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# Faster, Less Expensive Dies Using RSP Tooling

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**RSP Tooling is an indirect spray form additive process that can produce production tooling for virtually any forming process and from virtually any metal. In the past 24 months a significant amount of research and development has been performed. This resulted in an increase in the basic metallurgical understanding of what transpires during the rapid solidification of the metal, significant improvements in the production machine up time, ceramic developments that have improved finish, process changes that have resulted in a shorter lead time for tool delivery, and the testing of many new alloys. RSP stands for Rapid Solidification Process and is the key to the superior metallurgical properties that result from the technology. Most metals that are sprayed in the process leave the machine with the same physical properties as the same metal normally achieves through heat treatment and in some cases the properties are superior. Many new applications are being pursued including INVAR tools for aerospace composite materials, and bimetallic tools made from tool steel and beryllium copper for die casting and plastic injection molding. Recent feasibility studies have been performed with tremendous success.**

**Keywords** composite tooling, production tooling, rapid tooling, spray forming

## 1. Introduction

The recent developments in rapid production of 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 but can continue after part approval to run high-volume production. The best of these approaches is an indirect spray-forming process invented by Dr. Kevin McHugh of the Idaho National Laboratories (INL). The advantages can be found in its accuracy, finish, cost, and speed compared to the other rapid tooling processes (Ref 1).

The commercialization effort for this spray-forming process started in February 2002. The beta production machine was operational in November 2003 and began to produce production tooling in February 2004. Since that time, tooling has been produced and put into production in many forming industries and a significant number of case studies now exist. In all but the simplest tools, the process has proven to be less expensive and take less time than standard machining of tools or any other rapid production-tooling process. Research and development of the process has continued making the process faster, more accurate and less expensive to operate. Also a better understanding of the underlying rapid solidification metallurgy has been obtained.

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## 2. The Method

RSP Tooling is a spray-forming technology that was developed by Dr. Kevin McHugh for producing molds and dies (Ref 2-5). The general concept 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 (Fig. 1). 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 225 kg/h. Thus, the spray time for a $180 \times 180 \times 150$ mm steel insert is only 9 min. 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 boltholes and water lines are added.

The turnaround time for cavity or insert is unaffected by complexity. From receipt of a CAD solid model to shipment of the cavity is 8 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.

Generation of the physical model or "master" is straightforward. A number of 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 (Ref 2), 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 (Fig. 2). Since this study, models made on new printing type systems and models machined from wax on a small CNC mill have been tried with even more accurate and less costly results.

The ceramic patterns are made by slip-casting or freeze-casting ceramic slurry, typically made of alumina or fused silica on to the tool master. Ease of casting, material cost, surface roughness, strength, thermal shock resistance, maximum use

