Final Technical Report

Development of Functionally Graded Materials for Manufacturing Tools and Dies and Industrial Processing Equipment

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Acknowledgment, Disclaimer and Proprietary Data Notice

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List of Acronyms

CPP	-	Carpenter Powder Products
PNNL		Pacific Northwest National Laboratory
SDSMT	-	South Dakota School of Mines & Technology
THT	-	THT Presses
OI	-	Owens Illinois
GKN	-	GKN Sintered Metals
FGM	-	Functionally Graded Materials
LPD	-	Laser Powder Deposition
SSDPC	-	Solid State Dynamic Powder Consolidation
HVOF	-	High Velocity OxyFuel
DEFORM		Metal forming process simulation software
ProCast		Casting process simulation software
ANSYS		Engineering simulation software
DICTRA		Diffusion controlled phase transformation software
Thermo-Calc		Thermodynamic and phase diagram software
RC		Rockwell C Hardness
DM21	-	Nickel Base High Temperature Alloy
CCM Plus®	-	Cobalt Base High Temperature Alloy
CCW Plus	-	Cobalt Base Wear Resistant Alloy
DM21/H13	-	Bimetallic FGM Tooling
CCM Plus/H13	-	Bimetallic FGM Tooling
M2	-	High Speed Steel
H13	-	Hot Work Tool Steel
AerMet® 100	-	High Toughness Alloy Steel
NiMark300®	-	Nickel Maraging Steel
4340		Low Alloy Steel
8620	-	Low Alloy Steel
M4	-	High Speed Steel
NT60	-	Nickel base plus Tungsten Carbide Alloy
V-Nb	-	Vanadium coated niobium
V-H13	-	Vanadium coated H13 Tool Steel

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1.0 Executive Summary

Hot forming processes such as forging, die casting and glass forming require tooling that is subjected to high temperatures during the manufacturing of components. Current tooling is adversely affected by prolonged exposure at high temperatures. Initial studies were conducted to determine the root cause of tool failures in a number of applications. Results show that tool failures vary and depend on the operating environment under which they are used. Major root cause failures include (1) thermal softening, (2) fatigue and (3) tool erosion, all of which are affected by process boundary conditions such as lubrication, cooling, process speed, etc.

While thermal management is a key to addressing tooling failures, it was clear that new tooling materials with superior high temperature strength could provide improved manufacturing efficiencies. These efficiencies are based on the use of functionally graded materials (FGM), a new subset of hybrid tools with customizable properties that can be fabricated using advanced powder metallurgy manufacturing technologies [Ref. 1,2]. These new technologies demonstrated the ability to place materials with superior high temperature strength on appropriate surfaces of the tooling subjected to the rigors of hot forming operations. Modeling studies of the various hot forming processes helped identify the effect of key variables such as stress, temperature and cooling rate and aid in the selection of tooling materials for specific applications.

To address the problem of high temperature strength, several advanced powder metallurgy nickel and cobalt based alloys were selected for evaluation. These materials were manufactured into tooling using two relatively new consolidation processes. One process involved laser powder deposition (LPD) and the second involved a solid state dynamic powder consolidation (SSDPC) process. These processes made possible functionally graded materials (FGM) that resulted in shaped tooling that was monolithic, bi-metallic or substrate coated. Key process parameters were developed for both processes. Manufacturing of tooling with these processes was determined to be robust and consistent for a variety of materials.

A materials characterization study was conducted on the powder metallurgy tooling materials evaluated since the basic mechanical and physical properties of these materials were not available in the literature. This data was needed to aid in the selection of a tooling material for a specific application and as input data for the modeling studies conducted on the various hot forming processes. Results showed good high temperature strength up to 1400F for the tooling materials selected. Results also showed that the limitations on LPD FGM tooling was due to substrate materials that lost strength quickly at temperatures of 1200F and higher.

Prototype and production testing of FGM tooling showed the benefits of the nickel and cobalt based powder metallurgy alloys in a number of applications evaluated. Improvements in tool life ranged from three (3) to twenty (20) or more times than currently used tooling. Improvements were most dramatic where tool softening and deformation were the major cause of tool failures in hot/warm forging applications. A significant improvement was also noted in erosion of aluminum die casting tooling. In some instances no improvement was observed with FGM tooling when compared with current tooling because of issues with tool design, extremely high stresses, or boundary conditions associated with lubrication or rapid cooling.

Significant cost and energy savings can be realized as a result of increased tooling life, increased productivity and a reduction in scrap because of improved dimensional controls. Although LPD and SSDPC tooling usually have higher acquisition costs, net tooling costs per component produced drops dramatically with superior tool performance. Less energy is used to manufacture the tooling because fewer tools are required and less recycling of used tools are needed for the hot forming process. Energy is saved during the component manufacturing cycle because more parts can be produced in shorter periods of time. Energy is also saved by minimizing heating furnace idling time because of less downtime for tooling changes. While not quantifiable, it is estimated that an energy savings of 25% can be achieved for a given hot forming process using standard tooling. Full implementation of the FGM concept with advanced tooling materials could yield an energy reduction by as much as 120 trillion BTU/yr by 2030. Use of this tooling could also significantly reduce environmental emissions.

