

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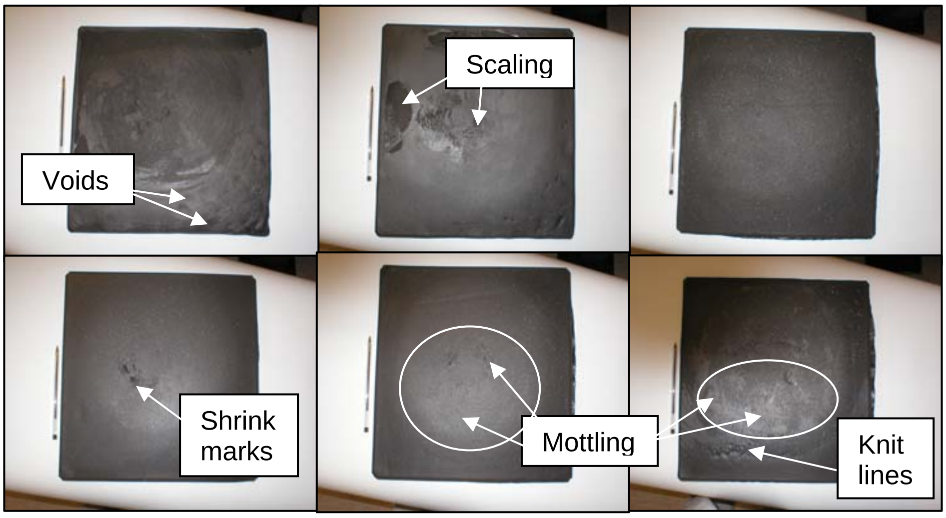
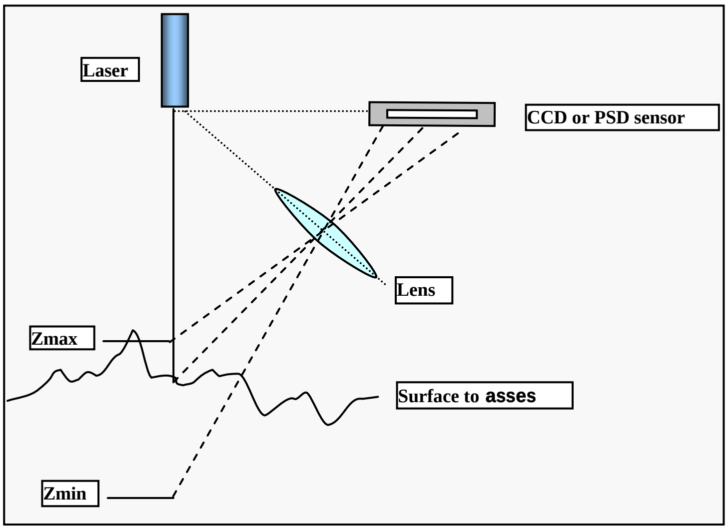


Figure 11.



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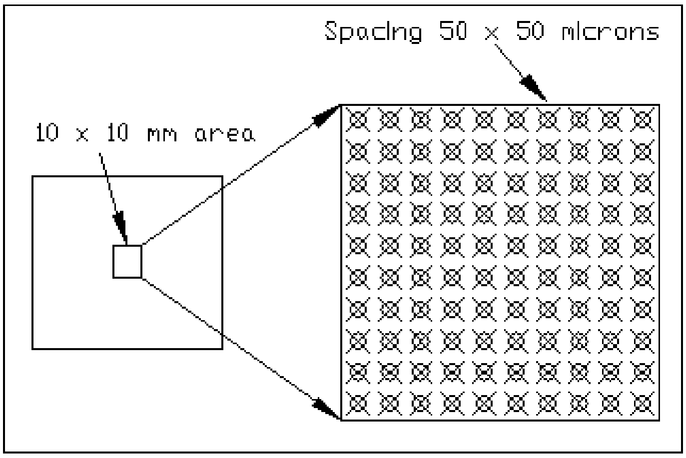

