CONFORMAL COOLING WITH SOLID FREEFORM FABRICATION TECHNOLOGY: ISSUES AND OPPORTUNITIES

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Abstract

Solid freeform rapid tooling technologies of various sorts have promised new conformal cooling advantages for plastic tooling. In principle these technologies offer geometric design freedoms unavailable by machined or EDMed approaches. In practice, all solid freeform approaches are not equal. This paper will discuss opportunities and limitations on design freedoms, and important issues associated with material properties; and will show that raster-scanned 3D Printing technology has matured to a point of delivering on the promise.

Introduction

Conformal cooling for plastic injection mold tooling is a concept that attempts to optimize the removal of heat from mold components in order to reap benefits that can include reduction of mold cycle time, improvement of part dimensional accuracy and stability, and improvement of surface quality.

In general, conformal cooling attempts to place internal cooling channels within mold components uniformly equidistant from the hot plastic heat source. Thus, in cores and cavities, the cooling channels ideally mimic the contour of the molded part, some small distance away from the external surface inside the mold. Water-cooled gate inserts are another opportunity, where the cooling channel contour attempts to conform to the shape of the plastic delivery channel.

Traditional cooling methods, on the other hand, are generally limited to straight drilled channels that intersect each other and use plugs in order to create cooling circuits. These techniques are unable to maintain a uniform or optimal distance from the source of heat, but are the only reasonable option if a mold component is manufactured as a single metal object with traditional machining or EDM techniques.

If one is willing to manufacture a mold component as multiple slices which are later joined by brazing or other techniques, it is possible to machine channels into each slice that, when assembled, provide much better conformance to the molded part surface. These techniques have been around for some time, but have been limited in both geometric effectiveness and in-service reliability, and are quite costly.

The recent advent of rapid prototyping technologies known as solid freeform fabrication have opened up new possibilities. These processes build an object by successively adding small amounts of material until the desired three-dimensional shape is attained, rather than starting with a block and subtracting unwanted material. Among other advantages, the additive process can create internal cavities of fairly arbitrary shape as it builds up a solid object. It is capable, for instance, of building the proverbial ship in a bottle, and doing so just as easily and economically as building a simple solid object devoid of internal cavities.

Since 1999, ProMetal and D-M-E Company, a global supplier of mold technologies for the plastic injection molding and die casting industries, have been engaged in ongoing collaborative research on conformal cooling for plastic injection mold tooling. D-M-E's focus is the discovery and evolution of optimal cooling channel design, and verification of performance in both laboratory and real-life operational environments. ProMetal's focus is on the development and evolution of a solid freeform creation process that maximizes geometric design options for internal cavities and generates production-mold material quality.

The synergy of this partnership stems from D-M-E's leading position in mold component supply and their broad access to customer design challenges, coupled with MIT's unique 3DP™ metal solid freeform rapid production technology under license to ProMetal, and ProMetal's internal focus on process and materials development.

This three+ year collaboration has so far evolved through four successive generations of design concepts, each presenting new challenges to the component creation process in the quest for optimal cooling. Much of what is now known to the partners is considered hard won trade craft, and will not be comprehensively disclosed here. Nevertheless, we will look at some broadly useful conceptual understandings, some specific performance results, and an appreciation for what can and cannot be expected of the current state of the technology.

At the risk of belaboring what to some may be well known, or even better known, a brief outline of technology and process employed in solid freeform rapid object creation is provided. The purpose is to lay a foundation for expectations, and an understanding for applicability. You can't make a silk purse from a sow's ear, as the saying goes, and all processes are not equally suited to all objectives. The author is more intimately familiar with the MIT-developed 3DP™ technology and processes licensed and evolved at ProMetal than any of the others, and so begs understanding for a less comprehensive or less current representation of these other technologies. In any event, it is not the intent here to provide a comprehensive comparison of different processes, but to focus only on those issues relevant to the production of conformal cooled plastic injection mold tooling.