Carpenter Powder Products, a business unit of Carpenter Technology Corporation, is a major manufacturer of tooling and die materials who emphasize product made via powder metallurgy technology. CPP developed the SSDPC process, installed full scale manufacturing equipment and is commercially marketing tooling produced by this process. A number of project partners have adopted this tooling as bill of material for specific applications based on performance and energy savings. South Dakota School of Mines & Technology has successfully demonstrated use of the LPD process in applying advanced powder metallurgy alloys to critical surfaces of standard tooling materials resulting in improved performance. Technology transfer is available to commercial manufacturing companies with laser equipment.

2.0 Introduction and Background

While materials currently used for tools, dies and equipment in hot forming metal and glass components have performed adequately for many years, they represent a weak link in regards to current objectives related to increasing manufacturing efficiency and reducing energy consumption. In many hot forming applications, monolithic tooling materials have reached the limit of their usefulness. Tooling failures associated with softening, thermal cracking and thermal erosion reduce tool life, reduce machine uptime and reduce overall plant efficiency. These failures also increase the use of energy associated with manufacturing the tooling itself and with the manufacturing of the hot formed component.

A potential solution lies in the development of advanced functionally graded materials (FGM) that can be designed via the use of powder metallurgy technology to overcome the shortcomings of existing materials used in the hot forming industries. The goal of this project was to implement advanced FGM solutions into manufacturing environments associated with hot forming applications in the forging, die casting and glass industries. Specific markets included automotive, truck, medical and glass container applications. The approach involved a multi-discipline team with basic science capabilities and manufacturing technology expertise. The objective was to significantly increase tooling and equipment life, increase manufacturing efficiency and potentially decrease energy consumption. Since the team was comprised of major companies who manufactured tooling and companies who used the tooling, technical success would provide a ready made path for commercially using and exploiting FGM tooling. Overall success would better enable basic and mature U.S. industries to maintain or gain a competitive edge in a global market for forgings, die castings, medical implants and glass containers.

Current tools, dies and processing equipment used in hot forging, die casting and glass forming are inefficiently manufactured using antiquated high energy processes and tooling materials developed in the 1940's and 1950's, The primary issue associated with currently available materials used in hot forming applications is one of thermal management. Removing heat from tooling while attempting to maintain manufacturing efficiency and component quality creates an environment that leads to severe tool degradation. Existing materials can suffer from inadequate high temperature strength, erosion and wear, thermal fatigue cracking, sticking of tooling, etc., all of which detract from the desired performance demanded by current manufacturing processes. This performance deterioration is a major cost driver in these industries, resulting in manufacturers spending millions of dollars each year on replacement tooling and scrapping components that do not meet blueprint specifications. This in turn forces expensive production downtime in order to correct the problems. The use of shorter production runs also has an impact on energy usage. Downtime requires heating furnaces to idle and use nonproductive energy. More energy is also needed to redress or remake hot forming tooling more often. All of this leads to higher costs and increases in the amount of energy required to manufacture these products.

Part of this project, partly funded by the Department of Energy Industrial Technologies Program, was to research and develop functionally graded materials (FGM's) that can be designed to overcome shortcomings of existing tooling used in the hot forming industries. A potential solution lies in new metal forming technologies that are now available to efficiently produce advanced alloys, bimetallic materials and other functionally graded materials. The project investigated two advanced metal forming technologies, Laser Powder Deposition (LPD) [Ref. 3] and Solid State Dynamic Powder Consolidation (SSDPC), and several advanced high temperature materials in order to address the limitations associated with tools, dies and equipment used for hot forming operations.

While thermal management is key to developing improved tooling material, there are a number of technical barriers that arise for different hot forming processes. In many applications current material cannot withstand extended times at high temperature. In other applications, current materials have poor hot toughness and/or low thermal shock resistance. In yet other applications corrosion and erosion are major problems. Solving these barriers required a new approach to materials selection and the manufacturing of these materials with advanced powder metallurgy material and processing technology [Ref. 4]. Failure analysis, process modeling, thermal management and the use of powder metallurgy technology was the key to achieving functionally graded materials with superior performance capabilities. By combining basic information obtained in the initial phases of the project with the advanced metal forming technologies being addressed, prototype tooling was developed and beta tested in a commercial environment on production equipment.

Carpenter Powder Products assembled a very qualified and diverse team with the following qualifications:

- Carpenter Powder Products: The prime contractor, a global supplier of tool and die steels and specialty powder metallurgy products.

- Pacific Northwest National Labs – PNNL: A Department of Energy Laboratory with significant expertise in the development of advanced material science and technology.

- South Dakota School of Mines & Technology – SDSM&T: A university with materials and metallurgical engineering know-how with a significant amount of expertise in laser technology

- FormTech/Metaldyne: One of the largest independent producers of automotive forgings in North America.

- Sintered Metal Products: One of the largest independent producers of forged powder metallurgy connecting rods for the automotive industry.

- Arvin Meritor: A leading global supplier of automotive and truck forgings.

- AsahiTec/Metaldyne: A major supplier of die cast components for the automotive industry.

- Owens Illinois: A large multi-national supplier of glass containers.
- THT Presses is an independent manufacturer of specialty die casting equipment.

The project team was supplemented by additional U.S. industrial companies that provided resources and time on their production equipment to beta test prototype FGM tooling. Companies in this aspect of the project included

- American Axle: A large manufacturer of automotive components
- Chamberlain Manufacturing: A leading supplier of large-caliber projectile metal parts to the government.
- Accellent: A manufacturer of medical components.
- Dynamic Flowform Corporation: A precision flowforming manufacturing company that produces thin-walled components to net or near-net shape.