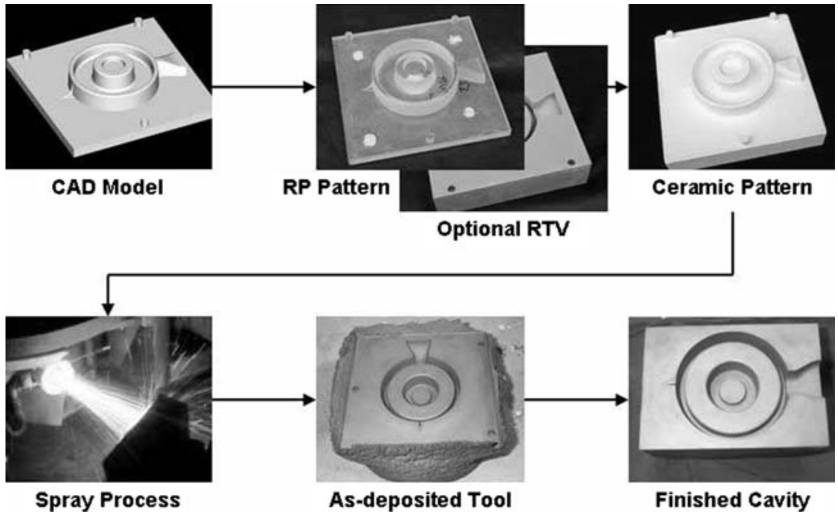



**Fig. 1** Process sketch

**Fig. 2** Various model methods

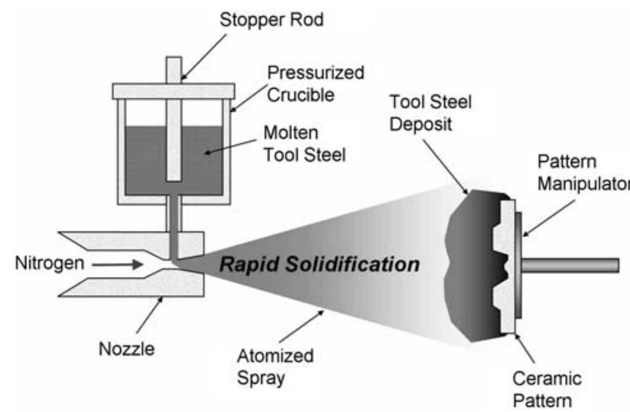



**Fig. 3** Machine process

temperature, flatness, and dimensional accuracy were assessed. With the right equipment and procedures, accurate and reproducible ceramics are easily made.

The spray-forming step is at the heart of the RSP Tooling process. Spray forming involves atomizing, i.e., breaking up a molten metal stream into small droplets, using a high-velocity gas jet. Aerodynamic forces overcome surface tension forces by producing an array of droplet sizes that are entrained by the jet and deposited onto the pattern, as shown in Fig. 3.

The processing of tooling by spray forming can be divided into two distinct but closely related stages: first, flight, and then, deposition. During flight, the thermal energy of the atomized droplets is extracted via convection heat transfer between the droplets and the atomization gas and via radiation heat transfer. During flight, the temperatures and the solid fractions of individual droplets can be calculated using an equation of energy conservation. As a result, a combination of liquid, solid, and ''slushy'' droplets impact the ceramic, and ''weld'' together to form a coherent deposit.

During deposition, heat conduction within the spray-formed material can be assumed to be along the thickness of the spray-formed material because the thickness of molds/dies is usually much smaller than their width/length. The buildup of the deposit occurs via discrete deposition of individual droplets, i.e., there exists a time interval between two groups of droplets that successively arrive at the previously deposited material's surface. At the end of this time interval, a new group of droplets is incorporated to the previously deposited material to generate a new deposit (Ref 6). Figure 4 demonstrates the effect of rapid solidification with molten tin sprayed on a party balloon.

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 was cast onto the ceramic. The rapid solidification rate also results in nonequilibrium solidification, extended solid solubility, and very limited segregation as can be seen in Fig. 5 and 6.

## 3. Accuracy

Dimensional accuracy and repeatability of all processing steps have been analyzed by Colorado State University personnel and industry partners using coordinate measuring

