Investigating the Impact of Phase Change Direction on the Properties of Investment Casting Wax

Abstract

Wax patterns are produced by a variety of techniques involving phase changes in the pattern material brought about by changes in temperature. This paper investigates how the direction of said thermal changes during wax conditioning may influence key performance characteristics. Working with a local foundry, Paramelt uses a variety of techniques to characterize the impact of thermal conditioning direction on the dimensional and mechanical properties of actual investment casting patterns.

C.Holek / H.Fielder

Paramelt US

April 2018

Investigating the Impact of Phase Change Direction on the Properties of Investment Casting Wax

C.Holek / H.Fielder

Paramelt US

Introduction

Most patterns, runners, and other wax assemblies used in today's investment casting activity are produced by injecting 'hot' material, in a liquid or pasty state, into an appropriately shaped tooling cavity.

Once the injection cycle has finished, the hot material cools to ambient temperatures, yielding a solid article suitable for subsequent processing.

In preparing wax for injection by this approach, the material is heated above its melting point, solubilizing the numerous organic fractions in the composition, creating a homogenous mixture. This mixture is then cooled to the desired temperature for injection. The keyword here is 'cooled' - in both liquid and paste injection scenarios, the molten, 'superheated' wax undergoes a reduction in temperature after melting, to bring it to the desired state for processing.

What about conditioning waxes for injection using a reversed thermal gradient? Wax extrusion techniques, typically using billet feedstock, meet this criterion. Here the cylindrical wax mass is softened by warming, placed in a heated chamber and forced through an orifice to form an extruded shape, or through a nozzle for pattern injection.

A key concept here is heating the wax to its injection point rather than cooling it from a melt, like wax used for liquid or paste injection. In an extrusion process, the wax does not undergo an obvious liquid to solid phase change before injection. Remember that whatever the conditioning route, the injected parts still have to cool back down to ambient temperatures before subsequent processing.

Given this fundamental difference noted above, the obvious question arises – What, if any, variation might there be in wax performance from these two approaches to wax conditioning? This paper investigates…

Planning

How to realistically compare extruded vs liquid injected parts? Shellcast, Inc. based in Montague, MI is located close to Paramelt's US headquarters. They produce complex steel castings for the commercial and aerospace sectors using unfilled pattern and sprues waxes. Parts are injected in paste form using Cerita 971 through MPI presses. Runners are formed from billet using a reclaimed sprue wax through Ebbert wax extruders.

Paramelt approached Shellcast and asked if they would participate in experimental work using their wax injection processes. They agreed and a program of injections was designed and executed. Many thanks go out to Bob Johnson (Owner and President), Tom Braun (General Manager) and the other Shellcast Inc. staff for providing access to their facility and working closely with us to realize this project.

Experimental Details

Shellcast injects 971 pattern wax in paste form @ 130°F. Figure 1 shows a Viscosity-Temperature overlay from three 971 lots tested at $50s^{-1}$ shear - apparent viscosity is ~19000 cPs @ 130°F.