Solid Object Creation Technology

Solid freeform manufacturing, also known as layered manufacturing, is an additive process that builds three dimensional objects according to CAD solid model data that is sliced into a series of thin layers. The build machine constructs a solid object one layer at a time, growing the object in the Z direction as successive layers of X-Y-plane data guide the creation of solid material. The thinness of the layers determines the resolution of the object, typically producing what is known as a near-net shape. If layers are thin enough, an object satisfying net-shape tolerances may be produced, where this tolerance is a function of the object's intended purpose.

Material systems for layered manufacturing variously include liquid polymers that are solidified one layer at a time, extruded waxes and plastics that are deposited one layer at a time, or powdered materials that are bonded, sintered, or melted together one layer at a time. Powdered materials range from starch and plaster typically used for appearance models, to coated and uncoated metals typically used for prototypes or finished parts, tools, and goods, and ceramics used for metal casting molds and filtration applications.

Our focus of interest here is on metal that can be employed directly in the construction of plastic injection mold tooling. Specifically, cores, cavities, and gate inserts where conformal cooling is an objective.

Rapid Metal Technologies

There are three different powdered metal technological approaches of current principal interest, which I will differentiate as powder-bed-bonding (e.g. 3D Systems and ProMetal), powder-bed-fusing (e.g. EOS and Arcam), and powdered metal deposition (e.g. Optomec and POM). There are further variations within each category that can be important considerations when seeking an optimal approach for a specific task and operational environment.

Powder-Bed Binding

This approach employs a powder supply chamber and a build bed. A spreading mechanism takes powder from the supply chamber and deposits a thin layer of fresh powder in the build bed. Some means is employed to selectively bind together powder into a desired 2-D pattern. The bottom of the build bed is lowered after the pattern is created to accommodate a fresh layer of powder for subsequent pattern binding. When all layers are completed, one or more three-dimensional "preform" solid objects exist within the build-bed, surrounded by free unbound powder. Buried in the powder bed during build, objects made this way have natural in-situ support for overhangs, undercuts, and internal cavities. After completion preforms are removed from the build bed and the unused powder is recycled for subsequent use.

After the bound-powder preform is built it is put through a multi-step thermal processing phase in separate furnace equipment that may include a binder-curing step, removal of whatever portion of the binder material is not intended to remain, partial sintering of the metal powder, and subsequent densification of the partially sintered object by either filling the voids with a metal infiltrant or continuing the sintering process to full density.

Shrinkage occurs in the sintering activity: typically as little as 1.5% with partial sintering and as much as 15% with full density sintering, in each of the x, y, and z directions. The expected shrinkage is compensated for during the build. Uncontrolled shrinkage can cause warped, cracked, and otherwise dimensionally undesirable results. With good thermal behavior knowledge and process compensation knowledge, shrinkage becomes a non-issue.

Shrinkage is not the only material and thermal behavior knowledge necessary in order to make predictable and desirable results. Other metallurgical characteristics determined or strongly influenced during thermal processing include granular structure, hardness, porosity, uniformity, heat transfer properties, and residual stress to name just some. The early years of powdered metal processing, whether in now-routine metal-injection molding or in the more recent solid freeform approaches, are littered with unacceptable results.

Differences in powder-binding technology exist. 3D Systems employs polymer-coated metal powder and a laser heat source that selectively fuses the polymer coating of adjacent powder particles together. ProMetal employs uncoated powder, and an ink-jet-like printing head to selectively deposit parallel streams of binder into the powder bed, much like an ink-jet printer puts a graphic image onto paper.

Powder-Bed Fusing

This approach shares mechanical similarity to the aforementioned powder-bed binding. It employs a powder supply chamber, a build bed, and a spreading mechanism that similarly deposits a thin layer of fresh powder in the build bed. However, some heat-source means is employed to selectively fuse (sinter or melt) together the powdered metal particles into a desired 2-D pattern. The bottom of the build bed is lowered after the pattern is created to accommodate a fresh layer of powder for subsequent pattern sintering. When all layers are completed, a three-dimensional sintered solid object exists within the build-bed, surrounded by free unbound powder. Again, objects made in a powder bed this way have unused powder support for overhangs, undercuts, and internal cavities. When objects are removed from the build bed the unused powder is recycled for subsequent use. The user is not required to have much in the way of metallurgical process knowledge, as the complete process is automated.

