QuickCast™ & Rapid Tooling:

A Case History at Ford Motor Company

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Background:

The technology of Rapid Prototyping & Manufacturing (RP&M) began with Chuck Hull's invention of StereoLithography and the founding of 3D Systems in March, 1986 (Ref. 1). The first StereoLithography Apparatus, the SLA-1, was previewed at AutoFact in November, 1987. The first SLA-250 was announced in March, 1989; followed by the sale of the first SLA-500 only four years ago (Ref. 2).

During 1988 and 1989 many visionary people recognized that StereoLithography (SL) possessed remarkable potential. Nonetheless, from a pragmatic viewpoint the early parts were very brittle, accuracy was mediocre at best, and surface finish was still rather rough. Consequently, the initial parts were really useful only for ***visualization***. However, this capability *alone* was extremely valuable. It enabled designers and engineers to uncover basic errors in a design while inspecting actual, physical, three dimensional objects. These discrepancies were often previously overlooked when reviewing a complex set of two dimensional drawings. As a result, *improved product visualization* was almost certainly the dominant justification for the purchase of an SLA through mid 1990, and *still* remains an important advantage of RP&M.

However, about four years ago a number of key developments in software, hardware, resin formulation and process methods, coupled with a growing understanding of the fundamental science of SL, began to bear fruit. Figure 1 shows the various advances that have been made in SL part accuracy during this period. Here we plot $\varepsilon(90)$, ("epsilon ninety") as a function of time. Note that this accuracy metric is defined such that ninety percent of the actual measurements on a part will lie within $\varepsilon(90)$ of their intended CAD value. Hence, $\varepsilon(90)$ gives the reader an indication of the "90th percentile error" for parts made using StereoLithography. The data shown in this figure were taken from the so-called "UserPart" accuracy test, described in detail in Ref. 3.

Early values of $\varepsilon(90)$ were almost 400 micrometers using the original Tri-Hatch build style. When $\varepsilon(90)$ was reduced to about 300 micrometers, with the advent of the WEAVE™ build style in June 1990, SL users began to migrate towards applications involving design ***verification*** (Ref. 4). At this point, the parts were "good enough" that engineers and designers could begin to check for component interferences, improperly positioned holes, problems with cable routing paths, etc.

When the values of $\varepsilon(90)$ reached about 200 micrometers, after the release of STAR-WEAVE™ in August 1991, SL users began to adopt the technology for applications involving design ***iteration*** and ***optimization***. Stories of designers and engineers building multiple versions of inlet manifolds, impellers, or aerodynamic nose sections, and then performing flow tests to determine the "best" design, became more commonplace (Ref. 5).

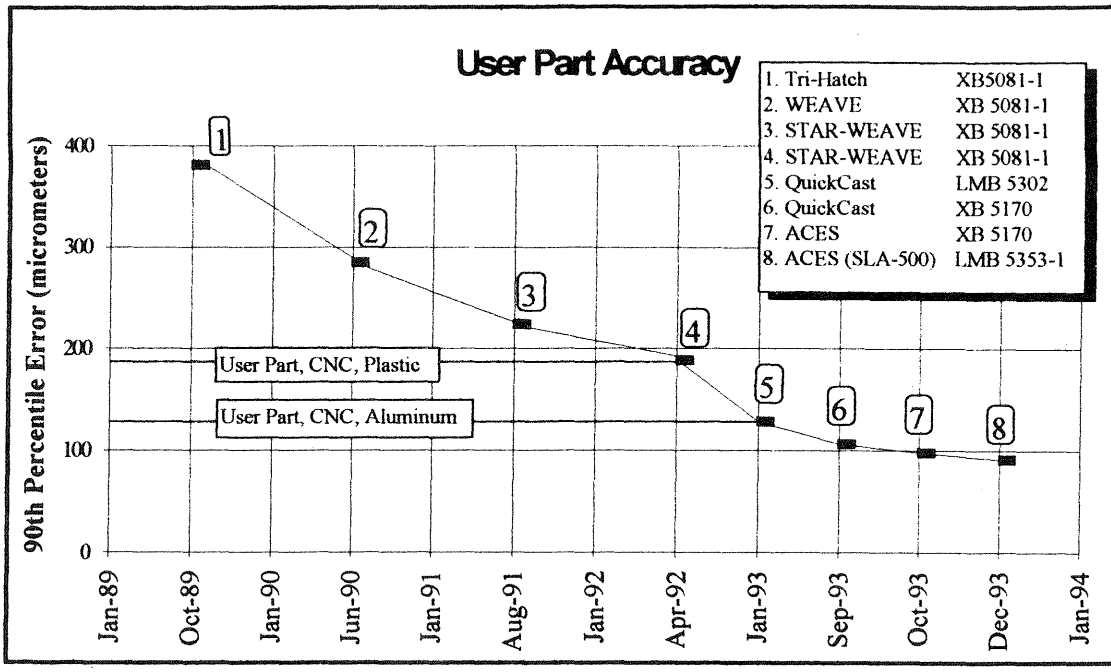

Figure 1

By mid 1993, with the availability of the new epoxy resin XB 5170, the values of ε(90) began to approach 100 micrometers. When the QuickCast™ build style was also released in July, 1993, it became possible for users to go directly from an accurate SL pattern to a quality shell investment cast *metal prototype*. With this step, designers and test engineers rapidly moved into the realm of ***fabrication*** for functional end-use prototypes. During the past year, dozens of corporations and universities in the U.S. and Europe have followed this path for the production of over a thousand functional prototypes in aluminum, stainless steel, carbon steel, tool steel, ductile iron, inconel, copper, beryllium copper alloys, silicon bronze and titanium. All these functional prototypes were investment cast directly from QuickCast patterns (Refs. 6 - 10).

During December 1993, StereoLithography moved to an improved level of UserPart accuracy, when a value of ε(90) = 91 micrometers was achieved This value was obtained when utilizing the recently developed and released *Diode Leveling Module*, as well as the new *Orion Imaging Technology* now available on the SLA-500/30. As a result, it is now possible for users to advance, albeit cautiously, into the arena of true manufacturing ***production***. This paper describes one of the earliest applications of StereoLithography to be focused on the creation of shell investment cast tool steel *negatives* using QuickCast. These steel negatives then become the basis of core and cavity inserts for Rapid Tooling.

This **"QuickCast Tooling"** process has the potential for truly dramatic cost and time savings. Data presented in this paper document the actual time and money saved by Ford on this project alone. Ultimately, QuickCast Tooling should enable rapid and economical generation of core and cavity inserts for either direct injection molding of *end-use production plastic parts,* manufacturing large quantities of *investment casting wax patterns*, or as dies for *direct die casting of production metal components.*

However, in order for this application to provide really substantial cost and time savings, it is essential that the *accuracy* and *surface finish* of the SL generated patterns continue to improve. With $\varepsilon(90)$ values currently at 91 micrometers, coupled with the surface finish of the latest QuickCast patterns, we are now moving "into the ballpark" of QuickCast Tooling. As $\varepsilon(90)$ is continuously diminished and "stair-stepping" is further reduced, this application will begin to grow rapidly; driven by the remarkable economic and schedule benefits attainable. When $\varepsilon(90)$ moves below 40 micrometers and SL pattern surface finish begins to approach that of machined tool steel, we believe that Rapid Tooling will become a dominant growth mechanism of RP&M.