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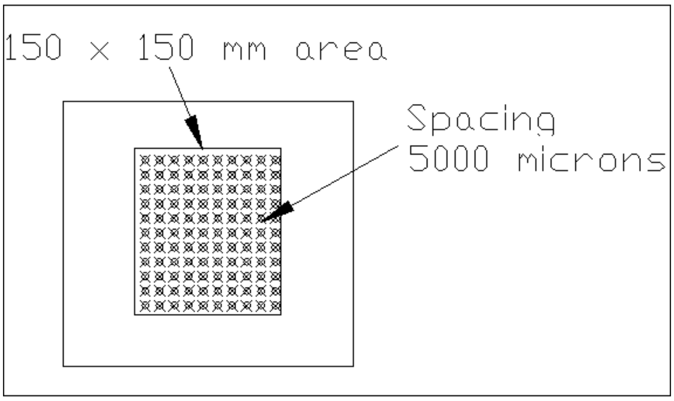


Figure 14.

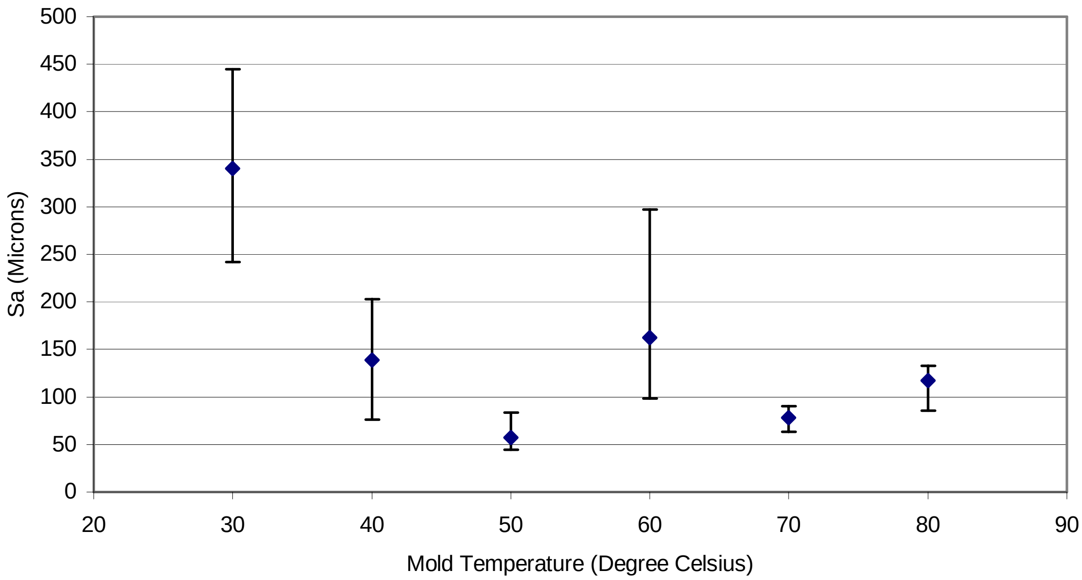
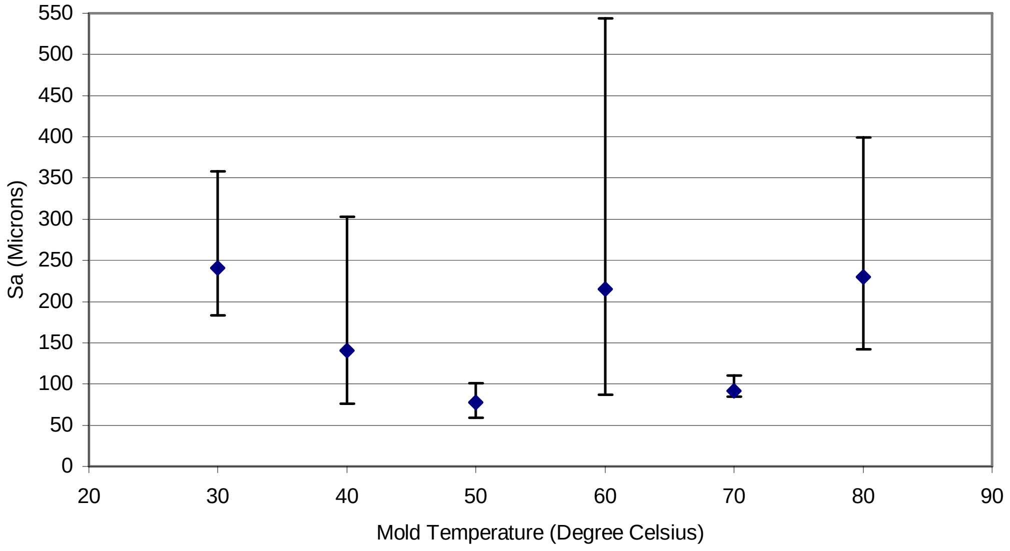