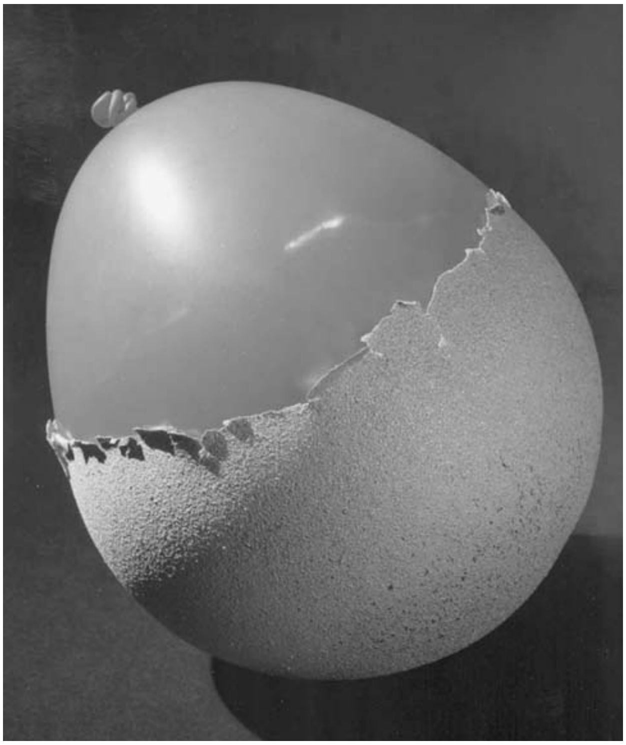


**Fig. 4** RSP in action

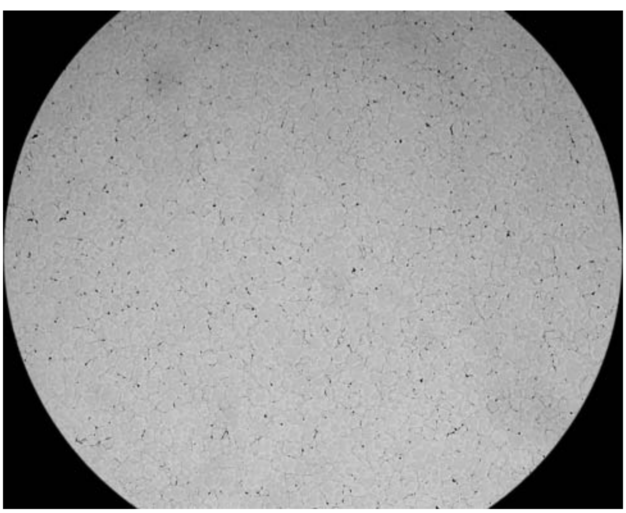


**Fig. 5** A2 tool steel at 550×

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. Repeatability for multiple cavities was developed using a forging net shape gear die. Multiple dies were produced from the same model. These were measured for tooth geometry and all measurements on eight tools were within a range of 10 microns (Fig. 7).

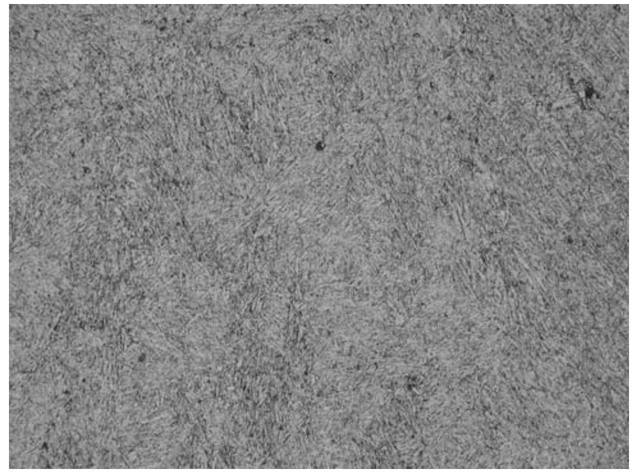


**Fig. 6** H13 tool steel at 500×

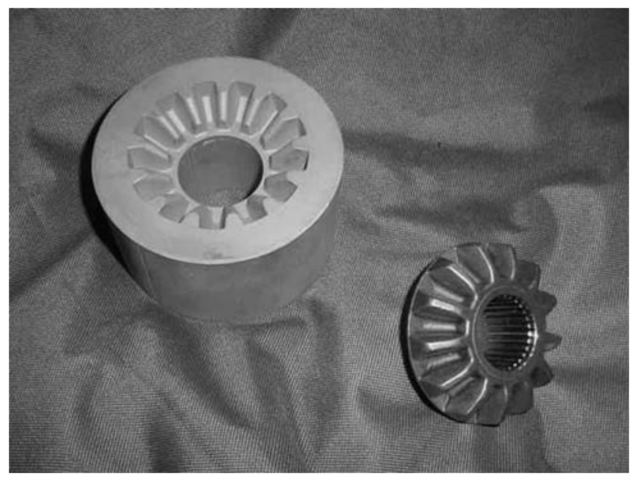


**Fig. 7** Gear die and part

Seventy percent of the dimensional variation comes from firing of the ceramic. Some ceramic formulations nearly eliminate this shrinkage. It has been demonstrated that modest variations in binder and firing temperatures have no effect on this variation. This variation results in a process that can maintain accuracies of .002 mm per mm. This is normally adequate for tools in the size range utilizing the present beta machine but is inadequate for very large tools like lay-up tooling for carbon composite components. As a result additional development was undertaken and methods to improve accuracy were demonstrated. The improvements result from machining the model from hard wax and the use of freeze-cast ceramics.

The freeze-cast ceramic has two advantages over the existing slip-cast ceramic. First, it uses a water-based binder and is frozen. Since water expands when frozen the ceramic expands into the mold instead of shrinking which eliminates most of the dimensional variation. Second, the mold is dried in an oven at low temperatures (350 °C) for 2 h instead of firing it at 1300 °C for 16 h as with the standard ceramic and thus reduces time and cost.

