Faster- Better Molds Through RSP Tooling

New Research and Advancements

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Reviewed, accepted August 19, 2004

Abstract

The recent developments in rapid production tooling have all but made the need for prototype tooling disappear. There are several approaches that are now as fast and inexpensive as prototype tooling, and after part approval can continue to run in high volume production applications. The newest of these approaches is an indirect spray forming process invented by Dr. Kevin McHugh of the Idaho National Engineering and Environmental Laboratories (INEEL). The advantages of RSP Tooling can be found in its accuracy, finish, cost and speed compared to the other rapid tooling processes [1].

The commercialization effort for this spray forming process started in February of 2002. The beta production machine was operational in November, 2003, and started to produce production tooling in March, 2004. Since that time tooling has been manufactured and run for many forming applications. In all but the simplest tools the process has proven to be less expensive and faster than standard machining of tools or any other rapid production tooling process. Research and development of the process has continued both at INEEL and at RSP Tooling, LLC making the process faster, more accurate and less expensive to operate. This research has also generated a better understanding of the underlying metallurgy of the process.

Method

RSP Tooling is an indirect spray forming technology that was developed by Dr. Kevin McHugh at INEEL for producing molds and dies [2-5]. The general concept (Figure 1) involves converting a mold design described by a CAD file to a tooling master using a suitable rapid prototyping (RP) technology such as stereolithography (SLA). A pattern transfer is made to a castable ceramic, typically alumina or fused silica. This is followed by spray forming a thick deposit of tool steel (or other alloy) on the ceramic pattern to capture the desired shape, surface texture, and detail. The deposit is built up to the desired thickness at a rate of about 500 lb. /hr. Thus, the spray time for a 7” x 7” x 4” thick insert is only 9 minutes. The resultant metal block is cooled to room temperature and separated from the pattern. Typically, the deposit’s exterior walls are machined using a wire EDM, and bolt holes and water lines are added.

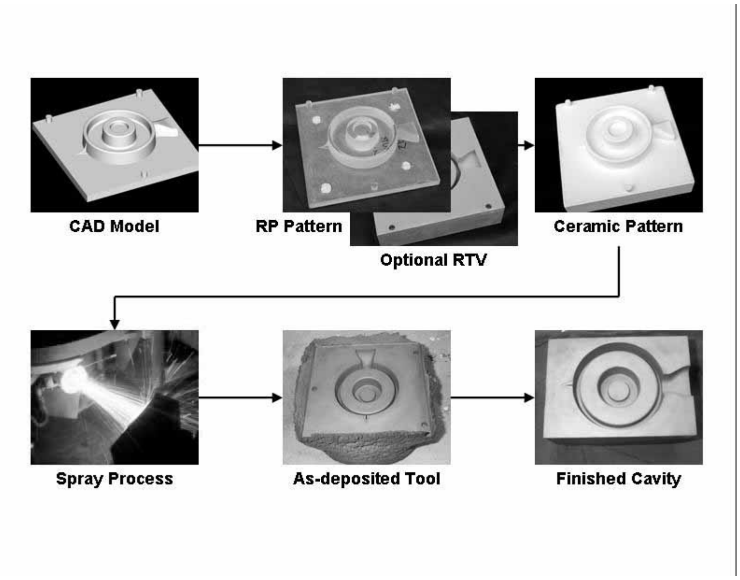

Figure 1 - Process Sketch

The turnaround time for cavity or insert is unaffected by complexity. From receipt of a CAD solid model to shipment of the cavity can be a little as 5 days but is typically 10 days. Molds and dies produced in this way have been used for prototype and production runs in plastic injection molding, die casting, and forging operations. Low pressure casting and extrusion dies have been made and are in testing.

Generation of the physical model or "master" is straightforward. A number of rapid prototyping (RP) approaches are available commercially to accomplish this, but they differ widely in terms of cost, accuracy, and surface finish. As part of an R&D study conducted with Colorado State University and an industry team [3], the suitability of various RP-generated physical models as well as physical models machined from aluminum and various tooling boards, was assessed for use with RSP Tooling (Figure 2).