While these levels of pattern accuracy and surface finish may still be a few years away, they are coming. This paper describes a successful project which indicates that we may be closer to the goal of Rapid Tooling than many people realize. Indeed, as shown in the cost and time comparison figures which follow, Ford Motor Company is already beginning to realize significant benefits from this new and important application of SL.

Introduction:

The automotive industry is constantly striving to find ways to produce final products with cost and time savings in the forefront of the designer's, engineer's and manufacturer's minds. Parts constructed more rapidly and economically offer obvious savings. When generated in production materials these parts allow several designs to be tested under real world conditions, enabling selection of the best possible design. The 1994 Ford Explorer "Wiper Module Cover" described in this paper, although a simple part, illustrates the potential of today's technology. Simply stated, the tools created in this project were used to ***injection mold production polypropylene material,*** and equally important, to do so for ***production quantities*** as well.

Process Alternatives:

At the time this project was started, two alternative processes for creating the tools were being considered. The first method involved the possible use of spray metal tooling backed by some sort of composite material. The Wiper Module Cover geometry was simple enough to use spray metal tooling. The primary question was whether the tools would survive the demands associated with production quantities. After some discussion with Ford's Alpha Manufacturing Development Center (Alpha MDC) concerning a project that had previously been accomplished using spray metal (kirksite) tooling with a composite backing, it was clear the tools would almost certainly *not* survive for the required production quantities.

Typical results Alpha MDC were seeing on spray metal tooling were as follows: on the first injection molded part a dimple occurred, although in this case the cause was probably due to excessively rushing the cycle time. At 100 parts, thin intricate sections started to deform. The tool was retired at 300 parts, although part quality was not yet unacceptable. Total production yield was expected to be between 300 and 1,400 parts on that specific spray metal tool. This is consistent with, albeit on the low end of, the results listed in Table 1 below.

Conventional Tooling				
Number of Required Parts	Mold Material Type	Fabrication Cost $(000)	Fabrication Time (weeks)	Mold Life Parts Produced
1 to 30	Silicone	$5	2 to 3	30
30 to 1,000	Epoxy Composite	$9	4 to 5	300
1,000 to 3,000	Kirksite (cast)	$25	12 to 14	1,500
1,000 to 3,000	Aluminum (cast)	$30	12 to 14	2,000
3000 to 250,000	Steel (machined)	$60	16 to 40	250,000
Rapid Tooling				
Number of Required Parts	Mold Material Type	Fabrication Cost $(000)	Fabrication Time (weeks)	Mold Life Parts Produced
1 to 30	Silicone	$5	2 to 3	30
30 to 300	Epoxy Composite	$9	4 to 5	300
300 to 1,400	Arc Metal Spray**	$25	6 to 7	1,000
1,400 to 15,000	Nickel Vapor Deposition**	$30	6 to 7	5,000
3000 to 250,000	Steel (machined)	$60	16 to 18	250,000
3,000 to 250,000*	Steel (cast)	$15	4 to 6	250,000
*Mold life study is still in progress.				
** Composite Assembly				

Table 1

The second process, called Nickel Vapor Deposition (NVD), was a more likely candidate for production tooling requirements. The surface quality of NVD is quite impressive, although estimates of tool life were uncertain. Again, Ford's Alpha MDC group provided some answers based on prior experience. As in the case with spray metal tooling, the NVD process would also require some sort of composite backing material. At the time, Alpha MDC had produced only one mold using the NVD process. That tool was able to withstand very limited injection molding conditions (i.e. 65 psi at 206 °F). These values were far below the requirements of the production tool (viz. 10,000 psi at 450°F - 500°F) as shown in Table 2. Nonetheless, the decision had been made to proceed with limited production quantities in order to establish baseline data for NVD tools.

The NVD tool was stopped at 300 parts, although it held up quite well during use, with little or no degradation evident. Nonetheless, Alpha MDC estimated the yield with the NVD process at between 1,400 and 15,000 parts. While an improvement relative to spray metal tooling, this was still not appropriate for quantities in excess of 100,000 parts.

Tool and Mold Information

Description	Data	Comments
Press	200 Ton	
Tool	12" x 15" Base	DME Cat #1215A-33-17
Pressures	10,000 psi	
Temperatures	450 F - 500 F	
Cooling Line Fittings	1/4" Pipe	DME Cat #JP252
Runner	1/4" Half Round	
Ejector Pins	1/4"	DME Cat #EX-17
Return Pins	5/8"	DME Cat #EX-37
Material to be Molded	Polypropylene	
Shrink Factor	0.018 in/in	
Draft Angle Required	1 degree	
Steel Selected	A2 Tooling Steel	Other possible steels include:
Shrink Factor	2% in all directions	A6 or H13
Mold Inserts Size	CORE - 6" x 8" x 3"	
	CAVITY - 6" x 8" x 3"	

Table 2

Process Selection and Implementation:

Ford Motor Company had been a Beta site for the QuickCast™ process during 1993. Recognizing the limitations of both spray metal and NVD tooling, as described above, Ford decided to try ***"QuickCast Tooling"***. Once the QuickCast Tooling process had been selected, the task of learning how to actually accomplish the desired outcome had begun. The software selected to create the CAD solid model of the Explorer Wiper Module Cover was Parametric Technology Corporation's PRO/Engineer (PRO/E). PRO/E was selected based on the availability of the PRO/Mold software package. PRO/Mold allows the designer or engineer to create ***negative*** molds based on the *positive* of the desired final part geometry. As a starting point, a CAD ***positive*** solid model of the Wiper Module Cover was created in PRO/E and subsequently forwarded to Ford's SLA-250 for creation. A photograph of the QuickCast positive is shown in Figure 2.

As it turned out, the positive of the part allowed the early detection of a packaging interference. A ***second iteration*** was created by altering the PRO/E solid model, and sending the new file to the SLA. This time the positive of the Wiper Module Cover showed no interference, but still required further changes in order for the final assembly to be more easily manufactured. Thus, a ***third iteration*** was generated in PRO/E.

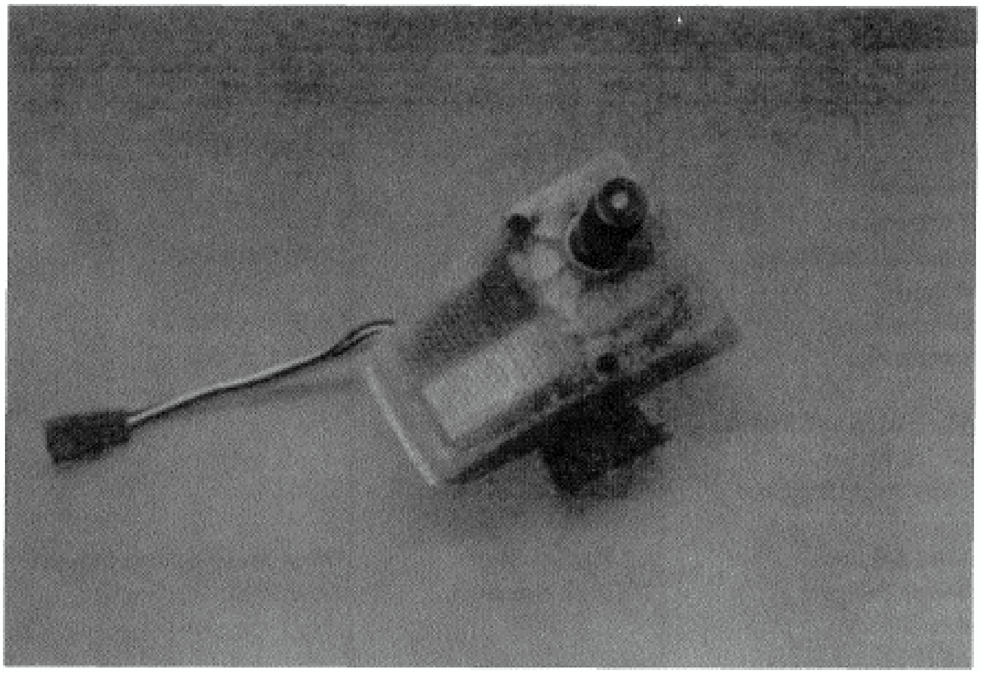

Figure 2: StereoLithography pattern mounted on the wiper module.