## 4. 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 (Fig. 8). In tests making a small stamping die with engraved details features as small as 0.075 mm could be transferred to the ceramic and then to the sprayed steel tool. All of the detail off of a laser burned model was transferred to a tool (Fig. 9). This is of even more significance now that the latest SLA machines can produce details as small as 0.127 mm in width and small CNC machines with very small cutters can do even small details.

## 5. 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 (Fig. 10). By so doing, it eliminates many steps in normal mold-making practices such as milling, EDM, benching, polishing, and engraving.

Since cost and timing of the spray-forming process are not affected by complexity, the savings achieved by using this process is variable based on the existing cost. On recent projects the cost savings varied from no savings to $15,000 per insert. Savings in time is proportional to the improvement in costs.

The large savings was in the production of a forging die. The cavity was large and deep with tight tolerances and zero draft on the sidewalls. In addition, the cavity ended in a flat with a 0.010 mm radius (Fig. 11 and 12). The normal machining process took over 3 months and usually needed to be sent back for corrections.

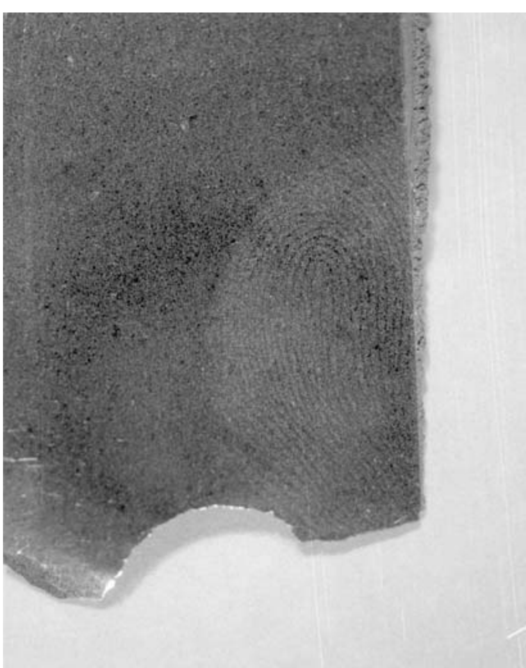


**Fig. 8** Fingerprint in steel

The timing for multiple cavities is always significantly improved. The first cavity takes 8 days but each subsequent