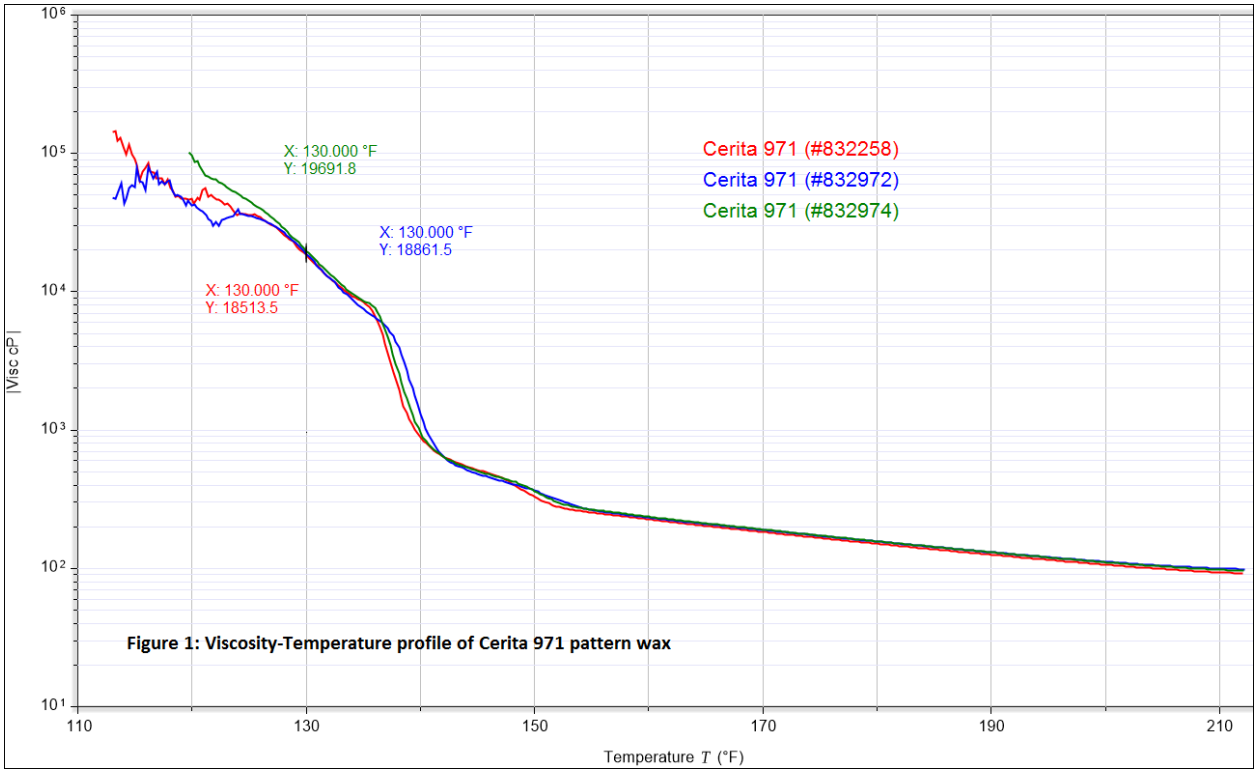
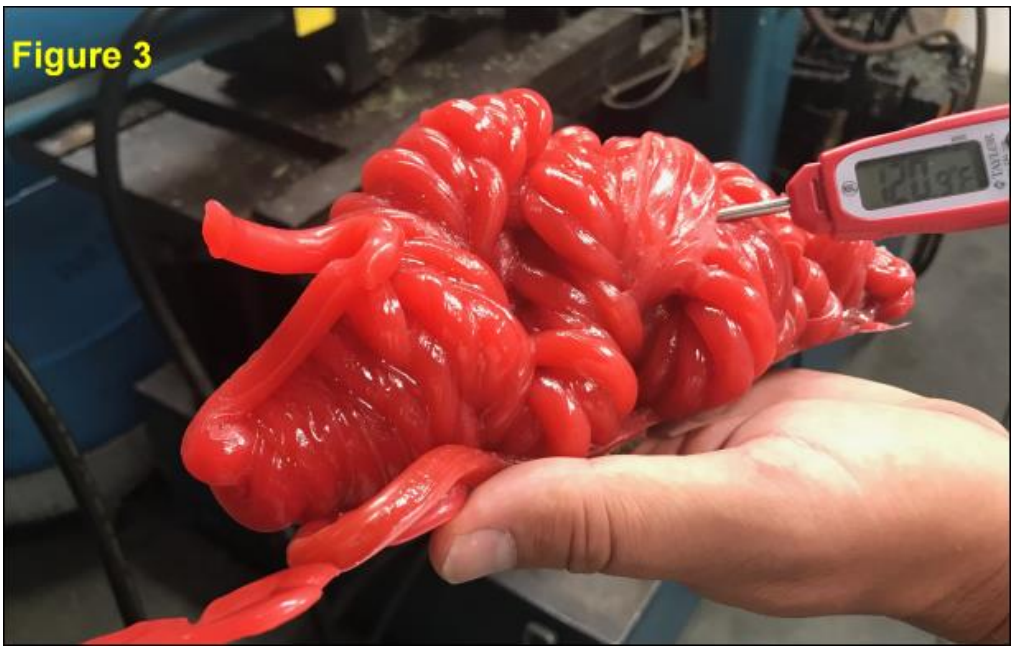