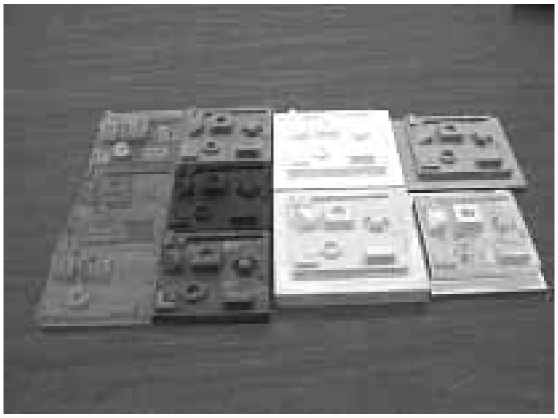

Figure 2 - Various Model Methods

More recent research by RSP Tooling, Colorado State University and Cleveland State University have shown that the Stratasys Eden 333 additive method and the Roland MDX-650 subtractive method can both reduce the cycle time and cost of the initial model by 75% while maintaining or improving the finish and accuracy of the final tool. The nature of the mold design determines which of these methods is the most appropriate. For example a tool with undercuts or deep features would be best run with an additive method, while reasonable flat designs would be easier with the subtractive method.

Comparison runs on the same tool were made using the 3D Systems 5000 and the Stratasys Eden 333. Accuracy of the XY dimensions are comparable while the Z axis of the Eden 333, because of its much smaller step size, is significantly more accurate. The flat surfaces of the SLA are better because the Eden 333 shows print lines. The angled surfaces of the Eden 333 are better because of the smaller Z step. Finishing times are approximately the same for both. The Eden 333 is the preferred system because it is significantly faster and less expensive than the 5000, while finishing costs and accuracy are comparable.

Ceramic patterns are made by slip casting or freeze casting ceramic slurry, typically made of alumina or fused silica, onto the tool master. This involves mixing a ceramic powder with a liquid activator or binder, pouring the mixture into a mold, allowing it to set up, demolding and firing of the ceramic in a furnace. Many ceramic formulations have been and are being evaluated for suitability in the process. Ease of casting, material cost, surface roughness, strength, thermal shock resistance, maximum use temperature, flatness, and dimensional accuracy are assessed. With the right equipment and procedures, very accurate and reproducible ceramics are easily made.

Forming the ceramic pattern is one of the most important steps of the process. It represents a significant variable in the cost, timing, finish, and accuracy of the final tool. The ceramic forming process is the most time consuming element in the cycle representing 40% of the entire turn-a-round time for a tool. Research into using a machined graphite or machined ceramic master has been performed and several tests have shown these to be feasible solutions that could eliminate the majority of the time consumed by this step. There are still several hurdles to overcome, and the approach is only feasible for “one of a kind” tools since the master gets destroyed in the process. No production tools have yet been made using either of these techniques, but development is continuing.

The spray forming step is at the heart of the RSP Tooling process. Spray forming involves atomizing: breaking up a molten metal stream into small droplets, using a high velocity gas jet. Aerodynamic forces overcome surface tension forces within the melt producing an array of droplet sizes that are entrained by the jet and deposited onto the pattern (Figure 3).