The focus of this team was to produce and test robust tooling that could increase productivity and save energy. Companies supplementing the team provided resources and time on their production equipment to beta test prototype FGM tooling. Besides the testing of FGM tooling, each of these companies supplied data on specific applications in their area of expertise.

3.0 Technical Approach

The project involved design and manufacture of tools and dies by the LPD and SSDPC processes to address high temperature material issues for various hot forming applications. Discussions with industrial project partners confirmed the premise that tool failures in the hot forging and die casting operations create productivity, cost and quality problems. Down time required for changing failed tools results in lost productivity and creates scheduling issues. Quality problems result in scrap, defective material and rework or sorting of finished parts. All of these issues result in cost problems. Extensive evaluations of numerous hot forging, die casting and glass forming tools by CPP and PNNL identified a variety of tool failure modes based on specific applications. Hot forge tooling evaluations included a punch tool knockout pin and spline die at FormTech, a core pin at GKN and a gear die at Arvin Meritor. Die cast tooling evaluations included die segments at AsahiTec and a piston head at THT. Glass forming tooling evaluation involved a high volume plunger used to manufacture glass containers.

Preliminary thermal management modeling studies were undertaken by project participants in the forging and glass forming industry. This information was needed to help design new FGM materials for hot forming applications. Work was first initiated on hot forging and die casting by PNNL, FormTech/Metaldyne and THT. Owens Illinois (OI) and Arvin Meritor joined the project at a later date and conducted thermal management modeling when some of the original industrial partners withdrew from the project for financial reasons.

Preliminary studies were also initiated by SDSMT and CPP to explore the variables of the LPD and SSDPC processes as a prelude to the manufacture of FGM materials. CPP studied SSDPC process variables and established parameters for manufacturing both monolithic and FGM bi-metal tooling. SDSMT similarly established LPD parameters for coating iron based tooling substrates to effect adequate bonds with an appropriate thickness. Compositions of materials used to manufacture FGM tooling along with the compositions of typical iron based tooling alloys are listed in Table 1. As a result of the SDSMT and CPP studies, a series of sample FGM tools were manufactured for initial forging trials at FormTech/Metaldyne and GKN Sintered Metals. This work was conducted in parallel with modeling studies by FormTech, GKN and PNNL to determine critical hot forming parameter issues that could be addressed by FGM tooling. The purpose was to obtain a baseline tool life, which would be used to judge the impact of subsequently designed FGM tools in similar applications.

Table 1: Chemical compositions

Element	CCM Plus	CCW Plus	DM21	NT60	AerMet 100	NiMark300	H13	8620
C	0.25	0.15	0.05		0.23	0.03	0.41	0.2
Mn								0.8
Si				3.5				0.25
Cr	28	27	11,6		3.1		5.35	0.5
W		4.5	6.5					
Mo	6	5.5	2.75		1.2	5.0	1.4	
Ta		1	1.5					
V							0.9	
Fe		1			bal	Bal	bal	bal
Co	bal	bal	10		13.4	9.0		
Al			4.5					
Ti			2.8			0.70		
B				1.5				
Ni		2.75	bal	bal	11.1	18.5		0.5
WC				60				

Little or no mechanical property or physical property data was available for the tooling materials used in the project. The major tooling materials were characterized for strength across the temperature range of 1000F to 1400F. Physical properties including coefficient of expansion, thermal conductivity, specific heat and Poisson’s ratio were determined at temperatures up to 1475F. This information was used to design tooling based on modeling results for a number of hot forming processes. The physical property characterization provided a database that could be used in models adapting new tooling material to specific hot forming applications. Similar data was obtained on bi-metallic SSDPC samples to determine bond strengths and/or design tooling that was more cost effective from an acquisition point of view. Specific data are shown in table form later in the report.

SDSMT initiated basic studies on a number of refractory metal binary pairs by laser depositing various chemical elements on H13 tool steel and 4340 alloy steel. This effort was done in order to characterize the interface of binary pairs as a prelude to developing FGM materials relative to bonding issues, the diffusion of one metal into another and the formation of brittle intermetallic phases. Bonded interfaces have been studied metallographically and by interface hardness traverses. DICTRA helped identify phases present in the interfaces and Thermo-Calc was used to compute equilibrium reaction products.

Early in the project, a limited number of prototype tools were manufactured at CPP with the SSDPC process and preliminary forging trials were run at Metaldyne. The purpose was to obtain a baseline of tool life, which would be used to judge the impact of subsequently designed FGM tools in similar applications. To duplicate and verify initial findings, a variety of tooling materials supplied by CPP were machined into tools by industry partners for trials on their production equipment. The trials were designed to compare new tooling materials with standard production tooling and determine any differences in tool life and failure modes. Based upon these differences improvements in tool life, cost reductions, capacity increases and energy savings would then be estimated.

The project was divided into three (3) phases with the final objective being the development and demonstration of FGM tooling exhibiting superior performance in hot forming applications involving the forging, die casting and glass industries.

- Phase I indentified root causes of tooling failures in specific applications and modeled various hot forming practices so as to identify FGM opportunities.

- Phase II involved optimizing the LPD and SSDPC processes, characterizing FGM materials and properties and manufacturing prototype FGM tooling.

- Phase III consisted of manufacturing production FGM tooling, establishing the robustness of the LPD and SSDPC processes and testing FGM tools in commercial applications to assess performance as related to economic and energy savings.