**Fig. 9** Small details replicated in steel

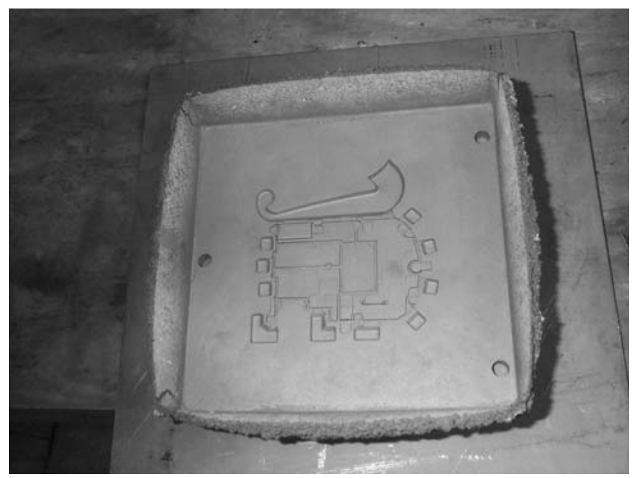


**Fig. 10** Die cast die insert

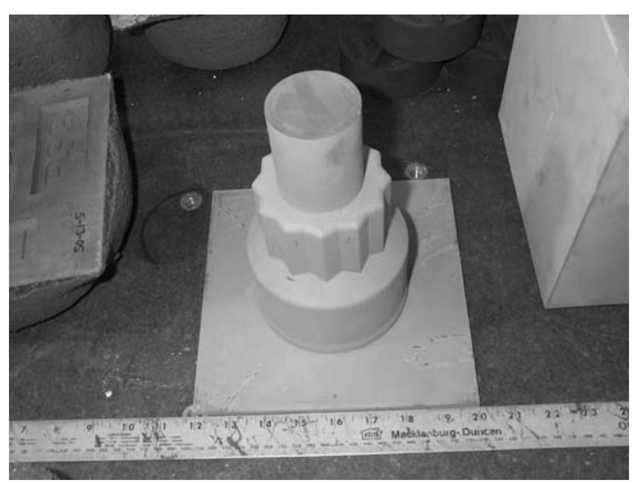


**Fig. 11** Forging die internal model

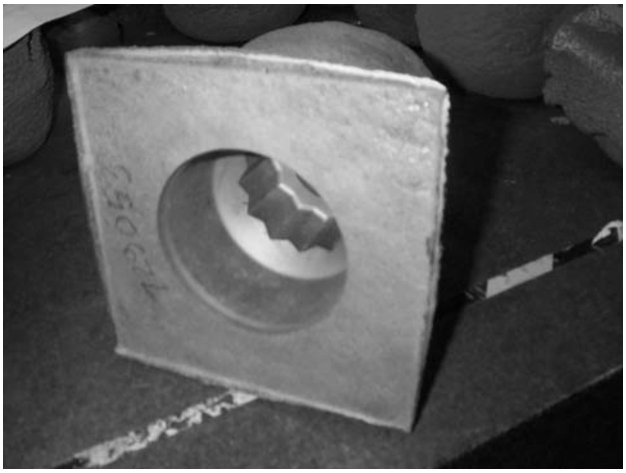


**Fig. 12** Forging die unfinished

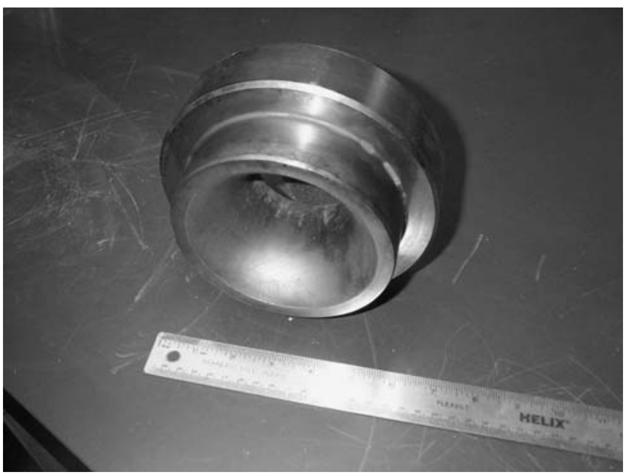


**Fig. 13** Preform extrusion die

**Fig. 14** Ceramic

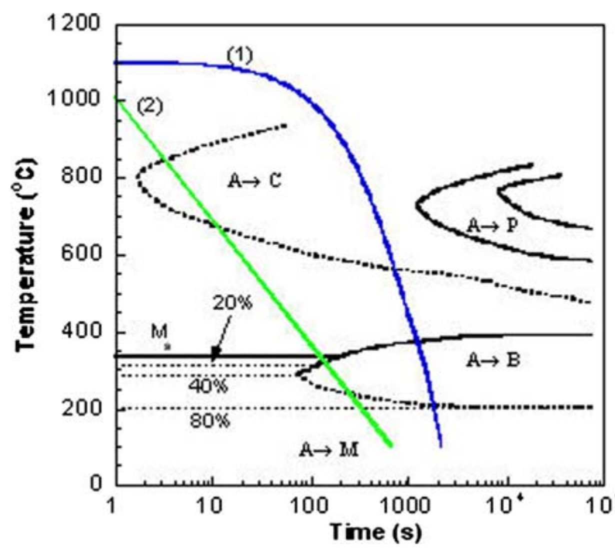



**Fig. 15** Cooling curve for H13 tool steel

cavity follows in 3 h intervals. This means 32 virtually identical cavities can be shipped in 10 days.

Another advantage of the RSP process is in the production of undercuts. Since the ceramic is destroyed in the process undercuts and zero draft create no additional difficulty. The extrusion tool shown in Fig. 13 and the ceramic in Fig. 14 demonstrate this. The tool is an extrusion die used as a preform mold for a forging operation and the product is made from titanium.

The cost for a RSP tool is also a constant except for the solid model cost and the material used. The master pattern varies depending on the method used, the size, and the material. With the improvements in the model manufactured discussed earlier both the cost and timing have been dramatically reduced. With the right ceramic process it is conceivable that the timing for delivery of an insert can be reduced to 8 h.

## 6. 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 most cases better, than machined tools of the same alloy. P20 when sprayed has the same tool life, strength, and hardness but a better grain and density than a standard machined tool.