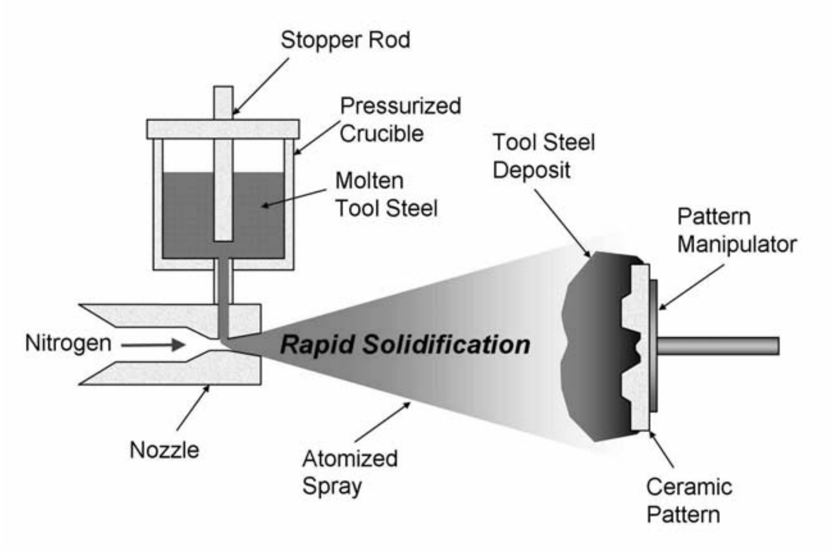

Figure 3 - Machine Process

As the droplets traverse the distance separating the atomizer and ceramic tool pattern, they cool at very high rates that vary depending on size. As a result, a combination of liquid, solid, and “slushy” droplets impact the ceramic, and “weld” together to form a coherent deposit. Figure 4 demonstrates the effect of rapid solidification with molten tin sprayed on a party balloon.

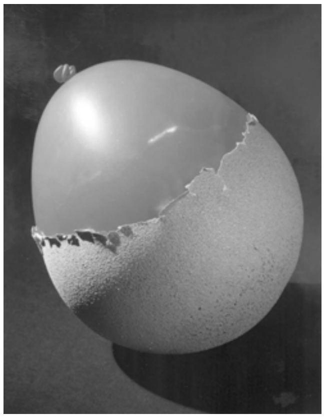

Figure 4 - Rapid Solidification in Action

The high cooling rate of the deposit greatly impedes atomic diffusion, so segregation is very limited compared to cast metal. It also minimizes the erosive interaction of the metal and ceramic tool pattern, allowing the deposited metal to accurately capture surface details of the ceramic that would not be possible if the metal were to be cast onto the ceramic.

The rapid solidification rate also results in non-equilibrium solidification, extended solid solubility, and very limited segregation [6] (Figure 5 and 6).

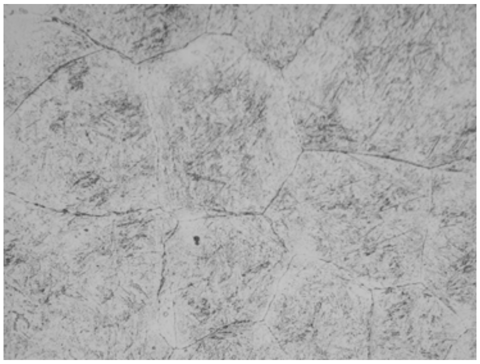

Figure 5 - H13 as Deposited at x500

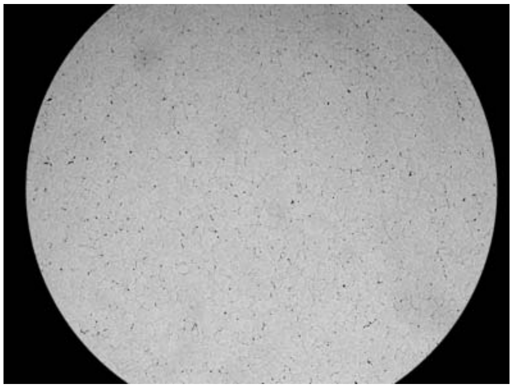

Figure 6 - A2 as Deposited at 50x

Machine Development

The Beta machine was completed in January of 2003**.** It took 14 months to reach the operational and cost parameters that were established at the beginning of the project. This development work focused on three different areas, machine reliability, ceramic performance, and tool quality. In the beginning the machine was prone to component failure which resulted in molten metal pouring into a sand pit below the nozzle. Most internal components assuming they held up for a run had to be replaced prior to the next run. Costs of the components were high and the cost per shipped tool was astronomical. The challenge was that the internal components run at temperatures of around 1600C. This is also the failure point of many of the materials. We also found that many “experts” were very knowledgeable concerning the standard operations for their products but had little understanding of the underlying science and therefore were of little help with a new application. Over the next 10 months virtually every internal component was changed to either a new material or better, less expensive supplier. By February of 2004 the machine uptime improved dramatically and component cost dropped to less than $50 per tool.