Figure 1: Viscosity-Temperature profile of Cerita 971 pattern wax

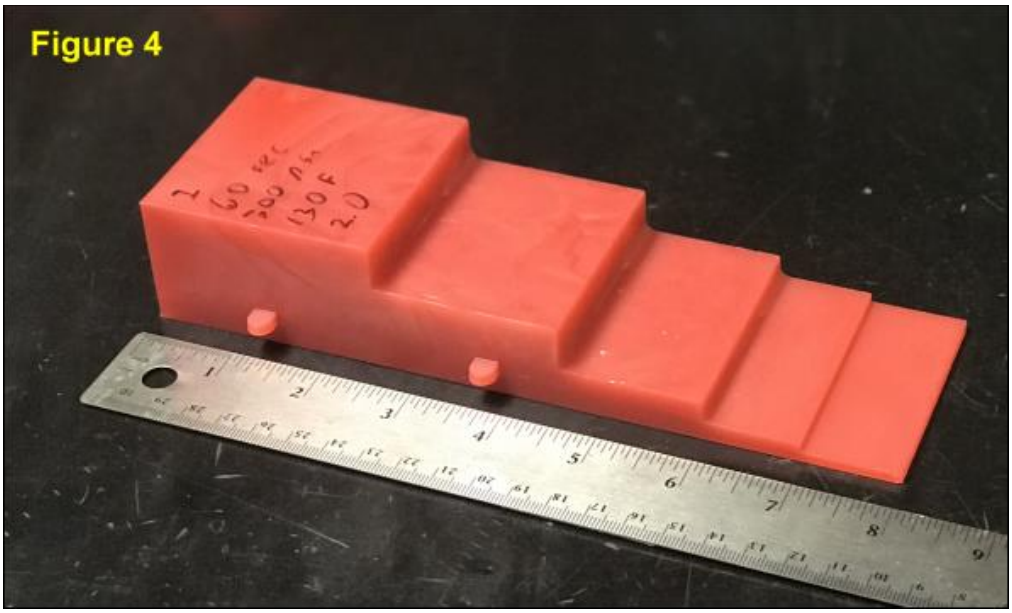
Figure 2 illustrates paste wax consistency after a purge shot, showing an indication of internal temperature.

To facilitate comparative injections, Paramelt manufactured a batch of 971 in billet form – the material is usually pelletized. These billets were conditioned in Shellcast's warming cabinet, sitting at 122°F for at least 48 hours. After conditioning, the test billet was loaded into an Ebbert extruder and used to make test parts.

Figure 3 shows wax purged from the extruder

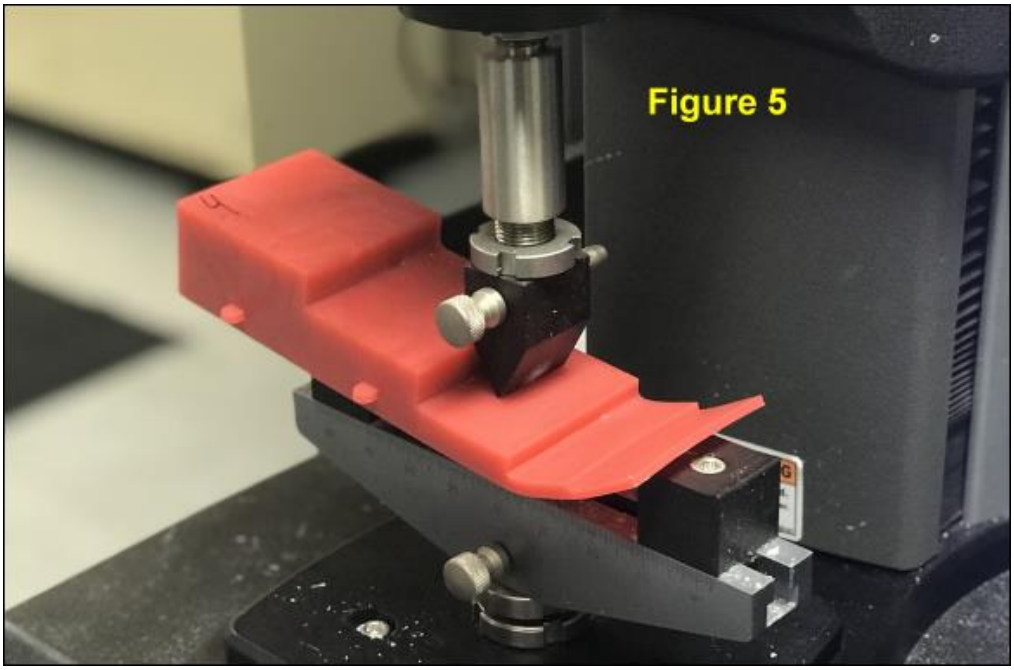


To minimize complexity and limit disruption to Shellcast's operations, we injected wax at their standard conditions into Paramelt's 8" step block tool to produce all the test pieces – Figure 4 shows an injected part.