The EOS approach employs proprietary blends of powder which include a lower melting temperature alloy component to form a liquid phase layer when heated by the system's laser, thereby locally fusing the adjacent non-melted material together into a solid.

The Arcam process is similar, but employs a higher heat. A high power electron beam in the Arcam EBM-12 machine locally melts powdered metal, which resolidifies into fully dense material. Because the Arcam process is performed in a vacuum chamber, even the more reactive titanium alloys can be processed.

Powdered Metal Deposition

This approach is considerably different than the preceding two. Basically it employs a high-power laser heat source that fuses metal powder as it is ejected from a nozzle directly at the point of application. Multiple powder nozzles are possible, opening the opportunity for selectively mixed materials. An integrated powder nozzle and laser head moving on the equivalent of a robot arm can apply material onto existing structures, offering the opportunity to repair molds or other metal objects that need new metal in worn or damaged areas.

Deposition time in grams per second is relatively slow for bulk component builds, but the ability to deposit metal on an existing mold offers a unique approach for mold repair. Process suppliers cite a much broader range of applicable materials than currently offered by suppliers of the two powder-bed approaches, and point to common mold tool steels as a benefit.

Here again, thermal processing is an integral part of the object creation act, with the operational steps and thermal process knowledge integrated into the build process for specific powder metal alloys. The laser melts the metal at the point of application on the substrate, building an object much like a welder might build-up a solid object. Questions exist about possible thermal stress and potential for subsequent dimensional creep, but no independent definitive case has been made as yet to this author's knowledge. Some applications may require thermal post processing to achieve optimum material properties.

As there is no in-situ support structure akin to the powder-bed approaches, some shape geometries can be problematic or even impossible, with or without building temporary supports that will later be removed. Potential solutions have been discussed for robotically articulating the part as well as the head, so that overhangs, for instance, can be rotated into a z-direction build to skirt the impossibility of a free unsupported x-y build. In any event, the bulk of the integrated nozzle/laser head limits the geometric freedom, where some shapes demand metal deposition in places unreachable by the head. Optimal conformal cooling design geometries are probably elusive.

Differences in powdered metal deposition approaches exist. POM's DMD 5000 flushes the work area with inert gas, while Optomec does the same but after pumping out the oxygen. Software feedback laser control is important and proprietary to both.

Conformal Cooling Design

As mentioned earlier, D-M-E and ProMetal have been conducting joint research and development activities toward optimal conformal cooling mold design and fabrication. At this point, D-M-E has evolved conformal cooling design through four generations of increasingly more efficient design concepts.

Figure 1, depicting an early first generation design approach, outlines the general differences between conventional and conformal cooling. Solid freeform technology offers an additional advantage in cooling channel placement, in that the geometric freedom allows channels to be routed around fixed-location mold components such as ejector pins. This same geometric freedom allows inlets and outlets to be placed at the most convenient locations for coolant hookup.

Design research activity makes extensive use of analytical tools, such as FEA for both thermal and structural load stress, with MoldCool, Moldflow, MoldWarpage, IDEAS, COSMOS and Mold-X in regular use. D-M-E also has a lab capability with plastic injection process machinery that facilitates analysis verification and live operational testing.