The ceramics used for patterns were also an issue. Ceramics are excellent for high temperature applications but they do not like sudden changes in temperature. In the RSP process the room temperature ceramic is heated to temperatures approaching the melt temperature of steel in less than an hour. Then molten steel is sprayed on to the ceramic. This is brutal treatment for this type of ceramic and most experts indicated it could not be done. A method also had to be developed to mount the ceramic on to the manipulator in such a way it could be easily be loaded and unloaded but still hold up to 100# of steel while being moved in 5 axis of motion. Initially the ceramics cracked so that they fell off or at best cracked and left deep fissures on the tool face. Through modifications to mixing and firing techniques a ceramic that could stand the rapid temperature change was achieved. Mounting systems were also modified so the ceramic could handle the weight and movement.

Once the machine was stabilized so that each run was consistent and the ceramic was dependable, work started on the surface and internal quality of the tool. Quality is a thermal issue. It is important to get the metal applied quickly in order to get a porosity free tool but if it is too hot sink holes can result. The first step in development was to achieve a consistent spray. This was achieved through the developments listed above and by redesigning the crucible so that it could be pressurized. Once the spray was stabilized it was a matter of trial and error until the right application rate was understood.

The machine is now capable of long term continuous operation at a minimal cost per tool and well within the initial cost targets. Research is now directed toward improving the various steps of the operation to improve speed and accuracy still further and to expand the process applications by developing technologies, like bimetallic tooling.

Accuracy

Dimensional accuracy and repeatability of all processing steps have been analyzed by Colorado State University personnel and industry partners using coordinate measuring machines (CMM). This has helped to identify suitable materials and processing conditions. Several conclusions have been drawn from the study:

- Molds made from the same master but different ceramic patterns were essentially identical which is of major importance in multiple cavity dies or replacement inserts. It also means that accuracy can be increased by making a test tool and then modifying the model to the dimensional data.
- Most of the shrinkage comes from casting and firing of the ceramic. Some ceramic formulations nearly eliminate this shrinkage. It has also been demonstrated that modest variations in binder and firing temperatures have virtually no effect on this shrink.
- The shrinkage does vary by feature; however this shrinkage is consistent and reproducible which means that a computer program to predict shrinkage by feature will improve the process accuracy.

The overall conclusion of the dimensional accuracy study is that the accuracy of molds made by the RSP Tooling method is comparable to the conventional practice of machining, benching, polishing and heat treating. Detailed algorithms are under development that will automatically apply scaling factors to a CAD drawing of an insert for various processing sequences.

Accuracy has been improved by making a significant reduction in the ceramic shrink rate and by use of the more accurate rapid prototyping model methods. Further improvements can be expected if machined ceramic or graphite is used.

Replication

The process can replicate very small features. When sprayed on quartz glass the process reproduced a fingerprint in steel that was accidentally left on the pattern (Figure 7). In tests making a small stamping die with engraved details, features as small as .003 inches could be transferred to the ceramic and then to the sprayed steel tool. All of the detail from a laser burned model was transferred to a tool (Figure 8). This is of even more significance now that the latest SLA machines can achieve details as small as .005 inches in width.