Eight test parts were made using each wax type, i.e. pasted and extruded. These were carefully transported back to Paramelt's Muskegon laboratory and conditioned for 18 hours at 73°F. The parts were then measured using calipers, a height gage, a micrometer and a laboratory balance.

After measurement, five parts from each group were subjected to three-point bend testing to identify any variation in mechanical properties due to the differences in wax conditioning. Figure 5 shows a part under test.



We also used Dynamic Mechanical Analysis (DMA) to simulate and compare the levels of shrinkage associated with the conditioning steps for each wax format. Results from each measurement thread are detailed below.

Results – Dimensional

971 Billet Injection @ Shellcast (122°F / 1000 psi / 60 sec / platten @ 65°F)				
Part 1	**L1 (")**	**Step 4 sink (")**	**Step 3 thickness (")**	**Weight (g)**
1	8.0340	0.0170	0.46655	254.86
2	8.0370	0.0140	0.46695	254.72
3	8.0375	0.0110	0.46675	254.75
4	8.0370	0.0120	0.46640	254.76
5	8.0380	0.0100	0.46655	254.78
6	8.0365	0.0175	0.46590	254.75
7	8.0395	0.0215	0.46685	254.84
8	8.0395	0.0110	0.46515	254.78
Mean	**8.0374**	**0.0143**	**0.46639**	**254.78**
Shrink ("/")	**0.0065**			
971 Paste Injection @ Shellcast (130°F / 300 psi / 60 sec / platten @ 65°F)				
Part 1	**L1 (")**	**Step 4 sink (")**	**Step 3 thickness (")**	**Weight (g)**
1	8.0245	0.0120	0.46285	251.66
2	8.0250	0.0210	0.46285	251.95
3	8.0250	0.0170	0.46250	251.68
4	8.0220	0.0210	0.46270	251.54
5	8.0200	0.0120	0.46315	251.61
6	8.0205	0.0100	0.46290	251.63
7	8.0220	0.0140	0.46355	251.45
8	8.0225	0.0180	0.46290	251.53
Mean	**8.0227**	**0.0156**	**0.46293**	**251.63**
Shrink ("/")	**0.0083**			

The table above details the dimensional and weight measurements taken from the two sets of step blocks. Figure 6 is a graphical summary of the recorded data.