4.0 Results and Discussion

4.1 Phase I Identify and Model Hot Forming Tool failures

Phase I, which involved identifying and modeling of hot forming tool failures, was comprised of two tasks. Task I reviewed tooling requirements and tool failures for various forging, die casting and glass forming applications. The goal was to identify opportunities where FGM materials could enhance tool performance. Task II modeled applications for each of the hot forming applications to determine process parameters that were critical to existing tooling and help with the design of FGM tooling.

4.1.1 Task 1 – Failure Analyses

Efforts on the project centered on identifying tool problems in the hot forming industries that involved forging, die casting and glass forming. Industrial participants in the project reviewed tooling and equipment issues and provided samples of failed tooling for detailed evaluation. The purpose of tool failure analysis was to establish the mode of failure and provide a path to develop functionally graded materials (FGM) that would improve tool performance. Extensive evaluation of numerous hot forging, die casting and glass forming tooling samples showed a variety of tool failure modes that were dependent on specific hot forming applications. In hot forging applications, tool failures can be attributed to:

- Thermal Softening
- Thermal Fatigue
- Wear
- Strength Limitations

In die casting applications that involve aluminum and copper alloys, tool failures can be attributed to

- Chemical reactivity
- Thermal softening
- Thermal fatigue
- Overstressing of the tooling

The principal mode of failure in one glass forming operation was due to thermal fatigue while failure on a coated tool used for glass forming was attributed to

- A non-uniform and porous coating
- Coating adhesion
- Cracking of the underlying tooling

Some specific examples concerning tooling failures for each of the hot forming operations follow:

Hot Forging Tool Failures - A GKN lower connecting rod die, as shown in Figure 1a, details the crack origin which propagated in a progressive overstress manner. In addition, wear grooves resulted from preform flash abrasion, as shown in Figure 1b. Modeling studies showed that regardless of the tool material, mechanical stresses are above the yield strength of available materials and that additional tool design and analyses are necessary to determine possible corrective actions.

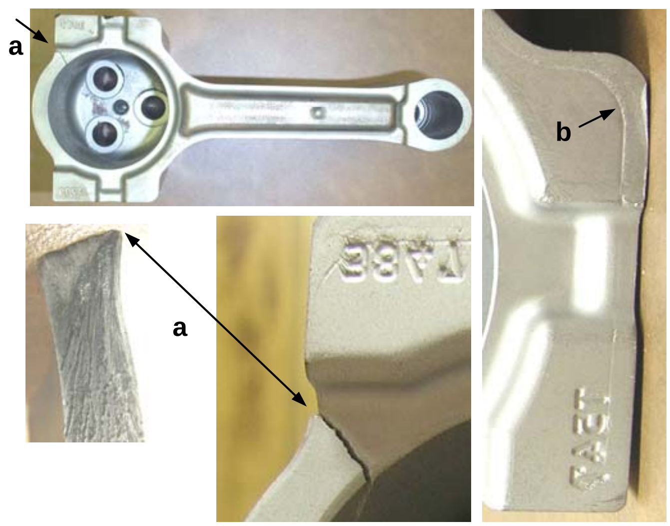


Figure 1: Die failure due to progressive overstress.
Arrows denote origin (a) and wear groove (b).

A typical analysis of a FormTech (Metaldyne) punch used on an automated Hatebur forge line is shown in Figure 2. A combination of thermal fatigue, thermal softening and wear resulted in severe cracking and deformation of the tool. Figure 2a shows the overall appearance of the tool after less than 7,000 cycles. Figure 2b shows the softening that occurs near the tool surface which leads to the thermal fatigue cracks in figure 2c. During the forging, thermal softening occurred below a nitride layer resulting in tensile weakness. In turn, the cyclic loading from both thermal and forge loads and a weakened surface from thermal softening resulted in cracking due to thermal fatigue. The thermal fatigue cracks coalesced which resulted in metal spallation and eventual failure due to tolerance loss or catastrophic failure.