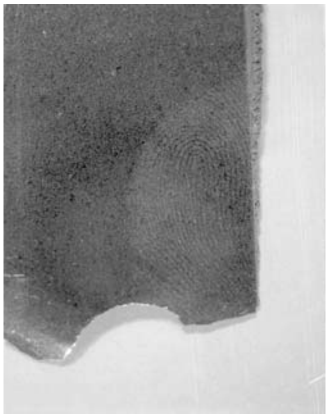

Figure 7 - Finger Print

Figure 8 - Leather Grain Surface

Work with Complete Surface Technologies in Detroit, Michigan has resulted in a process in which grained surface textures can be applied to the freeform fabricated master and then sprayed directly into the tool which eliminates the need to etch the tool after machining. This again will reduce the time and cost of getting a tool into production (Figure 9).

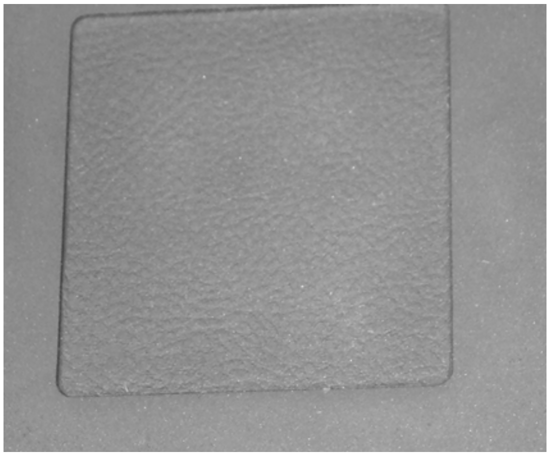

Figure 9 - Leather detail

Technical and Economic Benefits

The main benefits of RSP Tooling involve cost and turnaround time reductions without sacrificing quality or accuracy. When the atomized spray covers the surface of a ceramic tool pattern, it replicates the features very accurately, regardless of the complexity (Figure 10). By so doing, it eliminates many steps in normal mold-making practices such as milling, sink EDM, benching, polishing, and engraving.

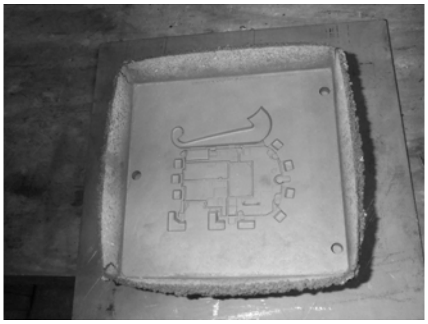

Figure 10 - Tool Detail

Since cost and production time associated with the spray form process are not affected by complexity, the savings achieved by using this process depends on the cost of the alternative process. On recent projects the cost savings varied from $0 to $3000 per insert. Savings in time were proportional.

The time required to produce multiple cavities is always significantly improved. The first cavity takes five days but each subsequent cavity follows in 3 hour intervals. This means 32 virtually identical cavities can be shipped in 10 days.

The cost for an RSP tool is also a constant, except for the costs of the solid model and the material used. The cost of the master pattern varies depending on the method used, the size, and the material. With the improvements in the model manufacturing methods discussed earlier, both the cost and production time will be dramatically affected. With the right ceramic process, it is conceivable that the delivery time of an insert can be reduced to 8 hours.

Die Materials

The RSP Tooling machine is designed so each tool can be made from a different alloy. Because of the rapid solidification of the metal the quality of the tool is the same or in some cases better than machined tools of the same alloy. P-20 when sprayed typically has a better grain and density than the standard machined tool but has the same strength and hardness. Tool life is generally the same.

Spray formed H-13 tool steel has significantly better properties than can be achieved by standard methods. As sprayed the tool has a Rockwell C hardness of 56. This can, through artificial aging, be increased to 62Rc. When H13 is aged the strength of the material is significantly increased (Figure 11).