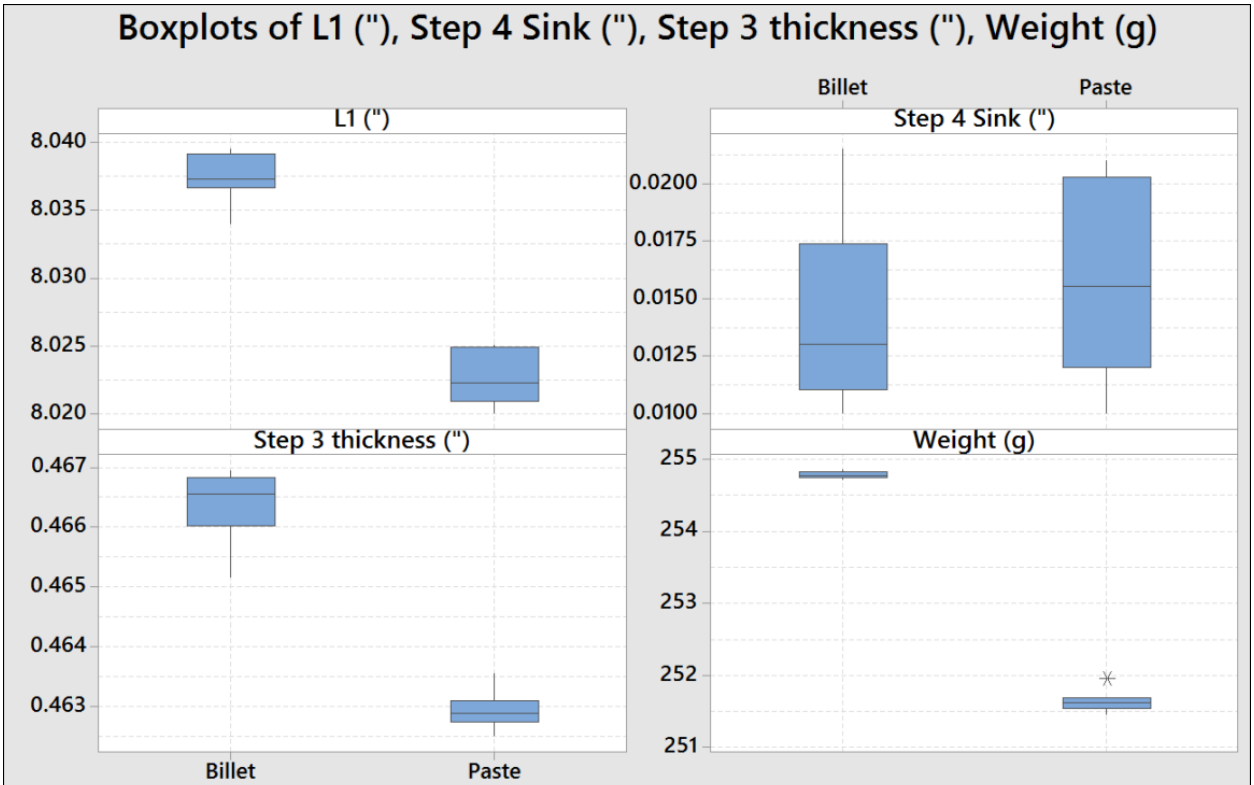


Figure 6

Results - Mechanical

971 Billet	Max Load (N)	Deflection @ Break (mm)	Max Slope (N/mm)
1	126.4	10.7	80.5
2	127.2	11.0	71.5
3	123.5	10.5	70.4
4	122.2	4.8	70.3
5	129.3	9.6	64.0
mean =	**125.7**	**9.3**	**71.3**
971 Paste	**Max Load (N)**	**Deflection @ Break (mm)**	**Max Slope (N/mm)**
1	106.4	*	57.2
2	107.3	*	59.2
3	110.6	*	57.9
4	110.0	*	63.3
5	105.5	*	52.9
mean =	**108.0**	*	**58.1**

The table above summarizes the mechanical property data gathered from the three-point bend testing experiment. Figure 7 shows load / deflection curves from the two data sets.