When the design, engineering and manufacturing staffs were in concurrence, mold halves were created by initially imbedding the CAD solid model in a block called a "work piece" in PRO/Mold. A parting line was then selected based on the manufacturer's requirements, and the two CAD solid model halves were then "separated." Next, the cooling lines and ejector pin holes were positioned on the PRO/Mold solid models of the mold halves. A schematic of the tooling set-up, showing the mold base, ejector plate, support plate, core and cavity inserts, and top clamping plate, is presented in Figure 3.

However, during a final meeting before actually preparing the STL file, the need for another design change became evident. This ***fourth iteration*** was made to the CAD solid model and was automatically incorporated into the mold halves. The STL files were then generated with the highest accuracy settings in PRO/E in order to obtain the best possible QuickCast pattern surface finish. A photograph of the final QuickCast negative mold insert patterns is shown in Figure 4. It is noteworthy that the classic SL sequence of design visualization, verification, multiple iteration and final optimization was very evident during this project. Had traditional methods been used, significant, expensive, and time consuming tooling rework would certainly have been required. In fact, it is quite possible that a new tool would have been necessary, adding many months to the delivery schedule.

Schematic of Tool

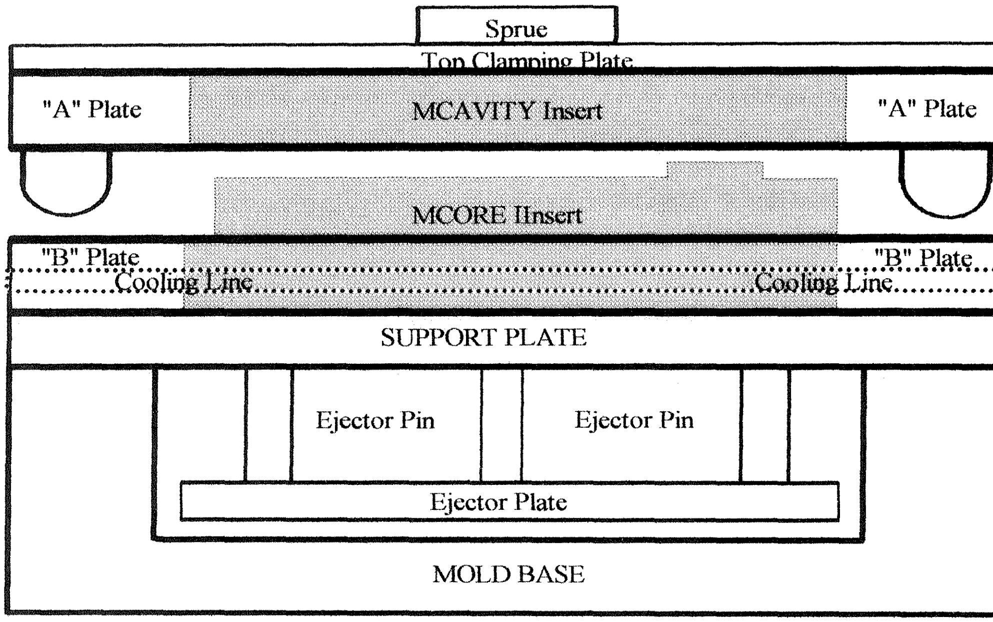

Figure 3

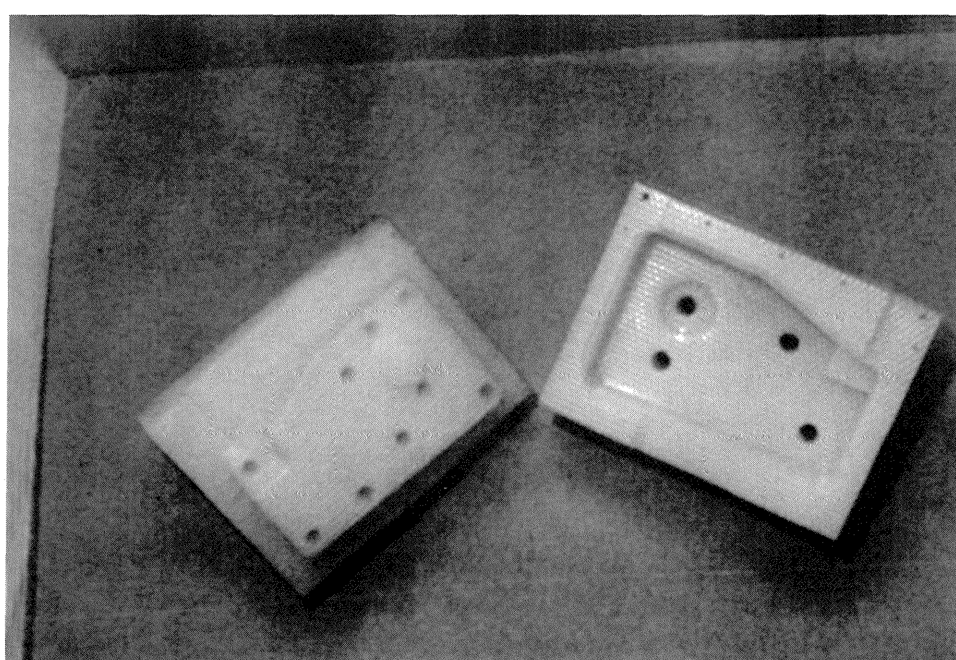

Figure 4: QuickCast core and cavity prior to investment casting.

QuickCast™ Patterns:

Creating the SL patterns was fairly straightforward using 3D Systems QuickCast build style. The build parameters are listed in Table 3. Some details should be mentioned concerning the build process. Three separate shrinkage factors are needed: the shrinkage factor of the final injection molded material (in this case polypropylene), the shrinkage factor of the StereoLithography resin (in this case XB 5170), and finally the shrinkage factor of the A2 tool steel. The latter was the hardest to determine as there was little data to be found on shell investment cast shrinkage factors for A2 tool steel. The best available information suggested a value of about 2% in all directions, although the exact value may be even slightly higher. Ford is currently running samples to determine the shrinkage factors of various tool steels, as well as other data including hardness, after shell investment casting.