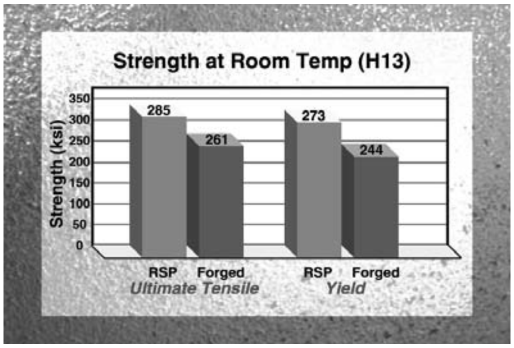

Figure 11 - H13 after Artificial Aging

This means that if high wear materials are used in plastic injection molding or if the process is die casting tool life can be extended by 25% or more over a standard H13 tool. Since the machine can use any metal with a melt point below 1500 degrees centigrade tool life can be further improved by using new or existing hard to machine alloys.

Dr. McHugh has a DOE grant which is funding research into new alloys which take advantage of the rapid solidification process to increased die life even more. RSP Tooling is investigating new materials such as NiAl which are too hard to machine to have been practical in the past but now can be made into tools at a nominal cost.

The density of a sprayed tool is equal to a tool using forged machined steel of the same specification. Tests with H13 have shown densities of 99.5 % to 99.7% [6]. This means that not only can water lines be machined with out fear of leaking but the material can be hand polished with out fear of opening up porosity (Figure 12).

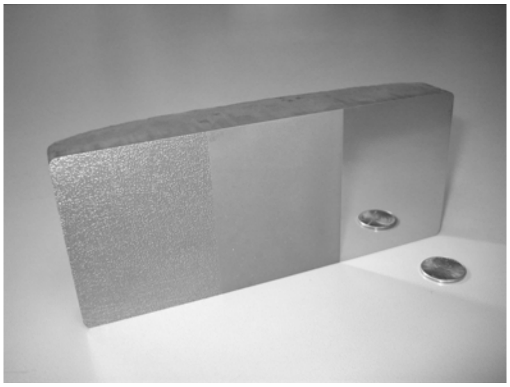

Figure 12 Polished to Three Finishes

A major distinction between this process and other RT processes is that the material used is the same as in a normal machined tool. Thus standard operational practices such as welding, stress relieving, and polishing can all are performed identically (although not as often). To demonstrate that the material is essentially identical tests were performed with sprayed and forged H13 both heat treated identically. Differential thermal analysis (DTA) is useful for analyzing the heat absorption or evolution that accompanies phase transformations, precipitation of new phases, resolution of phases, etc. DTA was performed on samples of spray-formed H13, spray formed/annealed H13 and commercial forged/annealed H13. Prior to testing, all samples were austenitized at 1015OC and air quenched. Scan data and peak assignments are summarized in Figure 13. Similar peaks corresponding to the exothermic precipitation and growth of carbides, the curie transformation, the ferrite-to-austenite transformation, gamma-to-delta iron transformation, and melting were observed for all samples.

Impact energy analysis was conducted at room temperature on spray-formed H13 tool steel in the as-deposited condition, following artificial aging, and following conventional heat treatment. Various deposition rates and quenching media were used in an effort to modify carbide formation and growth and the nature of the matrix phase, both of which strongly influence toughness. Spray-formed samples were produced at a deposition rate of ~250 kg/hr followed by cooling in still nitrogen, at ~250 kg/hr followed by oil quenching, and at ~100 kg/hr with still nitrogen cooling. The impact energy data for spray-formed samples is reflective of bulk rather than surface microstructural features and was strongly influenced by the amount of free carbide and the phases present in the surrounding matrix (martensite and bainite) Microstructural evaluation indicated that spray-formed material was somewhat more refined at the die surface than in the interior due to the higher cooling rates [6].