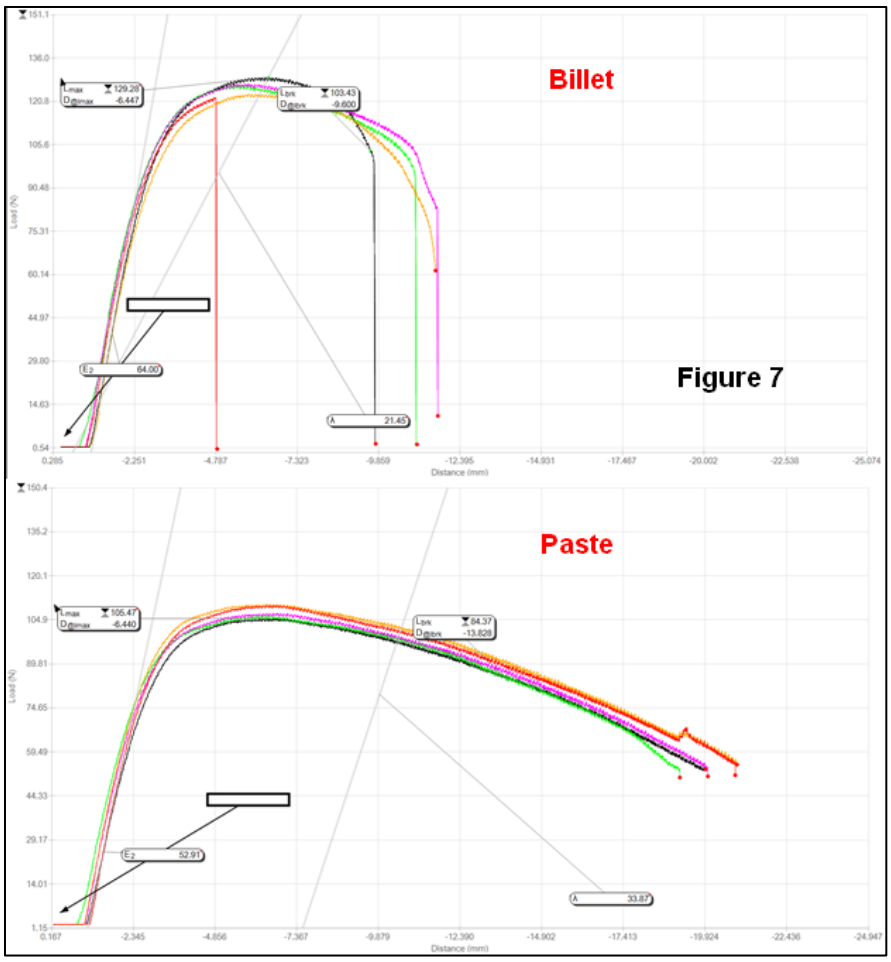


Figure 7

Results – DMA

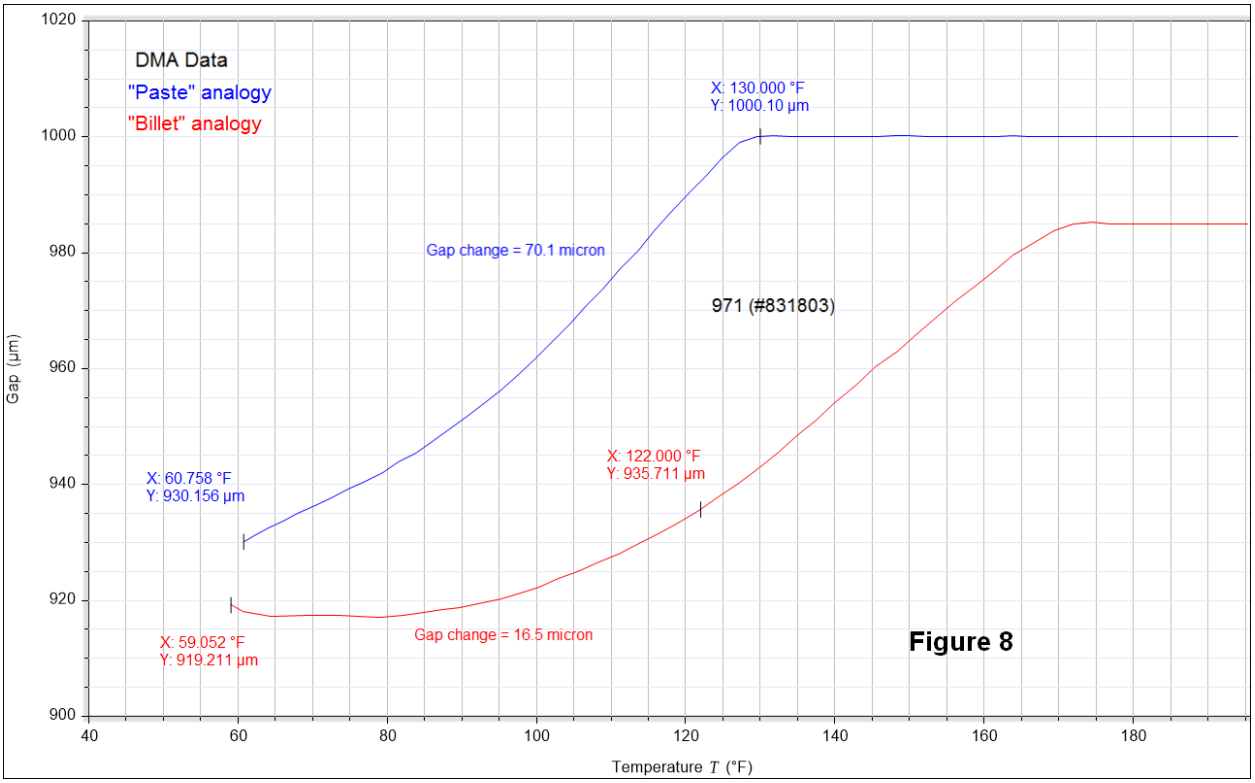


Figure 8

Figure 8 above presents data from torsional DMA experiments. In the "Paste" analogy, the wax under test is cooled in a controlled fashion from molten and the relative probe displacement is measured as a function of temperature. The "Billet" scenario involves heating the sample instead, starting with the wax in a solid state. Using the data, we can calculate the differences in probe shift and make inferences regarding the likely impact of wax conditioning direction on injected wax properties.