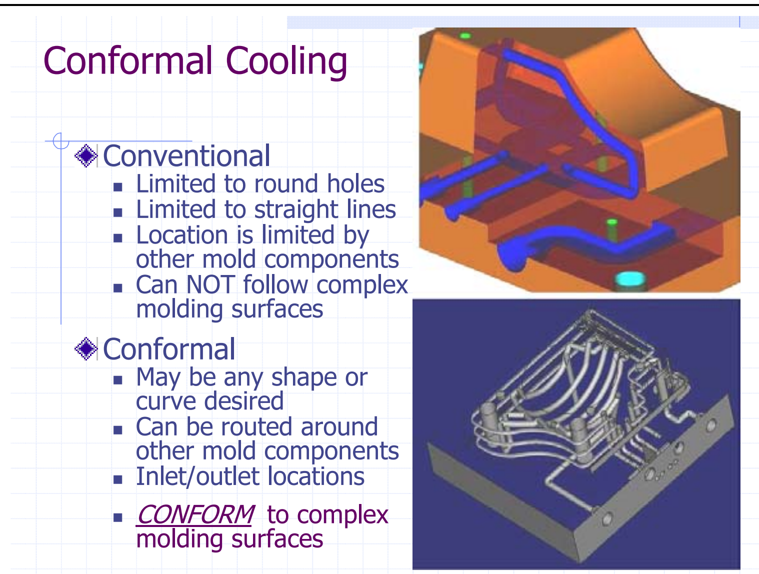

Figure 1: First Generation Design Concept
Shows Simple Full 3D Freedom Offered By Solid Freeform
(Design and art credits to D-M-E and Hasbro)

A four cavity mold base test setup has even been used to run four different design generations of a cup mold simultaneously, for comparative data collection and demonstration purposes.

Performance Improvement

Figures 2 through 5 deal with a conformally cooled capacitor cup core design. The initial objective was to

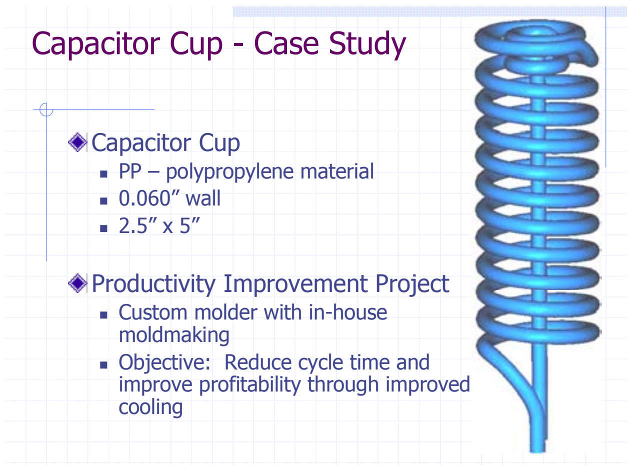

Figure 2: First Generation Design Concept
(Design and art credits to D-M-E)

compare performance of early conformal cooling design concepts to both a conventional non-conformal baffle approach and a typical multi-piece machined-insert conformal approach.

The first generation design approach was a helix coil with extra loops at the gate hot spot. The core was fabricated with ProMetal's S4 tool material, which is a composite of 60% 420 stainless and 40% bronze. It was a foregone conclusion that the result would be an improvement over the conventional hole-and-baffle approach, but the surprise was the amount of improvement over the H13-with-bronze-insert approach (Figure 4). Some of this improvement is undoubtedly due to the coolant turbulence instigated by roughed channel walls rather than smooth machined or drilled channels, and of course the single-piece freeform core won't have the leakage potential of the multi-piece machined insert approach.

This first generation design is geometrically simple and

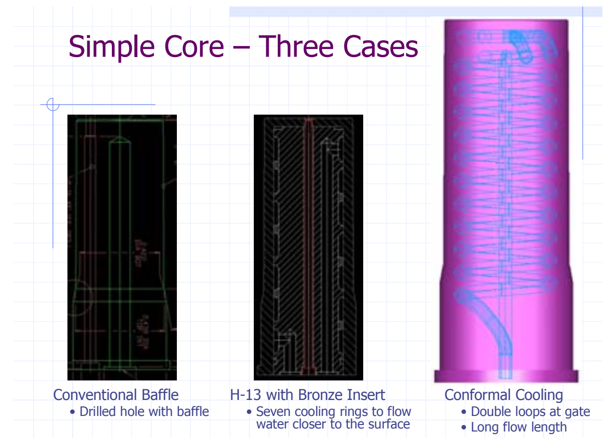

Figure 3: Comparison to Bronze Insert Approach
(Design and art credits to D-M-E)

can be produced by virtually any of the solid freeform technologies. Channel diameter is large enough that unused powder removal should not pose a problem to coated powders, and the overall bulk of the core is small enough that the slower processes shouldn't be cost prohibitive.