Also, the blade gap is an important parameter when working with XB 5170 resin and building parts in the QuickCast style. As can be seen in Figure 5, the horizontal lines perpendicular to the vertical or "Z axis" build direction are a telltale sign of blade contact during the build process. By using the recommended blade gap in conjunction with the new and more accurate Diode Leveling Module, the accuracy of the pattern in the Z direction, as well as the repeatability of the layer thickness, are both greatly improved. Consequently, in this configuration the chances of a blade collision are significantly reduced.

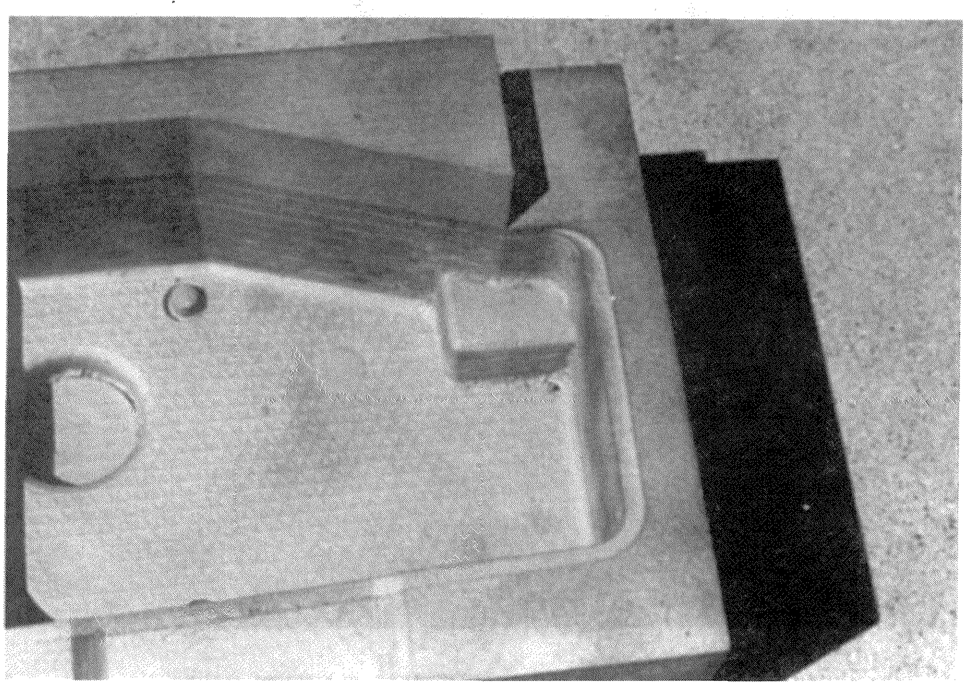

Figure 5: Vertical walls of the steel mold inserts. The layer shift is due to blade contact.

Investment Casting:

The QuickCast patterns were fully drained, cleaned, postcured, checked for the existence of any holes, and then shipped to Howmet Corporation, Whitehall, Michigan. They were then re-checked for holes at Howmet, and any pinholes missed earlier were filled with investment casting wax. The original patterns included the ejector pin holes. However, because this was Howmet's first time shell investment casting A2 tool steel, they felt more comfortable filling the ejector holes with wax; leaving only a small locating dimple. The ejector holes would presumably be drilled after the steel had solidified and cooled.

Subsequent to the patterns being gated and all holes being filled, the QuickCast patterns were cleaned and prepped for dipping. This included an alcohol wipe and a final check for any holes. The QuickCast patterns and their attached gates were then invested in a vat of very fine "face coat" ceramic slurry. After drying, the process is repeated with subsequent layers being sprinkled with refractory sand until the required ceramic shell thickness has been achieved.

On completion of the shell, the patterns, gates and ceramic shell assembly were then placed in a fully aspirated oven and fired at over 1800 °F for one hour, as described in references 6 through 10. This firing cures and strengthens the ceramic shell. It also simultaneously burns out the QuickCast pattern; provided sufficient oxygen is present for the efficient conversion of the hydrocarbon based resin to water vapor and carbon dioxide. After burn out was completed, the shells were checked for any small cracks or fractures. It was determined that in some areas the pattern had "stuck" to the walls of the ceramic face coat, causing some surface imperfections. However, these were relatively minor and could be accounted for in the final polishing of the tool.

Next, the ceramic shells were placed in an oven to preheat them prior to pouring steel. Howmet uses an induction coil to melt ingots of steel and pours the molten metal in a vacuum. After the steel was poured, the shells with the molten steel inside are placed in the open air to cool and harden.

As an interesting and potentially significant sidelight, the low thermal mass and relatively high surface-to-volume ratio of the shell investment casting process resulted in very rapid metal cooling and hence extremely hard tool steel core and cavity pairs. Furthermore, the high hardness was not just at the surface, but rather *it extended through the entire thickness of the mold inserts.* In fact, the resulting A2 tool steel was so hard that five carbide drill bits were dulled and rendered useless while attempting to drill the aforementioned ejector holes. Ultimately, the holes were drilled using diamond tipped bits. Quite obviously, in future QuickCast Tooling projects, any and all registration holes and or ejector pin holes will clearly *not* be filled with wax prior to casting. In fact, Figure 6 shows a hole that was accidentally created as the result of overheating while attempting to cut off the extremely hard A2 tool steel gating.

SLA Build Data

MCORE		MCAVITY*	
Description	Data	Description	Data
Build Time	48 Hours	Build Time	48 Hours
Laser Power		Laser Power	
At Start of Build	36 mw	At Start of Build	36 mw
At End of Build	36 mw	At End of Build	36 mw
X Shrink Comp:	2.06%	X Shrink Comp:	2.06%
Y Shrink Comp:	2.06%	Y Shrink Comp:	2.06%
Z Shrink COmp:	2.00%	Z Shrink COmp:	2.00%
Part Build Style	QuickCast XFILL	Part Build Style	QuickCast XFILL
Border Overcure	0.0070"	Border Overcure	0.0070"
Hatch Overcure	0.0050"	Hatch Overcure	0.0050"
Fill Cure Depth	0.0120"	Fill Cure Depth	0.0120"
Part Recoating		Part Recoating	
Z Wait	15 Seconds	Z Wait	15 Seconds
Pre Dip Delay	0	Pre Dip Delay	0
Post Dip Delay	1	Post Dip Delay	1
Z Dip Velocity	0.2	Z Dip Velocity	0.2
Acceleration	0.2	Acceleration	0.2
Number of Sweeps	1	Number of Sweeps	1
Sweep #1 Blade Gap	100%	Sweep #1 Blade Gap	100%
Period	8	Period	8
Support Style	Bridge Works	Support Style	Bridge Works
No Hatch	No Fill	No Hatch	No Fill
All Over Cure Settings	0.0050"	All Over Cure Settings	0.0050"
Support Recoating		Support Recoating	
Z Wait	9 Seconds	Z Wait	9 Seconds
Pre Dip Delay	0	Pre Dip Delay	0
Post Dip Delay	1	Post Dip Delay	1
Z Dip Velocity	0.2	Z Dip Velocity	0.2
Acceleration	0.2	Acceleration	0.2
No Sweeps		No Sweeps	
3dverify information		3dverify information	
Unit	Inches	Unit	Inches
Volume	145.522	Volume	131.859
Number of Triangles	4092	Number of Triangles	3510

* The part MCAVITY is a trapped volume and the first attempt at building the part failed. The solution was to place four half inch holes in the bottom of the part and fill them in with wax before casting.
For future tooling inserts more attention will be paid to the recoating parameters.