Figure 15.



550
500
450
400
350
300
250
200
150
100
50
0
Sa (Microns)
20
30
40
50
60
70
80
90
Mold Temperature (Degree Celsius)

Figure 16.

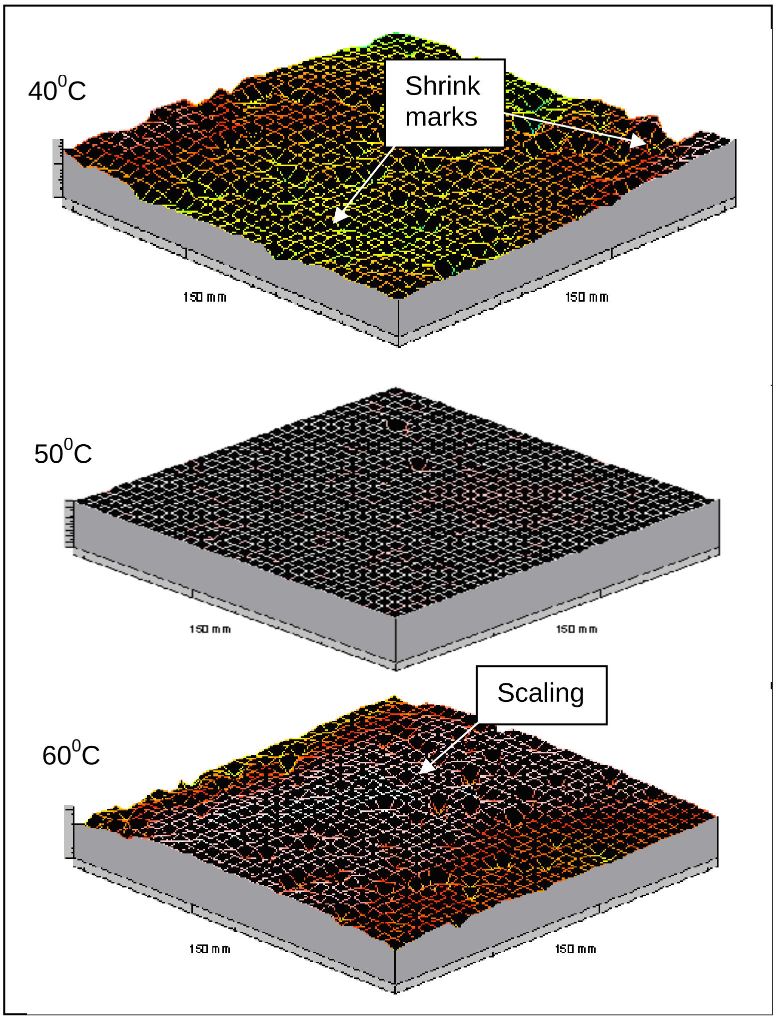
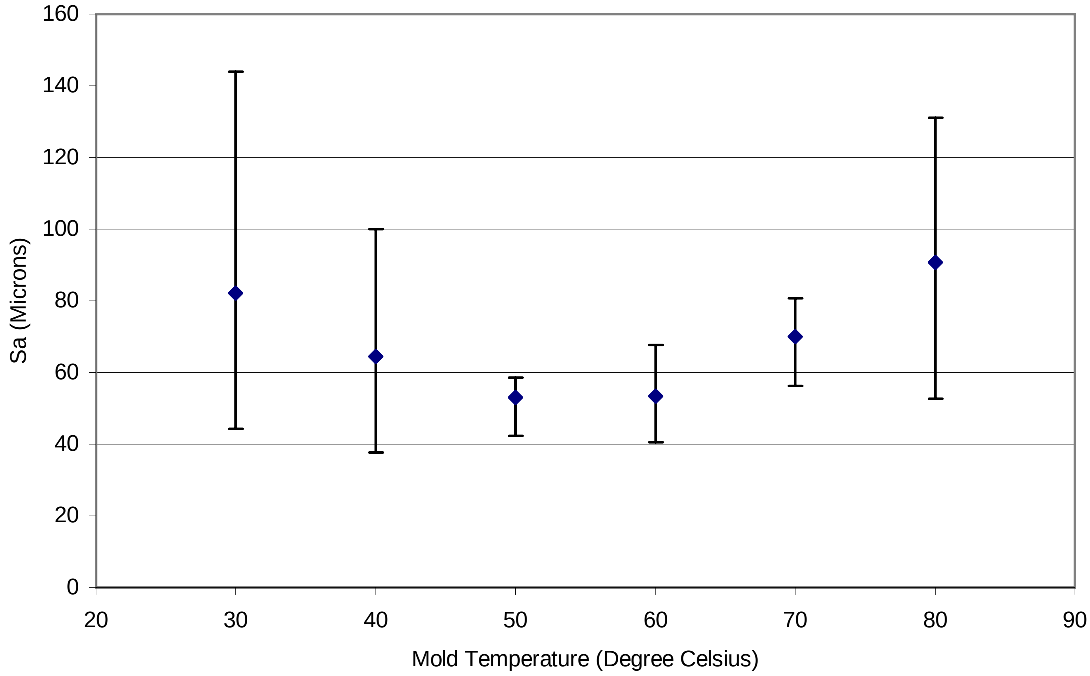