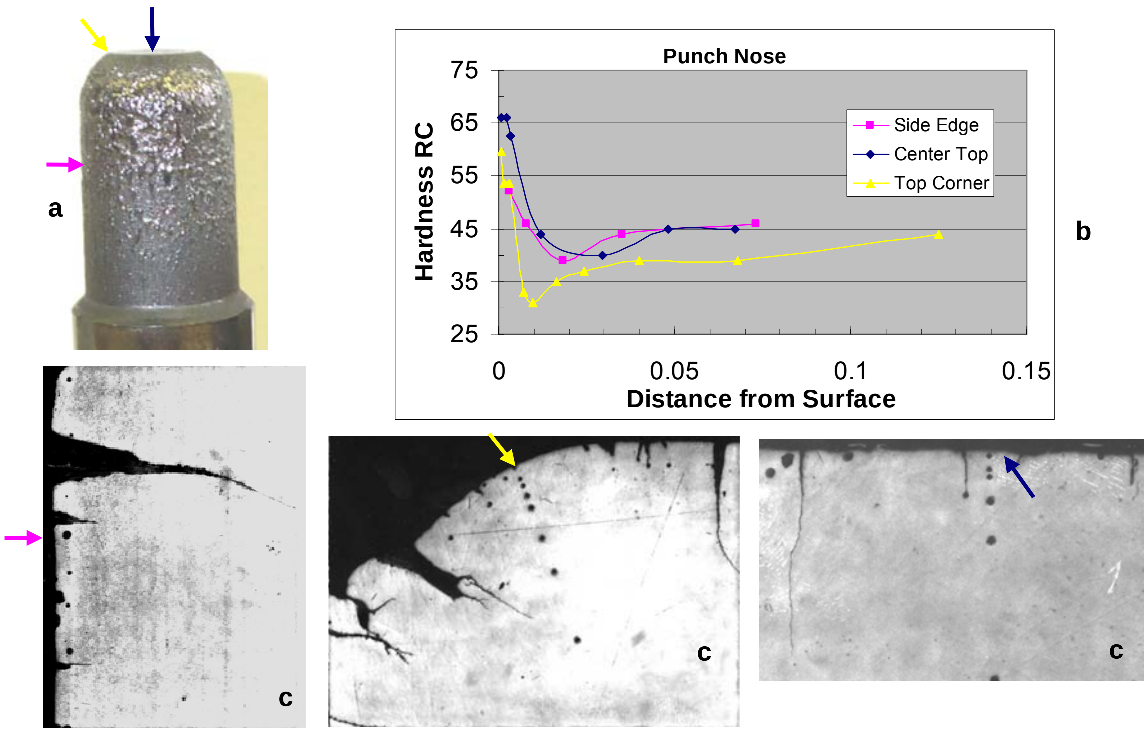


Figure 2: Thermal fatigue and thermal softening on H13 punch surface; a) overall tool, b) thermal softening graph, and c) thermal fatigue cracks.

A Chamberlain extrusion punch is illustrated in Figure 3 where typical failure occurs after ~50 cycles. The general appearance of the tool after failure is shown in Figure 3a. The severity of the deformation on the nose of the tool is shown in Figure 3b. Figure 3c shows the severe softening near the tool surface which results in the observed deformation. Although the punch is internally water cooled, the heat buildup on the outer die surface results in rapid thermal softening and severe plastic deformation of the H13 after relatively few cycles. Dimensional variations in the extrusion component necessitate a tooling change.

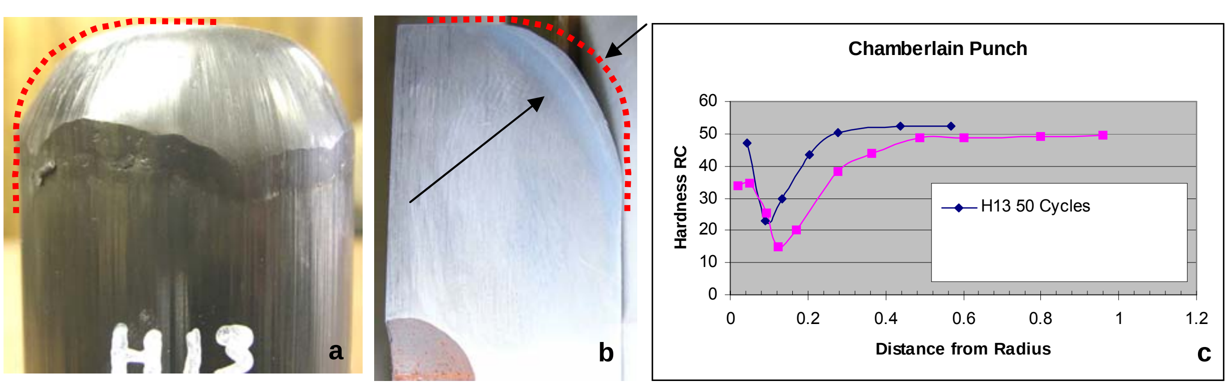


Figure 3: Extrusion punch showing significant wear due to thermal softening; a) overall tool, b) deformation of tool and c) thermal softening graph.

An M2 button die used to form automotive stabilizer bar ends at American Axle exhibits severe plastic deformation after ~2,000 cycles as illustrated in Figure 4. Figure 4a shows an as machined M2 button die. Figure 4b shows the deformation that occurs during forging after a small number of cycles. Figure 4c shows a hardness traverse on the failed tool with the as heat treated hardness of 50RC quickly dropping to 27RC at the surface.

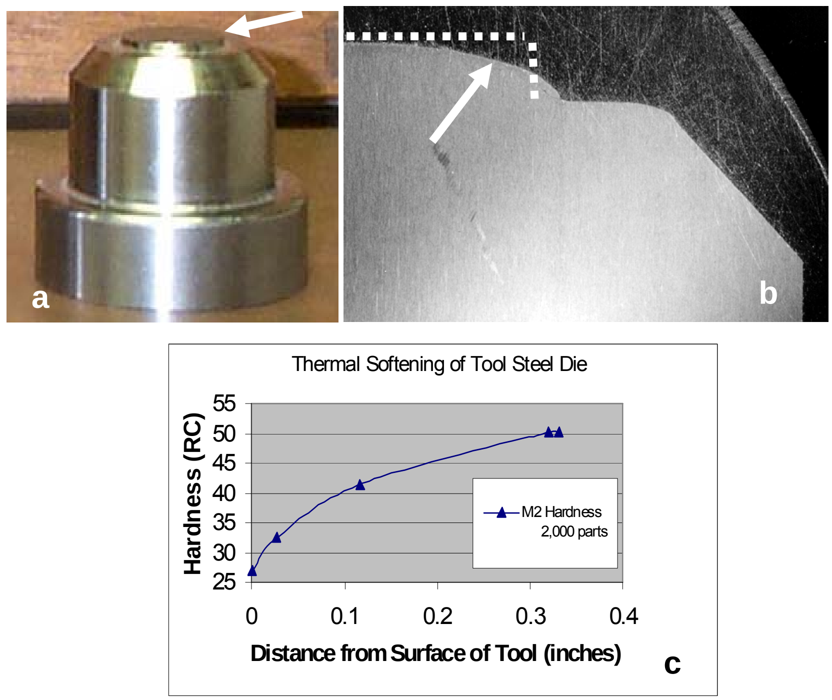


Figure 4: M2 tool steel die; (a) overall, b) metallographic section after ~2,000 cycles (b) hardness traverse from surface.