Table 3

Of potentially greater significance, however, is that the *increased hardness of investment cast tool steel,* relative to conventional billets of the same nominal material, may be of value in *extending the abrasion resistance and hence the life of production tooling.* Furthermore, it is quite possible that extended tool life can be achieved in this manner *without the need for additional heat treatment steps.* Heat treatment further increases tooling cost, extends tooling completion schedules, and can also lead to thermally induced distortion of the mold cavities, thereby requiring subsequent tooling rework and additional cost and time.

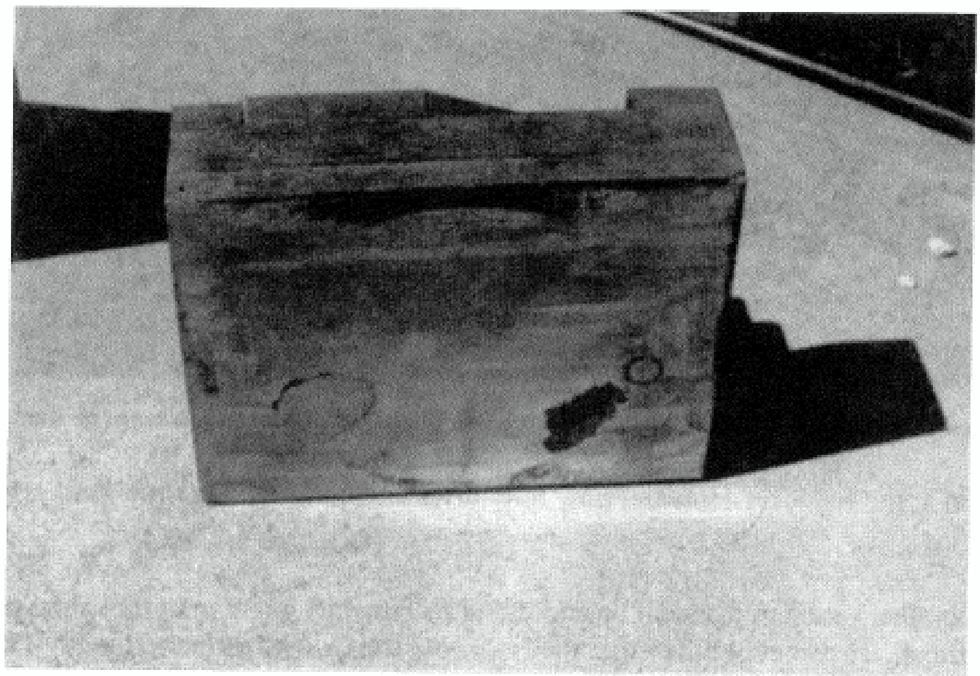

Figure 6: Core half showing a hole that was created while cutting off the pouring cup.

Tool Preparation and Injection Molding:

Upon completion of the investment casting portion of the project, the steel core and cavity inserts were forwarded to ATC Nymold Corporation, Brooklyn Heights, Ohio, for tooling preparation and injection molding of the Wiper Module Covers in polypropylene. Figure 7 is a photograph of the cavity mold insert surface, showing residual signs of the QuickCast triangular structure. This structure was present on the upfacing pattern surface and was later transferred to the tool steel insert during casting.

Further signs of surface degradation are evident in the radii also shown in Figure 7. It has been determined that during autoclave, the superheated steam not only melted out the wax gating and softened the QuickCast pattern as intended, but either the steam, or the alcohol used to clean the patterns, apparently also caused some sort of reaction with the still uncured ceramic shell material. This problem has subsequently been

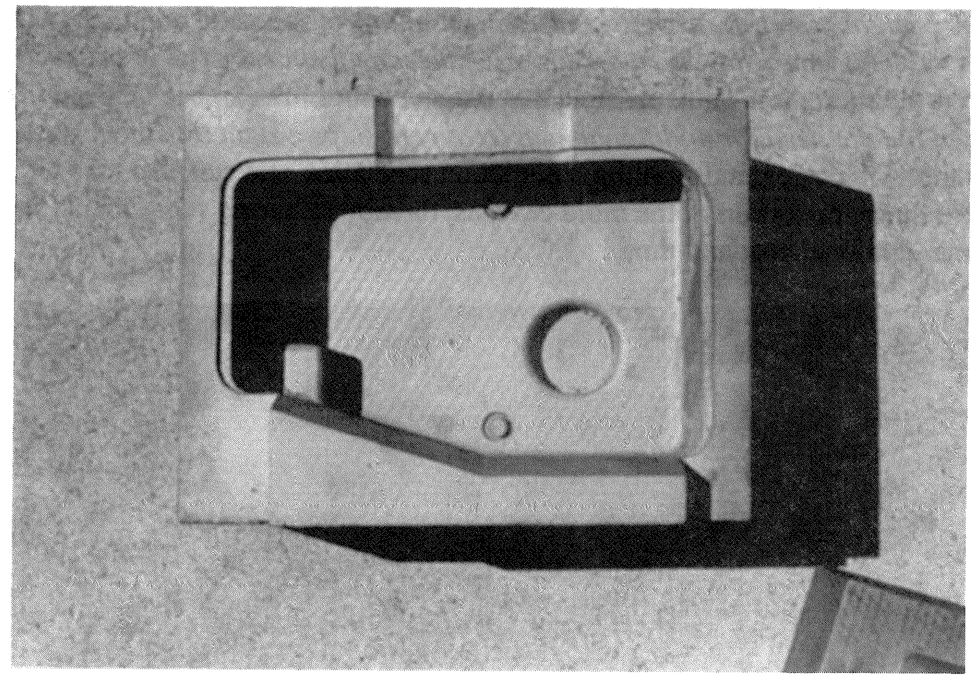

Figure 7: Surface finish of the cast steel inserts. The QuickCast pattern structure can be seen.

addressed at the foundry. Howmet now fully dries and cures the ceramic shell prior to autoclaving.

Another problem that will be addressed by Howmet is the matter of final pattern surface finish. Howmet believes that they can coat the QuickCast pattern with a very thin layer of wax prior to investing the face coat slurry. They believe that this will fill in the residual QuickCast triangulation pattern on the upfacing as well as the downfacing surfaces. However, because the thickness as well as the uniformity of this coating have not been studied at this time, the potential effect of this method on pattern accuracy is presently unknown.

The hardness of the cast pattern is an issue that requires careful attention. ATC Nymold reports that the hardness level of the shell investment castings were about 48 Rockwell C, or a full 18 points higher than the normal value for conventional A2 tool steel. This hardness level, although certainly desirable for the final tool, actually caused some problems in tool preparation. Figure 8 is a photograph of the core and cavity investment cast A2 tool steel mold inserts prior to surface finishing. On the core half a small indentation can be seen where one of the ejector holes was intended to be drilled, as noted earlier. The hole was only about 1/8 inch deep after breaking five carbide drill bits. Even after the holes were finally completed, using diamond tipped drill bits, ATC Nymold reported that these extraordinary hardness levels extended through the entire thickness of the part. They also reported that there were areas of exceptionally hard, brittle material they thought might be slag, although perhaps these regions are pockets of steel that were super-cooled and are therefore even harder than the remainder of the castings.