Dimensional Responses and Injection Quality

There are significant differences in the dimensional properties of the two groups of patterns. In terms of free linear shrinkage, the extruded parts are bigger, showing ~1.8 thou per inch less shrink than the paste injected parts. The extruded wax parts also exhibit marginally less cavitation, greater through-part thickness and heavier part weights.

The difference in injected part weight is interesting – the patterns formed from billet are 3.1g (~1.3%) heavier. We checked the specific gravity of the two pattern sets after cooling and found no significant differences between them. Extrusion packs more wax into the tool, presumably due to transitionally higher density.

There are also visual differences between parts made using the two injected wax states. Figure 9 is a side-by-side view of specimen parts from each group. There is a definite color difference – the extruded pattern is slightly brighter in color and marginally more opaque.

This difference is quantifiable. Using a BYK Gardner colorimeter outputting CIELAB color space ("lab") data, we measured values from sample test patterns – see the table below…

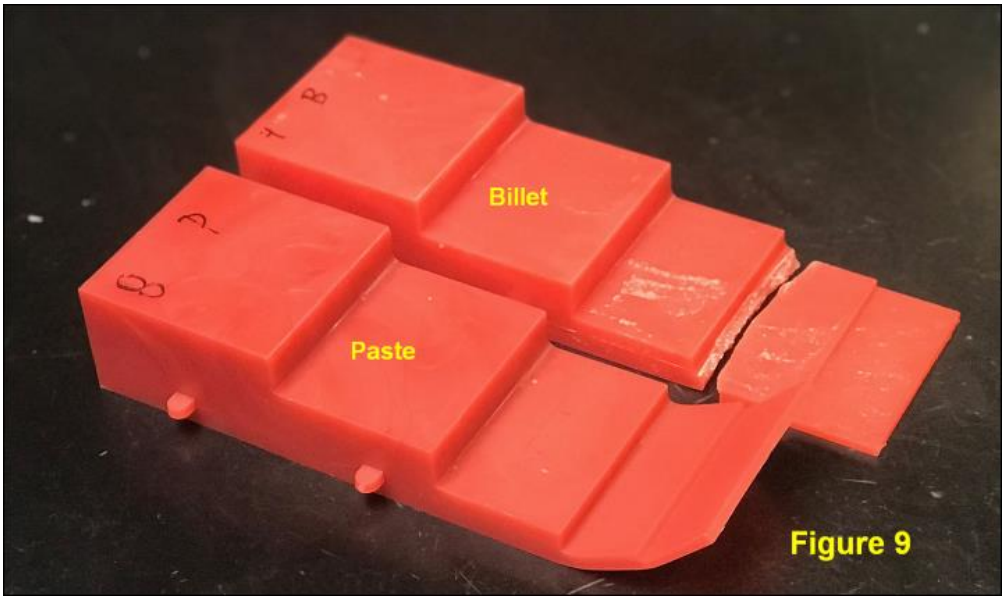
CIELAB Color Space data - 971 Patterns		
Wax state	**Billet**	**Paste**
L	35.19	32.41
a*	32.98	29.72
b*	12.29	9.31

The patterns extruded from billet also tended to exhibit patches of surface air rash (figure 9) and we noted that general surface quality was not quite as good as that seen with the pasted parts. Bear in mind, however, that we did not seek to optimize visual part quality during the injection session.

Mechanical Data Review

Figure 9 shows post-test patterns from each wax. Again, the test data shows a marked difference between results from the two pattern groups. Relative to the pasted parts those made from billets were significantly 'tougher' – they carried a 16% higher load and deformed less before all failed at the junction of Steps 2 and 3 with minimal local deformation. The higher 'Max Slope' values indicate that they were stiffer, too. The pasted parts did not fail and bottomed-out on the test fixture, exhibiting severe local deformation at the junctions of Steps 1, 2 and 3.