Though straight forward first generation designs show clear advantages, they were a learning experience much like discovering the next higher mountain from the vantage point of the first peak you've climbed.

Second generation designs focused on improving coolant

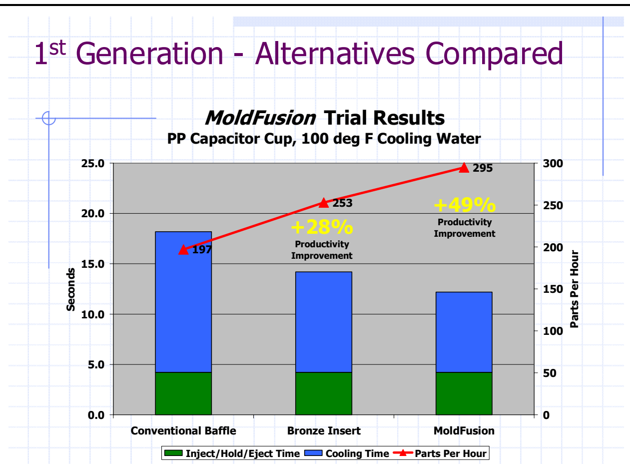

Figure 4: Dramatic Performance Improvements
(Design and art credits to D-M-E)

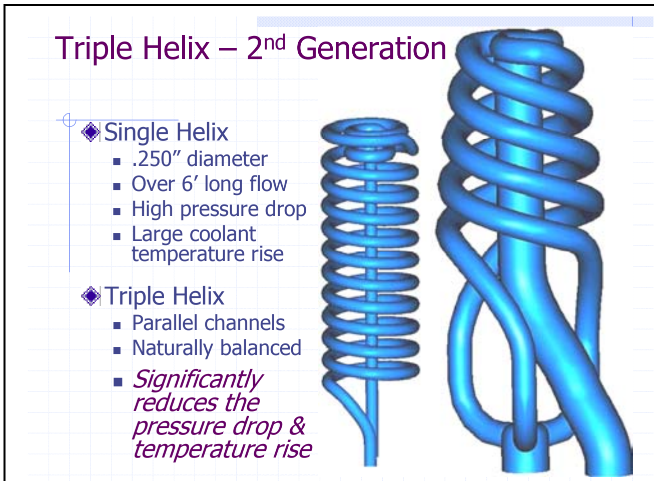

Figure 5: Second Generation Design Concept
(Design and art credits to D-M-E)

flow for better heat removal, resulting in the triple-helix approach shown in Figure 5. Third and fourth generation designs likewise found successively higher improvement issues to accommodate, making use of complex three dimensional geometries and channel aspects impossible for conventional fabrication techniques, but naturally suited in principle to freeform additive processes. These third and fourth generation design approaches will not be described here as they are considered proprietary trade craft at this time.

Fabrication Issues

Producing high performance conformally cooled mold components is not just a matter of cooling channel design, especially when solid freeform technology is employed. Powdered metal fabrication by a solid freeform technique in general is going to result in material properties different than machined wrought material, and in some cases, different technology providers are offering materials other than traditional tool steels, one common variant being a steel/bronze composite.

All technology providers appear to be exploring new material options, and each has a stable of standard materials they are prepared to supply as well as anecdotal information about customer experiments and their own systems under development.