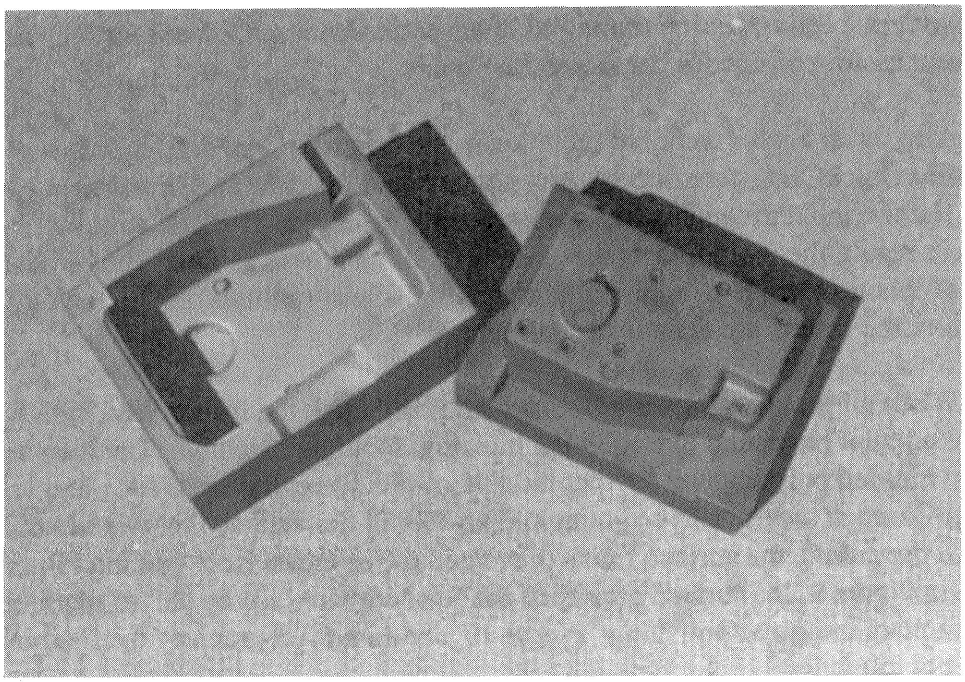

Figure 8: Mold core and cavity prior to surface finishing.

Three possibilities are evident to address the unusual problem of excessive tool steel hardness resulting from shell investment casting. The first, and perhaps the simplest, is to investigate the resulting investment cast hardness of other candidate steel alloys, and then select the optimum choice. Here one would want a material hard enough to insure long tool life, but not so hard as to impose special machining requirements on the finishing operations for the final tooling.

The second approach is to cool the casting in a programmable oven rather than the open air. In this way the casting temperature can be reduced more slowly and in a very controlled fashion to insure the desired metallurgical properties. Finally, one could also anneal the castings after the ceramic shell had been removed. However, this may prove to be the least desirable of the methods as the annealing process itself can lead to warpage of the inserts. Clearly, more work needs to be done to determine the best method of insuring optimal physical properties of the inserts consistent with the highest levels of accuracy in the shortest possible time and at the lowest cost.

Once the hardness issues were dealt with, the tool was fitted to the mold base. This also proved to be somewhat problematic because the two pieces were slightly different in size. The most probable explanation for the size difference was that the core and cavity were built in different orientations relative to the direction of recoater blade travel on the SLA-250. Although this is not normally a concern, the fact that contact occurred with the recoater blade during build might account for the size difference. A second possibility is that the shrinkage factors for the A2 tool steel might have been geometry dependent and hence not totally uniform. Again, further work is definitely needed with respect to the determination of accurate shrinkage factors for the shell investment casting of various candidate tool steels.

Also, draft angles were not included in the original CAD model or in the subsequent QuickCast stereolithography patterns and the resulting investment cast mold inserts. Rather, the draft angles were subsequently machined after the steel inserts were cast. As a result, the mold inserts had uneven wall thickness values. The obvious answer to this problem is to apply all draft angles, fillets, radiuses, etc. to the CAD design well before the inserts are actually investment cast.

When all these issues were resolved and corrected, the inserts were finally installed on their bases and placed in the injection molding machine. The resultant injection molded polypropylene wiper module covers were then used for water leakage testing. Although they would be going into an area of the vehicle that would not be visible to the public, the surface finish prevented the modules from gaining release status. As seen in Figure 9, the surface quality of the final core and cavity halves required extensive machining and polishing. Figure 10 shows a photograph of the final injection molded polypropylene wiper module cover mounted on an actual wiper module.

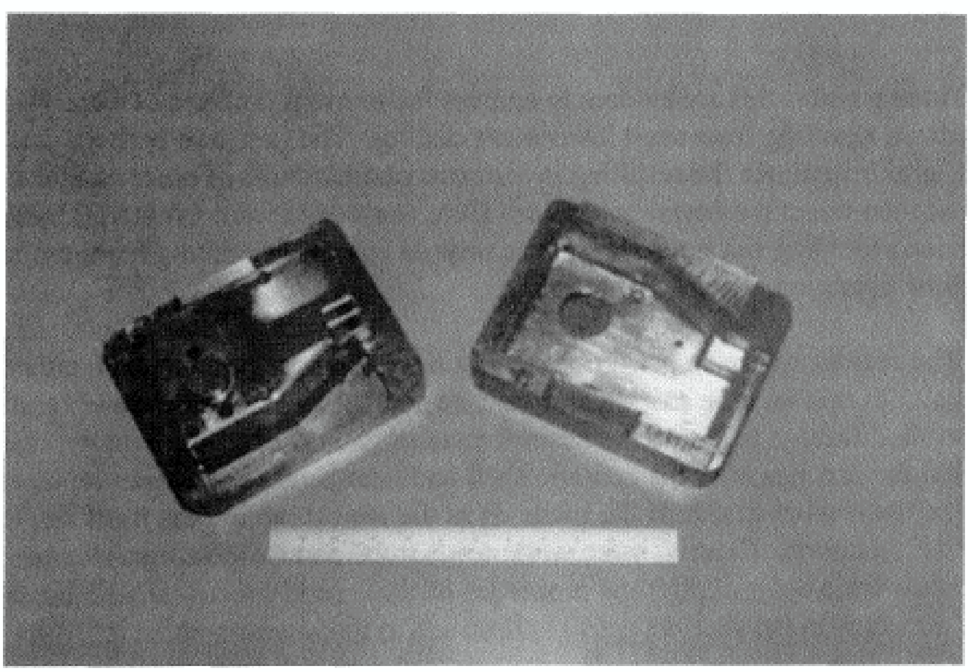

Figure 9: Mold core and cavity after surface finishing. Some areas of the QuickCast pattern were intentionally left unpolished.