Unlike P20, RSP-produced H13 tools have increased hardness and strength compared to conventional H13. The higher hardness values of spray-formed H13 (58Rc) as compared to those of conventionally heat-treated H13 (50Rc) can be explained through a review of Fig. 15. In order to do this, the average cooling curve during conventional air quenching is shown overlapping the transformation diagram of H13. During spray forming of H13 tooling, austenite decomposition starts from the austenite single-phase region, while in conventional quenching of H13 it starts from the phase region containing austenite and carbides. As a result, more alloying elements and carbon are dissolved in the matrix of spray-formed H13 tooling. However, the cooling rate in spray-formed H13 is slower than that in conventional quenching of H13, leading to more precipitation of alloying elements and carbon in the form of carbides. By combing the two factors, the former overwhelms the latter, leading to a higher aging hardness in spray-formed H13 (Ref 6).

Recent tests were also run using INVAR to produce composite lay-up tooling. The critical parameter for composite tooling is the Coefficient of Thermal Expansion (CTE). The challenge is to have the tool and material have near identical CTE to avoid dimensional variation and internal stresses. In these tests the RSP-sprayed INVAR had nearly the same CTE as standard heat treated, quenched, and tempered INVAR, and a CTE that was even closer to graphite composite than can normally be achieved with the standard machined material.

## 7. Cycle Time Improvement

An additional potential benefit of the spray-forming approach involves the ability to add conformal cooling lines which 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.

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.

Two approaches to solve this problem are being investigated. Dr. McHugh at INL 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 (Fig. 16).

The second approach is to make a clad tool with standard tool steel at the surface and a high-conductivity metal as the back up material. Preliminary results indicate that spray forming is well suited for producing these clad tools. Figure 17 and 18 show copper/steel clad tools which were formed by depositing a high-conductivity copper backing onto an H13 die insert. 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 high 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 the thermal cycling.

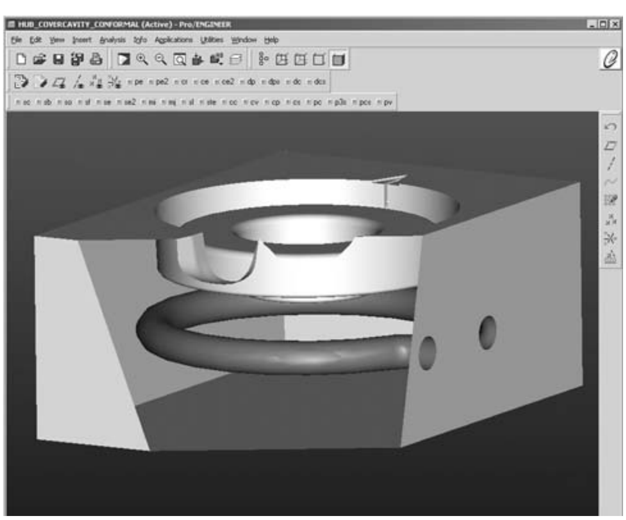


Fig. 16 Conformal cooling concept

## 8. Tool Life

Recent case studies have confirmed what the metallurgical data had predicted. The process increases hardness and strength and should thus increase tool life. Case studies have now documented that tool life does increase for die casting, forging, and extrusion tooling, at least when the typical failure modes are either wear or heat checking.