Reactive metals such as aluminum and titanium are of real interest to most if not all freeform technology suppliers, but they pose real problems at this time. Arcam is the one supplier currently with a controlled atmosphere surrounding the build chamber, and has demonstrated success with titanium as a result. Others have announced or informally discussed their development programs for aluminum, but no demonstrations have yet shown "standard" aluminum ability to this author's knowledge. I qualify the "standard" requirement because one system under development claims an aluminum capability, but in fact uses an anodized porous aluminum preform subsequently infiltrated to full density, which does not result in the same characteristics one expects from wrought aluminum.

Some traditional tool steels are currently available from the powdered metal deposition suppliers and, to a lesser extent, from the powder-bed fusing suppliers. The powder-bed binding technologies have focused initially on composites of steel and bronze, which though different than tradition tool steels, can provide advantages in thermal conductivity and, under some conditions, relative to some of the other freeform technologies, lower porosity and higher hardness.

The objective of course is high quality materials that can provide the conformal cooling advantages and rapid availability offered by solid freeform, without compromising on tool life or costing a prohibitive premium.

New material systems can be expected on a continuous basis from all technology suppliers. And with time, repeatability, uniformity, and acceptability of material characteristics for these new material systems can be expected to continuously improve as well.

The technology of solid freeform *shaping* is not the principal determiner of critical material quality issues. The thermal process that transforms metal powder into solid fused metal is where the critical material characteristics are determined, and this is a matter of both breadth of process control (Figure 7) and depth of process knowledge.

Thus, the technology itself is not the final determiner of material characteristics and tool quality, but rather the limiter of what is possible. It is the knowledge and procedures employed in the operating environment that will determine predictable and repeatable high quality tooling.

Knowledge changes what would otherwise be an art form into a science, and doesn't come in over the transom. ProMetal, for instance, decided at the outset that machine design would have to be driven by part-quality process knowledge, not by technology; and that the only way to accomplish this was to sell parts and tools under competitive conditions, as well as machines.

As a result, the company currently runs two, three-shift Rapid Production Centers, with seven metal-producing machines working around the clock. A sizable amount of the work done in these shops is material system experimentation, development, and refinement, as well as research and development of tooling and conformal cooling geometries and process guidelines.

Material Properties			
	S3 (316)	S4 (420)	S4H (420)
Alloy Family	SS+Bronze	SS+Bronze	SS+Bronze
UTS	59 KSI	99 KSI	111 KSI
	(406 MPa)	(682 MPa)	(765 MPa)
Yield	34 KSI	61 KSI	83KSI
	(234 MPa)	(420 MPa)	(570 MPa)
Modulus	21.5 MPSI	21.4 MPSI	22 MPSI
	(148 GPa)	(147 GPa)	(151 GPa)
Elongation	8.00%	2.30%	3.80%
Hardness	60 HRB	26-30 HRC	30-35 HRC
Thermal Conductivity	7.35 W/m° K	37.01 W/m° K	33.82 W/m° K
Mean CTE (at 300° C)	15.4×10^{-6}/° C	13.4×10^{-6}/° C	12.5×10^{-6}/° C
Specific Heat	164 J/kg° K	478 J/kg° K	497 J/kg° K

Figure 6: Material Properties for ProMetal Steel/Bronze Composites

Each shop has a companion materials testing lab used for quality assurance as well as material systems knowledge development; providing on site scanning electron microscopy (Figure 8), hardness testing, tensile testing, and other such laboratory equipment to support a process, materials, and metallurgical staff that includes four PhDs.