Die Casting Tool Failures - A failed Metaldyne H13 die cast insert is illustrated in Figure 5. Figures 5a and b show the general appearance of the die segment removed from a large aluminum die cast tool. Figures 5b and 5c show higher magnifications of the die segment and the large cracks that develop during the die casting operation. Figure 5d shows that although the tool body maintained its heat treated hardness of 49RC, the cracks that developed contained aluminum which had a hardness of 80Rb . The interface between the H13 and the aluminum formed a hard brittle phase with a hardness of 54RC. Although the surface appearance of mud flat cracking suggested a failure due to thermal fatigue, metallographic and SEM analysis revealed that failure was due to a metal reaction and pullout/erosion mechanism. Die segment failure occurs when the formed part sticks to the die surface or when the surface of the aluminum component becomes degraded.

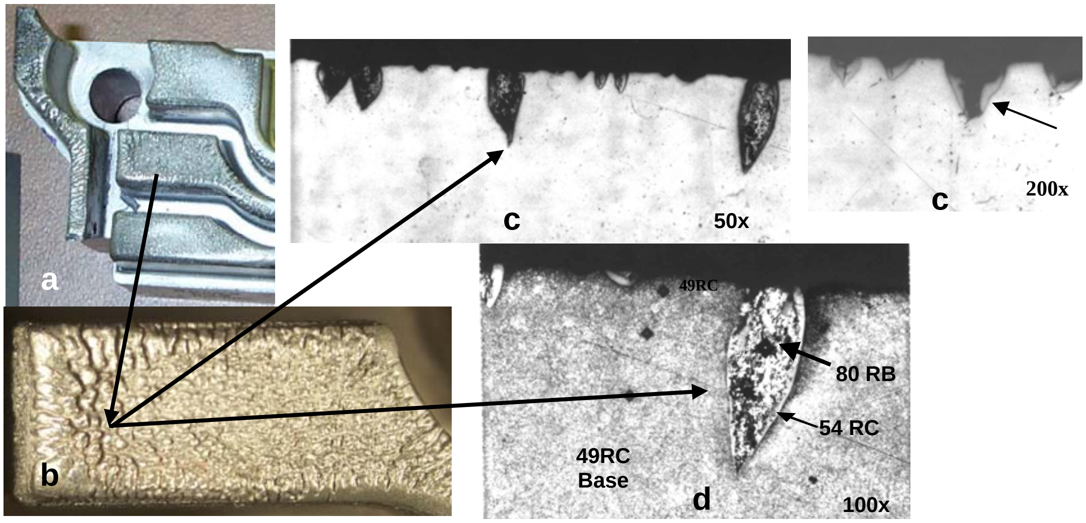


Figure 5: H13 aluminum die cast insert exhibiting metal reaction and pullout/erosion (arrows); a) overall, b) close-up of tool, c) pullout/erosion cracks and d) hardness response.

The THT piston head shown in Figure 6 illustrates gross heat check cracking which is one of 2 typical failure mechanisms that can occur during die casting operations. The other is thermal softening of the dovetail slots which collapse over time and inhibit biscuit removal.

Figure 6: Bimetallic shot piston showing early cracking on aluminum die casting trials.

Glass Forming Tool Failures - A failed glass plunger is illustrated in Figure 7 exhibiting 2 common failure mechanisms. Figure 7a shows a currently used plunger which consists of an AISI 8620 substrate HVOF coated with a metallic carbide material. Figure 7b shows a tool failure caused by spalling of the surface coating. Figure 7c shows the interface between the substrate and the porous coating. Figure 7d shows a failed tool with porosity which is related to an inconsistent coating process. Spalling of the coating (1) results in an immediate tool failure and pinhole type surface porosity (2) results in low impact strength to the formed glass bottle due to transferred imperfections which contribute to high glass bottle scrap rates.