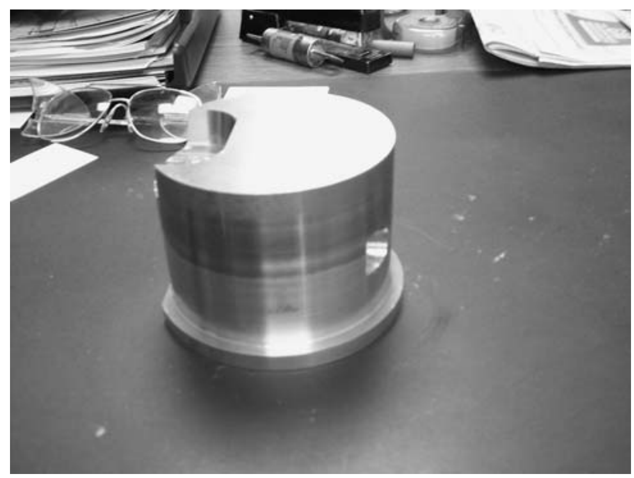


**Fig. 17** Die casting shot block steel/BeCu

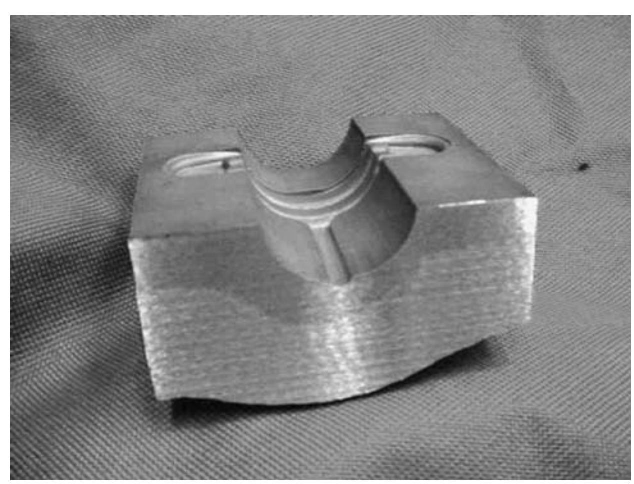


**Fig. 18** PMI die insert steel/copper

The first study was done in die casting by running identical cavities in a four-cavity die with the exception being the material or process used in producing the cavities. In three cavities steel alloys were used including premium grade H13 (as defined by the North American Die Casting Association) and two new and improved materials (QRO 90 and Anvalloy). The fourth cavity was made using a standard grade H13 but produced using RSP Tooling technology (Fig. 19).

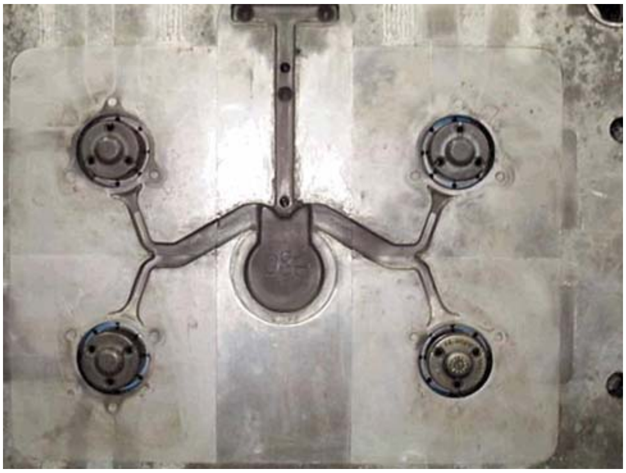


**Fig. 19** Four-cavity die set 203×152 mm (72×72 DPI)

**Fig. 20** RSP and standard test dies

The tooling was run in production until all cavities had reached deterioration to the point that the parts were unacceptable. The RSP insert was the last running and out performed the premium grade H13 insert by 35%. In this case the failure modes were both heat checking and wear. Additional studies by Case Western Reserve University showed that the RSP-produced insert had significantly less soldering than any of the other materials.

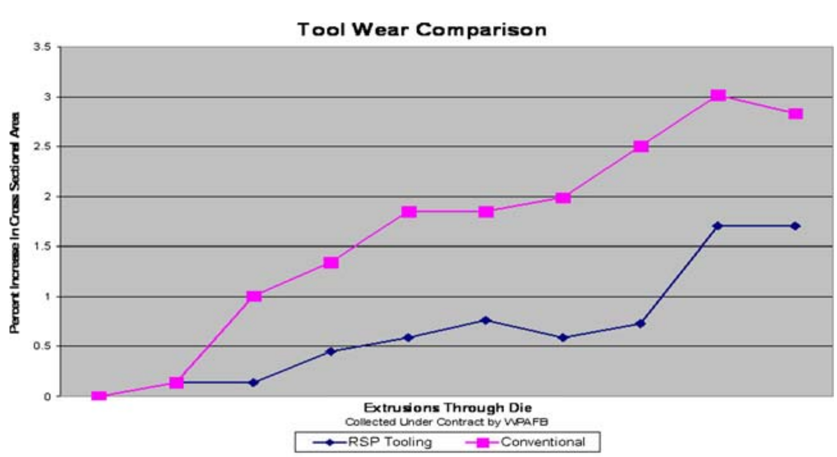
In the second study an extrusion test die was produced from standard grade H13 and run in a test facility at Wright Patterson Air Force Base in Dayton Ohio. This test procedure was designed to compare tool life of various materials for extrusion and forging operations. The test consists of pushing bars of H13 through the H13 die and measuring the length of each bar (Fig. 20). This gives a wear percentage as the bar becomes shorter (wear causes the hole to become larger). The RSP tool showed consistently less wear over the test run (Graph 1).