Normally, we run three point bend testing using small, hand poured rectangular bars with well-defined dimensions. In this case, it was not feasible to inject standard mechanical test pieces, so we decided to test the actual step blocks. The data obtained is surprisingly consistent and suggests that this direct approach may be useful for quantifying mechanical properties of injected waxes, instead of relying on small, hand poured test specimens.



DMA Data Review

The data presented in Figure 8 is in line with the results from the injection work conducted at Shellcast, i.e. the parts extruded from billet exhibit less shrink than the paste injected ones. The change in sensor position associated with cooling the 971 wax from 130°F to 60°F is 70.1 microns while the change seen heating the material from 60°F to 122°F is 16.5 microns, a difference of 53.6 microns.

Ideally, we would have injected the paste wax parts at the same temperature as the billet extrusion activity (122°F) but we did not want to interrupt Shellcast's wax room workflow by changing away from their standard injection temperature. Having noted this point, we can see that the difference in probe position associated with cooling the paste wax from 122°F instead of 130°F is 62.1 microns, still significantly greater than the change that occurs when heating the sample to simulate the billet-warming step.

Assuming these observed values are directly proportional to the amount of shrinkage associated with cooling the waxes post injection, it appears that this DMA technique provides useful indicators of relative dimensional performance

Conclusion and Discussion

The data presented here conclusively demonstrates that the thermal direction associated with conditioning the 971 pattern wax prior to injection has a significant impact on the subsequent performance characteristics of the material.

Extruded wax from softened billets makes a significantly bigger part, with less cavitation, relative to wax cooled to a paste state from a pre-melt. Mechanically, these extruded patterns are less prone to deformation under load. On the downside, extruded patterns are more likely to exhibit poorer surface finishes. In the laboratory, Dynamic Mechanical Analysis offers a way to characterize the relative levels of shrink associated with these approaches to wax preparation. What causes these differences?

Like most pattern waxes in use today, Cerita 971 is a complex blend of waxes (hydrocarbon, synthetic and natural) along with resins, polymers and other, low level, additives [It is, however, an unfilled material]. These ingredients have a relatively wide range of softening and melting points, so the blend has a wider melting range too – consider the offset between softening point and drop melting point typically seen with injection waxes. In the case of Cerita 971 we are looking at a typical separation of some 5°F.

As mentioned earlier, traditional liquid and paste injection requires melting of the wax followed by cooling and conditioning. Although some of the higher melting components start to seed out of solution, gelling the material to some extent and boosting apparent viscosity, a substantial amount of liquid remains. After injection, this residual melt solidifies, and linear / volumetric shrink associated with this liquid - solid phase change occurs.

In contrast, extruded wax from billets undergoes relatively gentle heating which softens the material to a point where pressure and shear force the material to flow. Most of the ingredients remain in the solid or semi-solid form and do not undergo a phase change so there is less shrink / sink as the pattern cools. This is probably one of the main reasons behind the differential wax performance reported here.

Another important contributing factor may be the physical structure of the wax blend matrix itself. We know that major ingredients like paraffin wax have a relatively coarse crystalline habit and that resins tend to be largely amorphous. Less is understood, however, about the internal structure of a multi-component casting wax blend itself. Several of the observations made during the experimental work do suggest significant structural differences between the two wax forms under consideration, variations in color / opacity and mechanical properties, for instance. At present, however, we do not have comprehensive explanations for the effects reported here.

Future Investigation

As we come to the end of this paper, we can consider (as always) future activities and experiments that will help develop a better understanding of the physical effects at play. We have touched on the use of DMA as a tool to partially characterize extruded and paste casting wax material. Other viable techniques that allow us to probe the molecular structure of solid and in-process casting wax will certainly be useful. X-ray crystallography, advanced thermal analysis and Nuclear Magnetic Resonance (NMR) spectroscopy spring to mind as possible candidates.

On a final, and more practical note, a detailed study at the foundry level of the pros and cons of billet versus paste or liquid injection could also prove useful. Paramelt makes a fair amount of wax in billet form but it seems that most extruders are currently used to produce runner stock. Based on the work presented here, it seems possible that advanced extrusion technology, coupled with custom wax formulation, could bring benefits related to improved pattern durability and reduced cycle times. As Bob Johnson of Shellcast notes, current extruders do not have the pattern quality capability and flexibility of modern wax presses so there is definitely room for improvement.