40⁰C
Shrink marks
150 mm
150 mm
50⁰C
150 mm
150 mm
Scaling
60⁰C
150 mm
150 mm

Figure 17.



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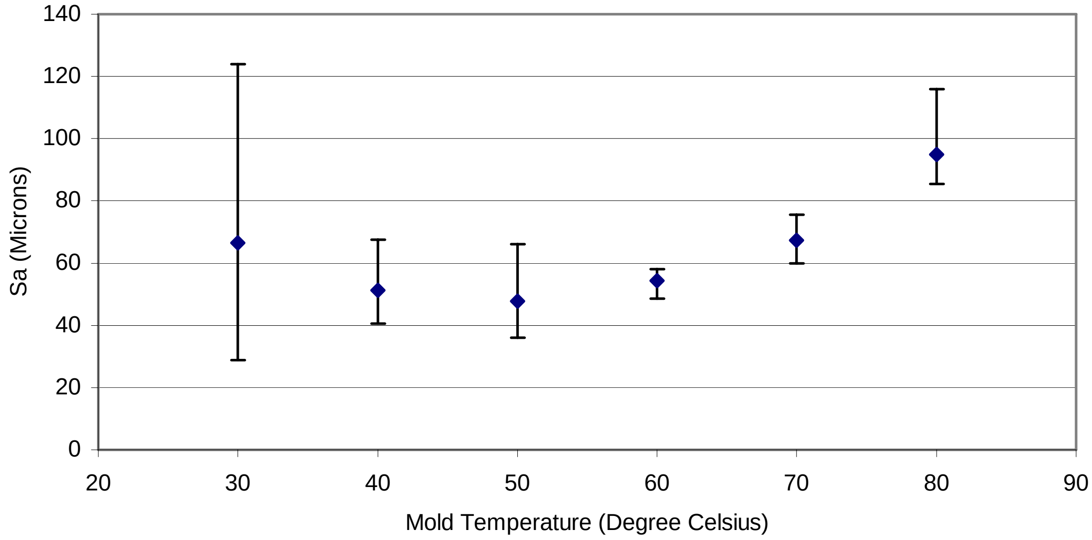