In the third study a forging die was run in production at Ken-Tool in Akron, Ohio. In a severe wear test the tool is made to produce a chisel in a 750 ton forge press with one blow and the standard tool life is 1000 cycles (Fig. 21 and 22). After 2500 cycles the RSP tool showed little wear and the operator indicated the metal flowed better over the die surface improving quality from the first part through the end of the run.

In addition to the sprayed H13 increasing die wear, research proposals have been written and submitted to investigate spraying NiAl to produce forging and die casting tooling. This material was developed for commercial operations by Oak Ridge National Laboratory and shown in tests by ORNL that tool life could be increased 10-20 times. The major draw back of the material is that it is extremely hard to machine and can only be used in simple-cast shapes (Ref 7, 8). Since a RSP tool would not need machining it is felt that once the process to spray the NiAl is developed it should represent an immense opportunity for any high-wear, low-tool life-forming operation.

## 9. Limitations

There are limitations to the size of molds and dies that can be produced with the current equipment. The original




**Graph 1** Tool wear comparison

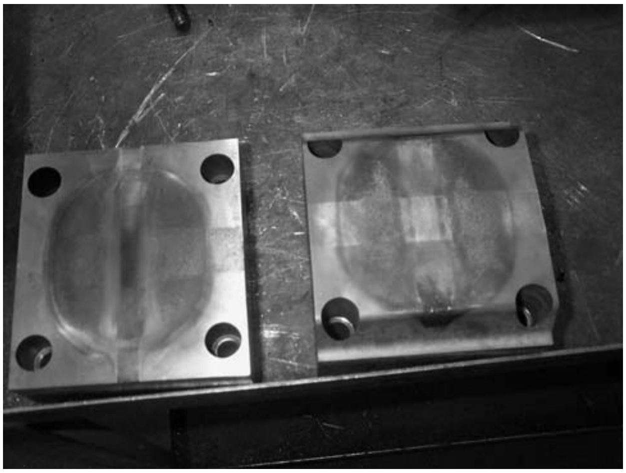


**Fig. 21** Forging dies used in life cycle test

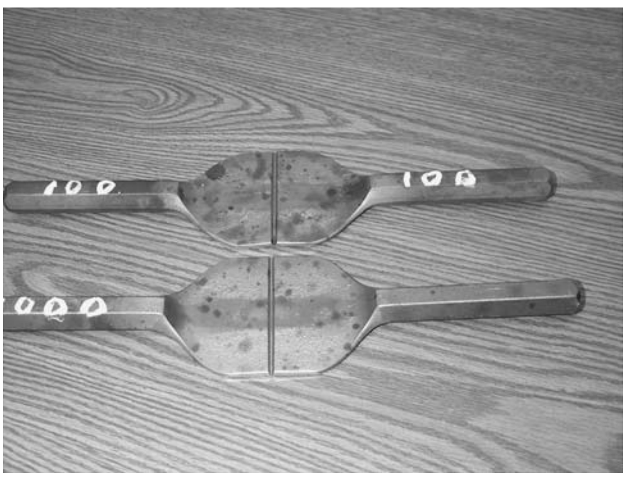


**Fig. 22** Forged parts

laboratory-scale equipment at INL can produce inserts that are about 75 × 75 × 50 mm. Commercial equipment located at RSP Tooling, LLC has increased this to 180 × 180 × 120 mm or 200 mm in diameter. However, the process has no inherent size limitation, and machines with larger capacity are being planned. Preliminary research has been done to show that multiple spray heads can be used. This will be the approach used in going to larger machines. Proposals have been submitted to build a machine capable of producing forging dies 1 m in diameter and graphite composite tools 3 by 10 m in size.

The second process limitation is the aspect ratio for standing 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 4:1 but for larger features the ratio is closer to 1:1 (Ref 9). 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. Conversely, spraying cavities is extremely easy. Since the metal is sprayed around a removable ceramic, parts with complex internal details can easily be reproduced.

## 10. 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 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.

The RSP Tooling process can produce tools faster, for less cost, and with superior properties than standard machining or any other prototype process and research is in progress to improve die life, cycle times, and machine capacity.

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