In addition to in-house development programs, the company is typically involved in five to eight funded

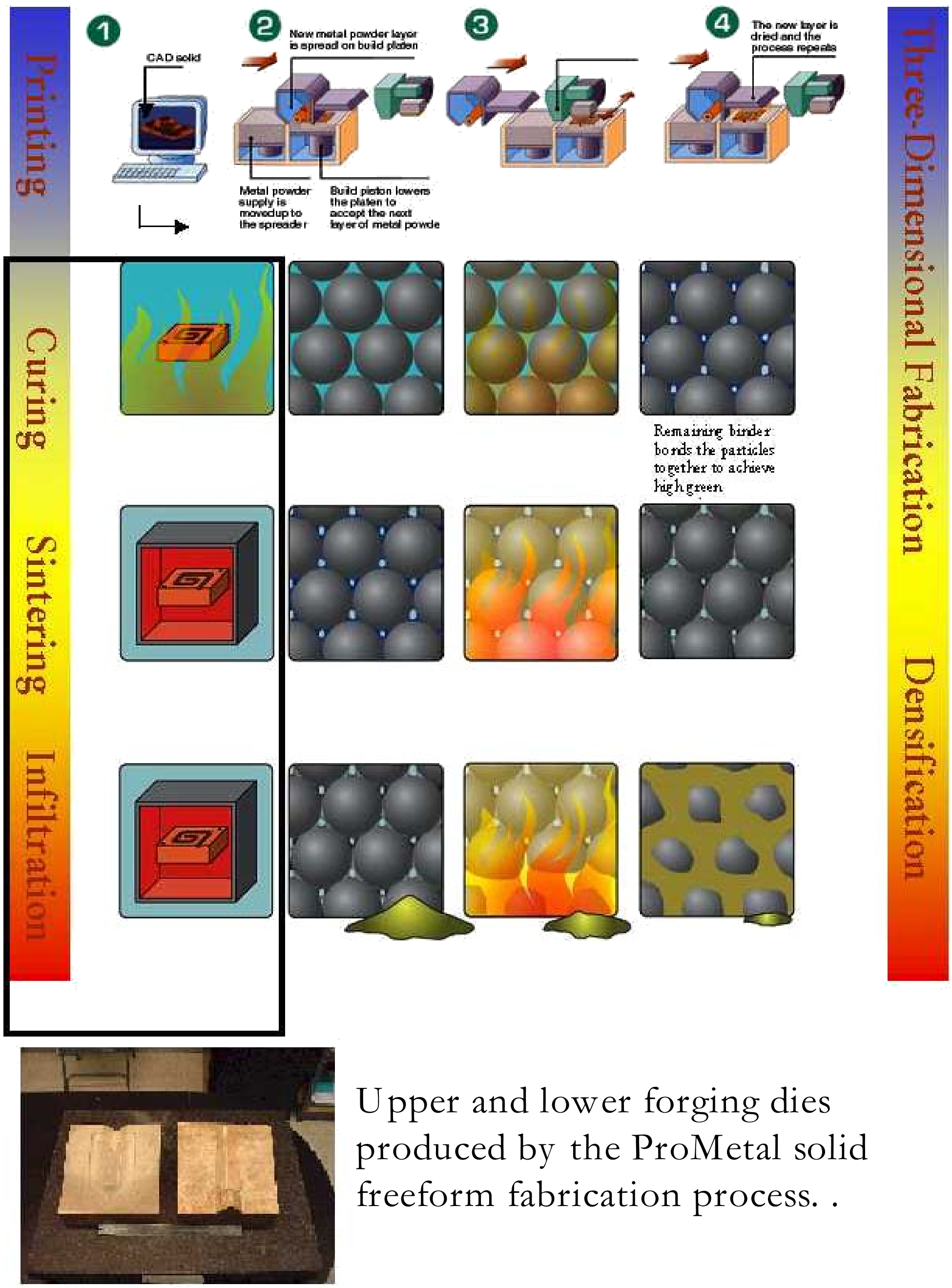

Figure 7 – Powder-Bed Binding and Controlled Thermal Processing
Poster from cooperative research program on aluminum forging die development, with Defense Logistics Agency (DLA) - the Industrial Capabilities Division (DLA J339), and the Logistics Research and Development Branch (DLA-DSCP), Forging Industry Association (FIA), Advanced Technology Institute (ATI) and the Forging Defense Manufacturing Consortium (FDMC)

cooperative programs with outside research institutions at any one time, working on specific material systems and new process objectives.