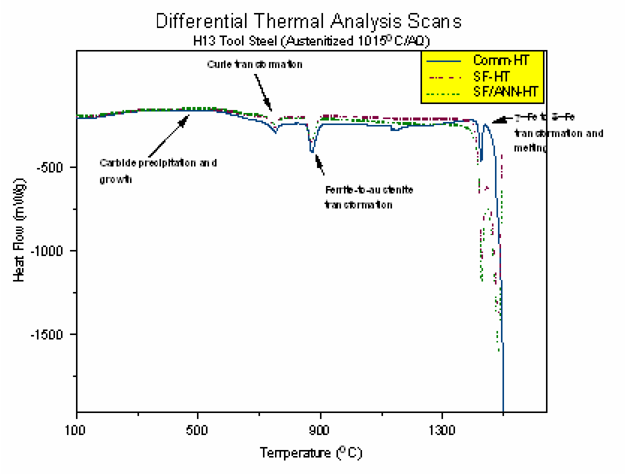

Figure 13 - DTA scans on austenitized (1015OC) and air quenched H13 tool steel samples of commercial forged/annealed (Comm-HT), spray formed (SF-HT), and spray-formed/annealed (SF/ANN-HT) materials.

Surface Finish

The surface finish that can be achieved is dependent on the ceramic pattern and the initial model. The spray system replicates the ceramic with extreme accuracy and can pick up details as small as .0001 inches. The standard process now in use can achieve a surface finish of 40 micro inches.

Several ceramics now being examined have the potential of significantly improving this finish. For extremely demanding applications, a fused quartz glass pattern could be sprayed which can result in a mirror finish (Figure 14).

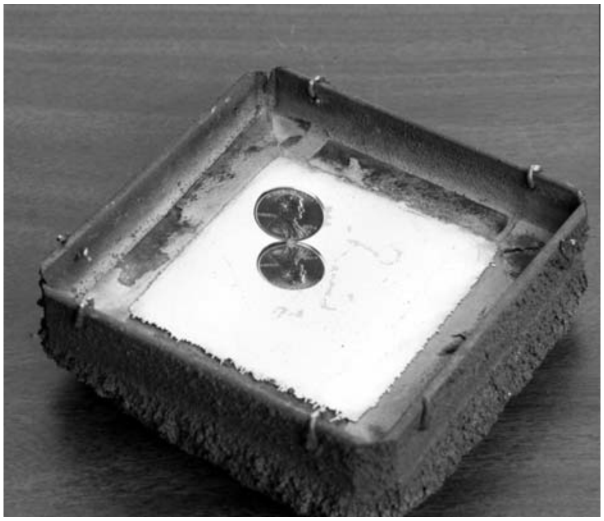

Figure 14 - Reflection of a Penny

Cycle Time Improvement

An additional potential benefit of the spray-forming approach involves the ability to include conformal cooling lines in a tool in order to rapidly cool the molding surface of a mold or die. Mold cooling accounts for about two thirds of the total cycle time in plastic injection molding, die casting and most other metal-mold casting operations. Ideally, cooling lines would be placed near the surface of a die, and would conform to the geometry of the die surface. This is referred to as “conformal cooling” and is viewed by molders as very beneficial because it provides better thermal management of the tool and reduced part cycle time. In plastic injection molding for example, conformal cooling has been shown to reduce part cycle time 15-50% compared to standard cooling practices. This improves productivity and reduces energy use [7, 8].

The incorporation of cooling lines has traditionally involved machining straight-bore holes into the back of the die insert. Unfortunately, conformal cooling lines can not normally be incorporated into machined dies due to their complex geometries.

Dr. McHugh at INEEL is working under a DoE grant to perfect a dissolvable core that would be inserted into the spray automatically and after the tool was finished the core would be removed resulting in conformal cooling lines (Figure 15).