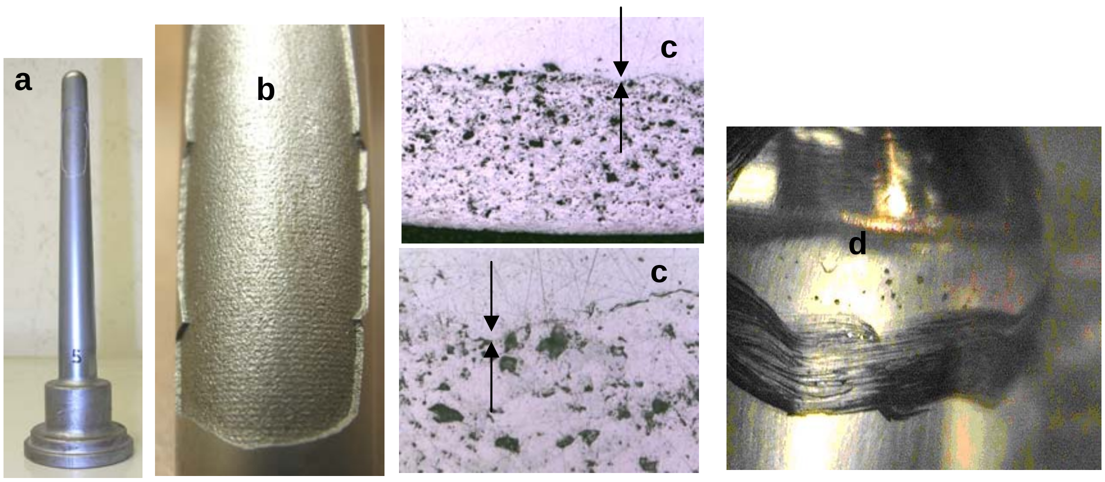


Figure 7: Glass plunger failures – (a) plunger, (b) spalled HVOF coating, (c) coating interface and (d) surface porosity.

4.1.2 Task 2 – Modeling of Tool Failures

Modeling was conducted on several hot forging processes, a die casting operation and a glass container manufacturing process. Although failure modes had been determined, key process variables that led to the failures needed to be defined and taken into account in designing a new tool or employing a new tooling material. Commercially available software including DEFORM, ProCast and ANSYS was used to model the various hot forming processes. Examples of modeling efforts and the results obtained for applications at several production facilities are described below.

<u>Chamberlain Manufacturing</u> – Analysis of the forging dies at Chamberlain, which usually fail at 50 cycles or less, indicated that the failure mode involved an overstressed condition in combination with the softening of the tooling. PNNL focused on thermal and structural modeling of the forge tooling to provide insight into the tooling processes required to withstand the forging loads encountered with this application. During the extrusion process, the punch tool surface as shown in Figure 8 expands rapidly in response to the material being formed, but is also restrained by the water cooled punch core. The result is high compressive stresses in the surface layer. After the extrusion, the surface of the tool rapidly loses temperature when it is oil quenched and the stresses are reversed.

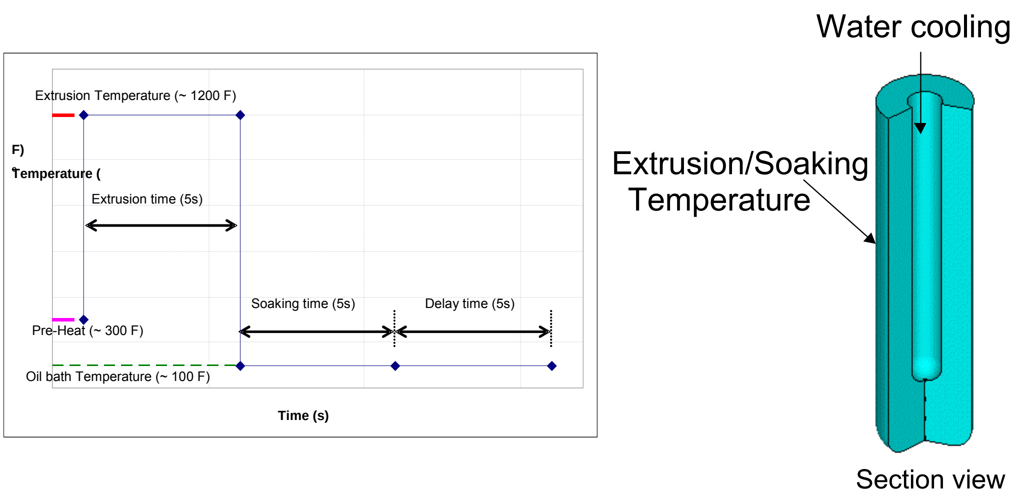


Figure 8: Punch tool temperature variation of forging cycle

The result is high surface tensile stresses. Modeling showed that this stress reversal on the surface of the tool can exceed the tooling material's yield strength, leading to high plastic strain and subsequent cracking. The thermal gradient on the tools occurs in less than five seconds, and the result is low cycle thermal fatigue cracking which significantly limits tool life. Additional modeling of the process showed that the forging/extrusion load induced stresses are very low compared to the thermally induced stresses and not a major factor in the tool failure. The results of the Chamberlain forging/extrusion operation indicate a need for:

- minimizing thermal quenching
- eliminating internal water cooling
- a tooling material with greater high temperature strength.

<u>GKN Sinter Metals</u> – GKN, a major manufacturer of automotive connecting rods, experiences tooling problems with a lower die punch that requires frequent reburns or complete replacement of the tooling. This tooling frequently exhibits cracking after 10K to 15K cycles in essentially the same location of each failed punch. Figure 9 illustrates the modeling results showing stress distribution in the punch and identifies locations of high stress in this tooling. The modeling also revealed high displacement in the region adjacent to the high stress areas. It appears that the forces are sufficiently high to spread the punch ears during the forging cycle which results in cracking.