Notable recent achievements in this knowledge development include a continuous improvement in the characteristics of the current main-line steel/bronze composites, now boasting a hardness of 35 HRc (Figure 6); a homogeneous fully dense stainless steel at over 40 HRc hardenable to over 50; the largest tool plate ever made in solid freeform metal (Figure 9); forging dies suitable for short run aluminum; thermal process profiles for large and bulky tools; and high strength binder that enables safe large tool handling and strong internal cavity structures.

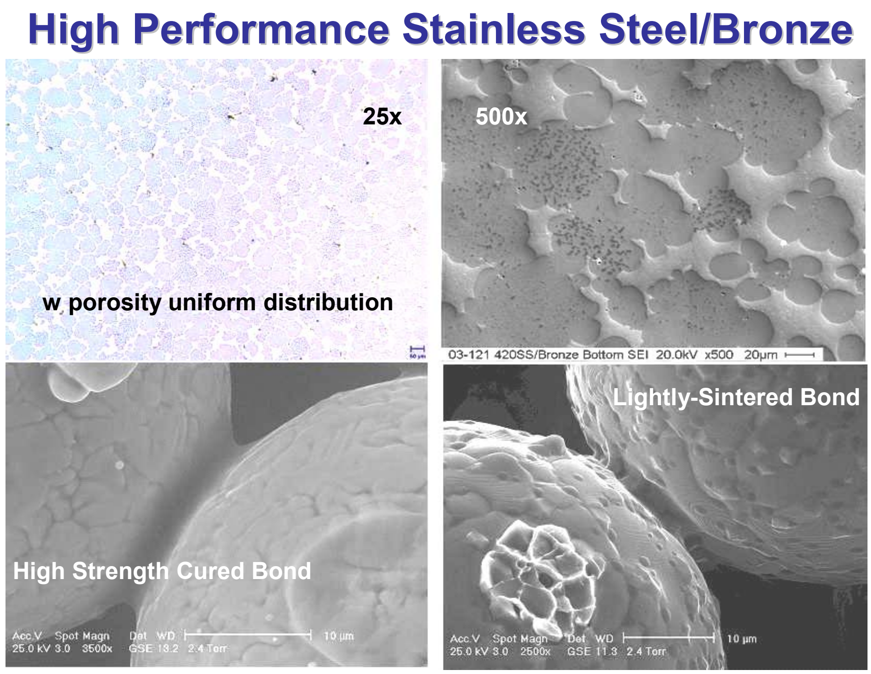

Figure 8: Process Knowledge and Control Determines Predictable and Repeatable Material Characteristic

Conclusion

Solid freeform technology can demonstrate unique and significant benefits to plastic injection molding operations with conformal cooling. A variety of technologies exist to serve these opportunities, each with its own special capabilities and advantages.

Acknowledgements

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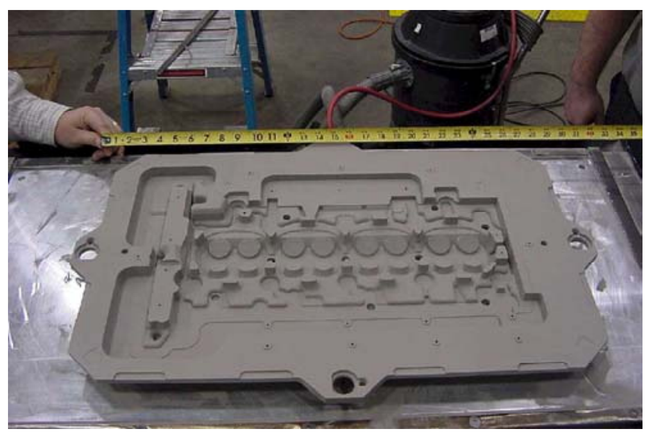

Figure 9: Largest Freeform Metal part Made to Date - Lost Foam Tooling Plate Made For NIST/ATP Cooperative Research on ProMetal R10 machine, in Partnership with General Motors and Cobra Pattern