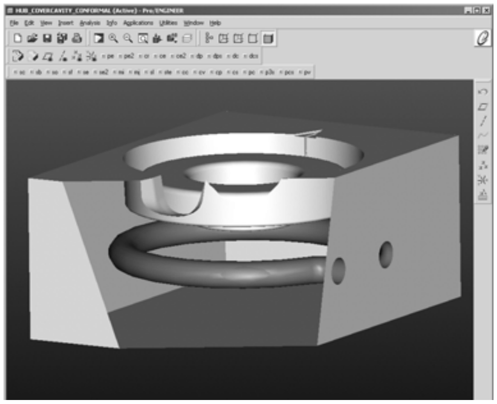

Figure15 - Conformal Cooling

Several experts have suggested that the cycle times of both plastic injection molded parts and metallic die-cast components can be substantially reduced by first depositing a high-strength wear resistant layer (H-13 Steel), followed by a high-thermal conductivity material (copper) [9,10,11]. Preliminary results indicate that spray forming is well suited for producing these clad tools. A copper/steel clad was formed by depositing a high conductivity copper backing onto an H13 die insert (Figure 16). This allows for a simple water line to be added through machining into the copper cladding yet the cooling will be uniform over the entire surface of the die. Copper backed tools have been manufactured and have shown to have an extremely strong mechanical bond due to the rough surface that is left when only a thin layer of steel is sprayed. Tests are now being run to determine the amount of additional heat that can be removed in this manner and to determine how long the bond holds up to thermal cycling.

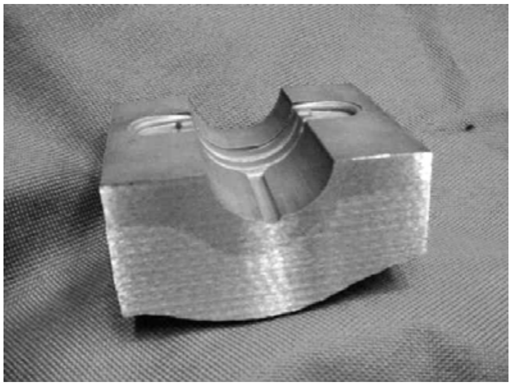

Figure 16 - Clad Tooling

Limitations

There are limitations to the size of molds and dies that can be produced with the current equipment. The original laboratory-scale equipment at INEEL can produce inserts that are about 3” x 3” x 2” thick. Commercial beta equipment located at RSP Tooling, LLC has increased this to 7” x 7” x 4” thick. However, the process has no inherent size limitation, and machines with larger capacity are being planned. Preliminary research has demonstrated that multiple spray heads can be used within the same machine. This will be the approach used in larger machines. The next proposed size will be 20x20x10 and the machine should be able to produce a tool in less than eight hours.

The second limitation is the aspect ratio for standing (boss) features of the mold. Cavity features on the mold surface do not present problems. However, boss features on the mold surface do. Recent projects have shown that this limitation is more significant than originally thought. For small features the process can now make features with aspect ratios of about 4 to 1 but for larger features (2”x2”) the ratio is closer to 1 to 1. This is because, when spraying molten metal down into a cavity in the ceramic the metal will tend to bridge across the hole before it is entirely filled. While R&D in this area continues, it is currently recommended that these types of features be inserted.

Conclusions

Spray forming has demonstrated great potential for reducing the cost and lead time for tooling by eliminating many of the machining, benching and heat treatment unit operations. In addition:

- Spray forming provides a powerful means to control segregation of alloying elements during solidification, carbide formation and growth, and the ability to create beneficial metastable phases in many tool steels. As a result, relatively low temperature artificial aging heat treatment can be used to tailor properties such as hardness, toughness, thermal fatigue resistance, and strength, which will increase tool life.
- Clad tooling with high heat conductivity metals will substantially increase cycle times in plastic injection molding and die cast operations.
- Successful production runs in plastic injection molding, aluminum die casting, and forging have been demonstrated.
- Tools are also being made for use in glass forming, extrusion, and permanent molding operations.

Acknowledgements

The author gratefully acknowledges support by the Office of Industrial Technologies, Energy Efficiency and Renewable Energy, U.S. Department of Energy under grants DE-FC07-01ID13982 and 1H132 and contributions by Dr. Kevin McHugh, Bruce R. Wickham of INEEL, Prof. James E. Folkestad, Colorado State University, Jon Tirpak and the Forging Defense Manufacturing Consortium (FDMC) including the Forging Industry Association, Advanced Technology Institute, and the Defense Logistics Agency.

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