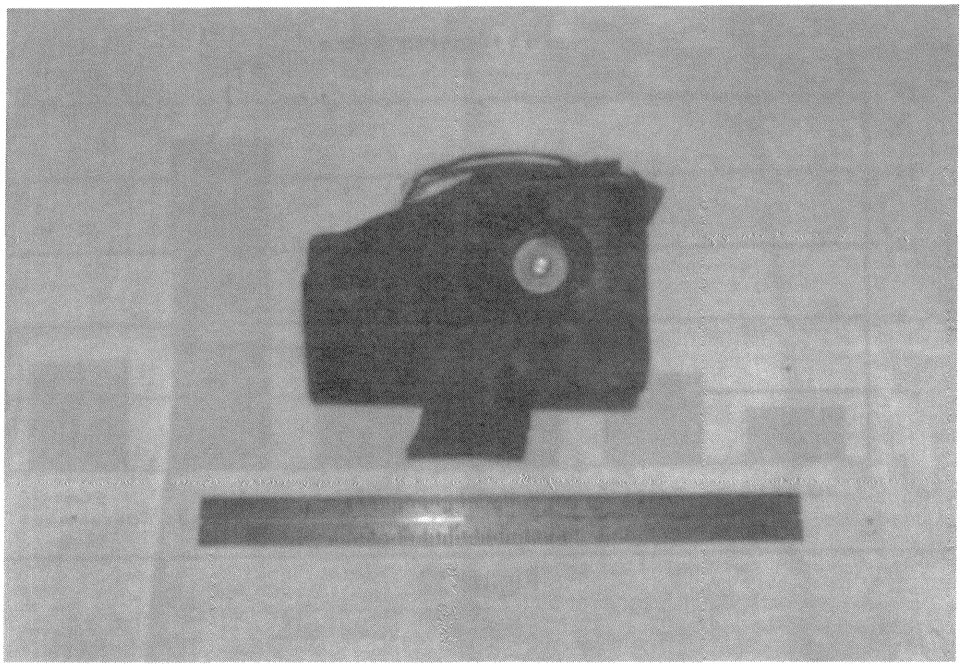

Figure 10: The final injection molded part mounted on a wiper module.

Figures 11 and 12 show Ford's estimates of the cost as well as the fabrication time required for various tooling fabrication techniques. The potential advantages of QuickCast Tooling through investment casting are clearly evident relative to conventional machined steel tooling. Figure 13 shows the actual cost and time comparisons experienced by Ford on this project. Remarkably, this data includes all the various problems associated with ascending the "learning curve" for the first time.

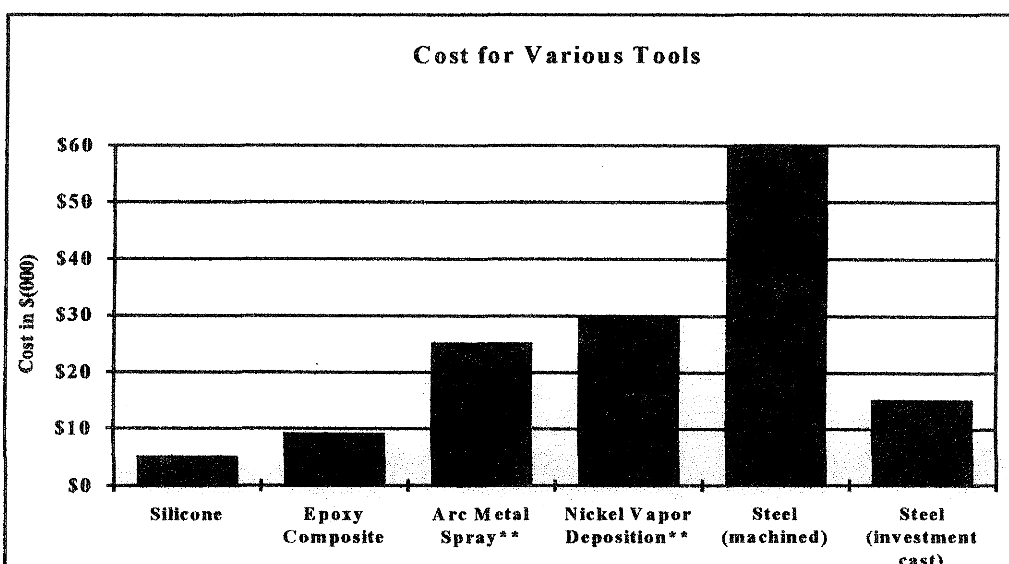

Figure 11

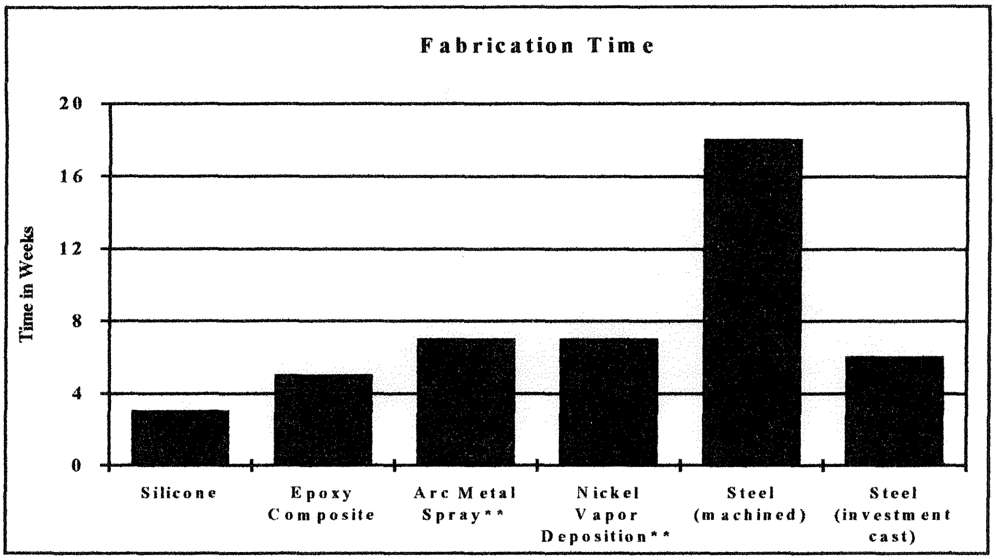

Figure 12

Figure 14 shows Ford's project plan for conventional tooling, while Figure 15 shows the actual results of the QuickCast Tooling project. Again, even with all the various "learning curve" delays, the time savings were noteworthy. Once the process is better defined, and additional information has been generated regarding the hardness as well as the shrinkage factors of various shell investment cast tool steel alloys, the time and cost savings relative to conventional tooling methods should be even more significant. Ford intends to monitor actual cost and time savings on at least two additional future projects, so that the potential advantages of Rapid Tooling can be more accurately assessed.