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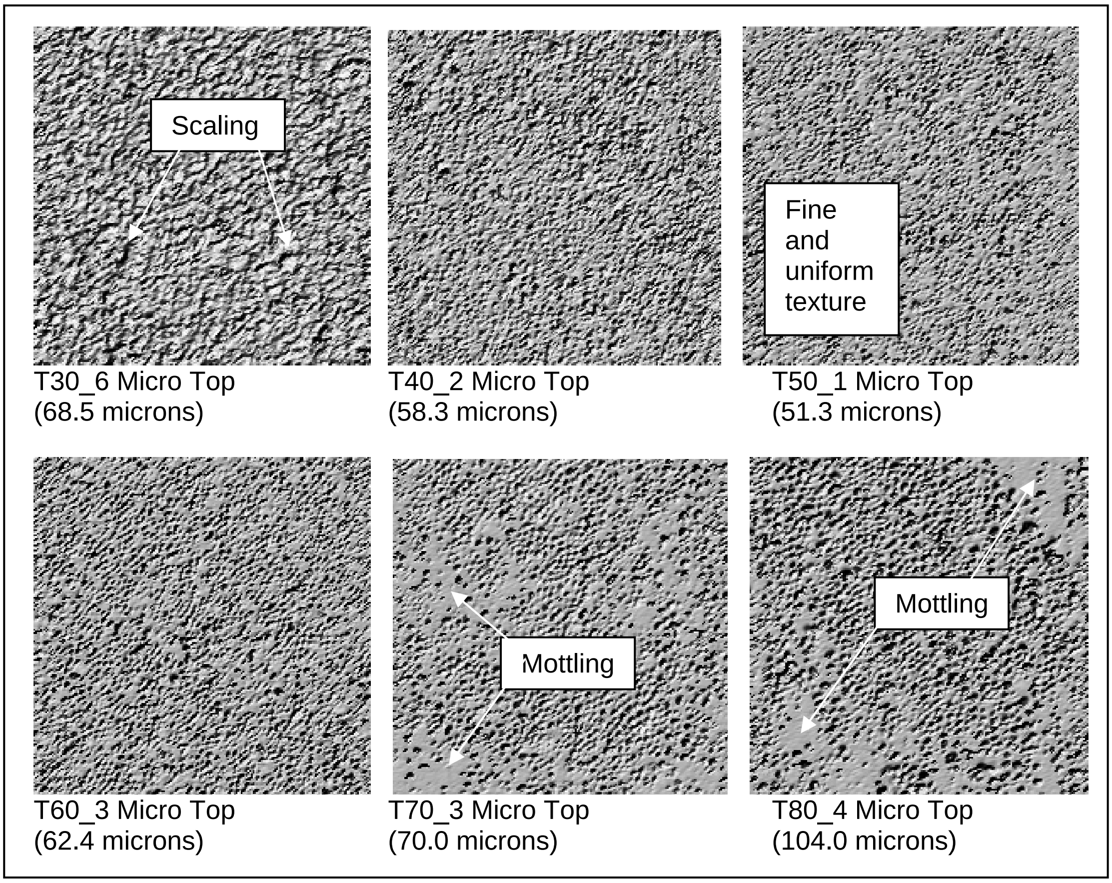
Scaling
T30_6 Micro Top
(68.5 microns)
T40_2 Micro Top
(58.3 microns)
Fine
and
uniform
texture
T50_1 Micro Top
(51.3 microns)
T60_3 Micro Top
(62.4 microns)
Mottling
T70_3 Micro Top
(70.0 microns)
Mottling
T80_4 Micro Top
(104.0 microns)

Figure 20.