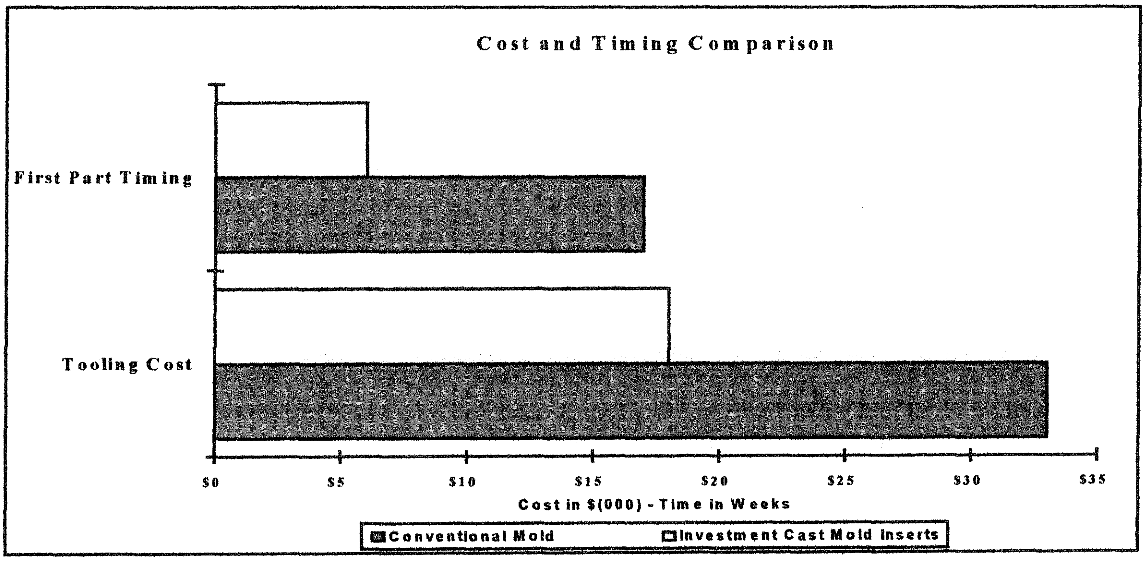

Figure 13

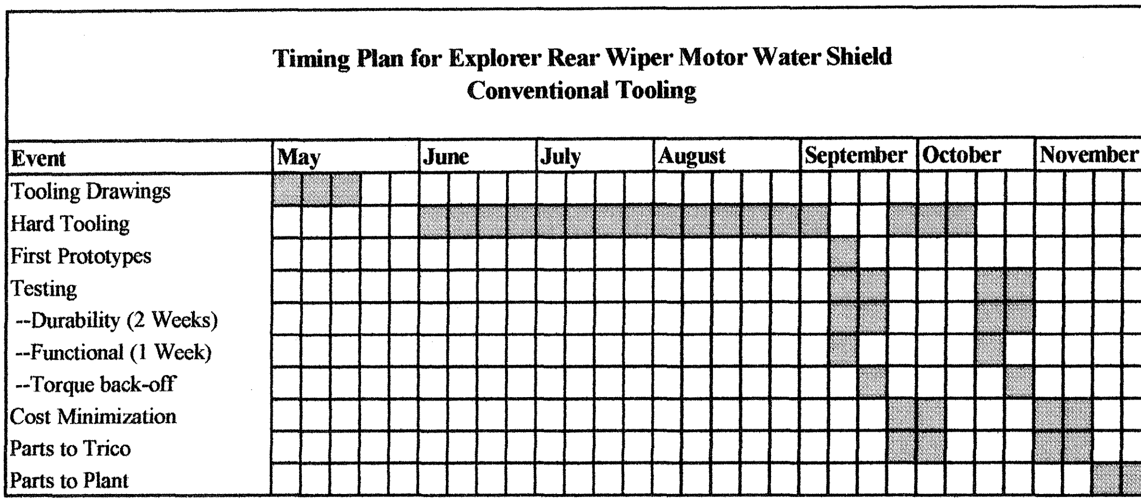

Figure 14

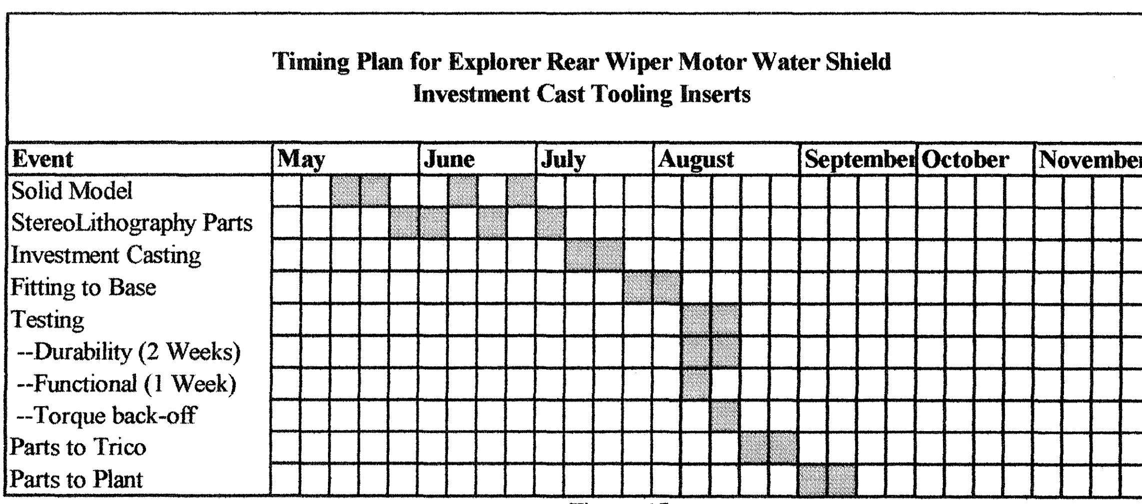

Figure 15

Conclusions:

With all the numbers laid out, and all the photographs, tables and comparison figures in place, the question still comes to mind................was this project successful? The answer is *most definitely yes!* When the project was started at Ford, the goal was to produce a part capable of being tested under realistic conditions while being fabricated from production material. A secondary goal was the possibility of using the resulting tooling for production run quantities. While we will not use the "first" rapid tool for production, we do intend to use subsequent QuickCast Tooling for actual production. Undoubtedly, the first QuickCast Tool will ultimately become a conversation piece. Nonetheless, its value should not be understated. This project has already changed Ford's thinking about providing parts to our testing facility as well as the way we will ultimately manufacture production run parts. From this first experience with investment cast tooling, the groundwork has definitely been laid. At this time, Ford has already authorized at least two additional QuickCast Tooling projects.

There are three areas where further research must be completed before we can consistently produce quality rapid tooling. First, the surface finish of the QuickCast patterns as well as the final investment castings must be improved. In this regard, 3D Systems has already developed and is now in the test and evaluation phase of an advanced version of QuickCast that directly addresses the issues of improved upfacing, downfacing and vertical surface quality, as well as the elimination of pinholes during support removal.

Second, is the matter of tool hardness. As discussed above, more data is needed on the hardness of shell investment cast steel alloys as a function of cooling rate. Additional data on shrinkage, tensile properties, abrasion resistance, etc. are also needed to better understand the relationship between cast and cut tool life. Ford and 3D will be actively working with a number of foundries to obtain such data. Assistance from other parties interested in developing a comprehensive data base would certainly be welcome.

Third, we must establish realistic cost and time estimates for QuickCast Tooling. Obviously, the project described in this paper is only the beginning. While we were able to produce these tools in a relatively short time, further reductions are definitely possible. However, because investment casting foundries have been used to the long lead times and large quantities of the aerospace industry, this may be viewed as typical. In the automotive industry we do not produce great numbers of investment castings, but we might use a smaller number of investment cast tools to injection mold very large quantities of mass produced products.

In conclusion, we believe this project has proven that QuickCast Tooling can work. With the creative thinking and energy that has typified the RP&M industry, this project can be considered to be the beginning of a very significant new application. As noted herein, much work remains to be done. However, we also believe that in the future Rapid Tooling will have a major impact upon manufacturing productivity.

Note: QuickCast is a trademark of 3D Systems, Inc.

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