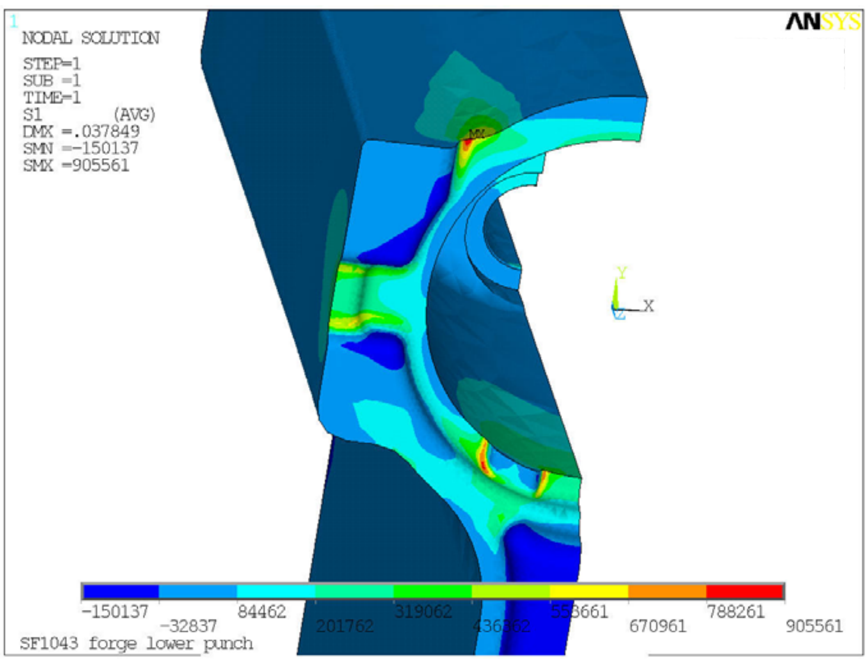
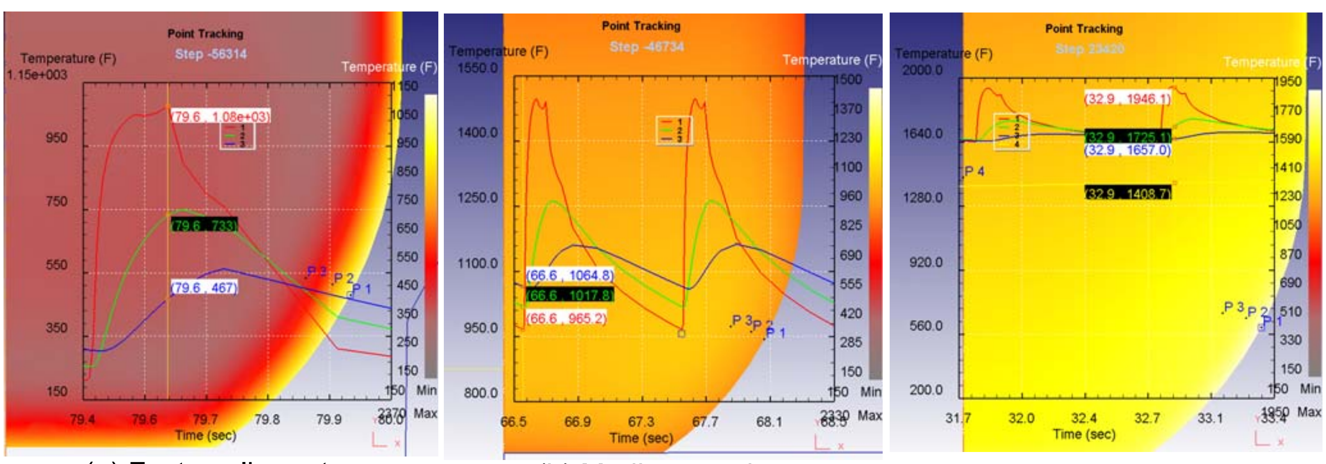


Figure 9: Modeling simulation of lower punch for connecting rod forging.

PNNL modeling studies confirmed the results obtained at GKN. The modeling work showed stress levels that exceed the strength level of any known material in the hot spots of this punch. The results indicate that tool design, not the tooling material, is responsible for the cracking observed in this tool. The solution may lie in design changes involving punch geometry, die wall clearances or a compression ring. Alternatively, a tougher material may extend the life of this lower die punch to a more acceptable level of cycles before replacing this tooling.

FormTech / Metaldyne – Modeling at FormTech involved cooling simulations on a punch tool of a Hatebur forging machine. This automatic 5 station horizontal forging machine produces one part every second. Forging deformation occurs in 0.2 seconds while part transfer and tool cooling takes 0.8 seconds. The third stage punch tool is critical to the efficiency of this equipment. Simulations of three different cooling rates were conducted on the punch tool which is a candidate for advanced FGM tooling. Temperature changes in the tool were determined for the three cooling rates, designated as high, medium and low. High cooling involves high pressure water that floods the punch tool. Medium cooling utilized less water and pressure while low cooling involved air cooling of the tooling with no water.

When forging a component, the punch tool temperature rapidly increases and reaches a steady state temperature in 30 to 80 seconds. Examples of temperature variations in the punch as a function of cooling rate are shown in Figure 10. Temperatures were determined at the surface of the tool and at two additional points further into the tool. For a fast cooling rate (Figure 10a), the surface of the tool rapidly reaches 1080F while points further into the tool reach temperatures of 733F and 467F respectively. When cooled, the surface also decreases rapidly to a temperature 100F to 200F below the interior tool temperature. The high surface temperature is responsible for tool softening and the rapid cycling is responsible for thermal fatigue cracks, especially as the difference between the surface and core temperatures becomes large.



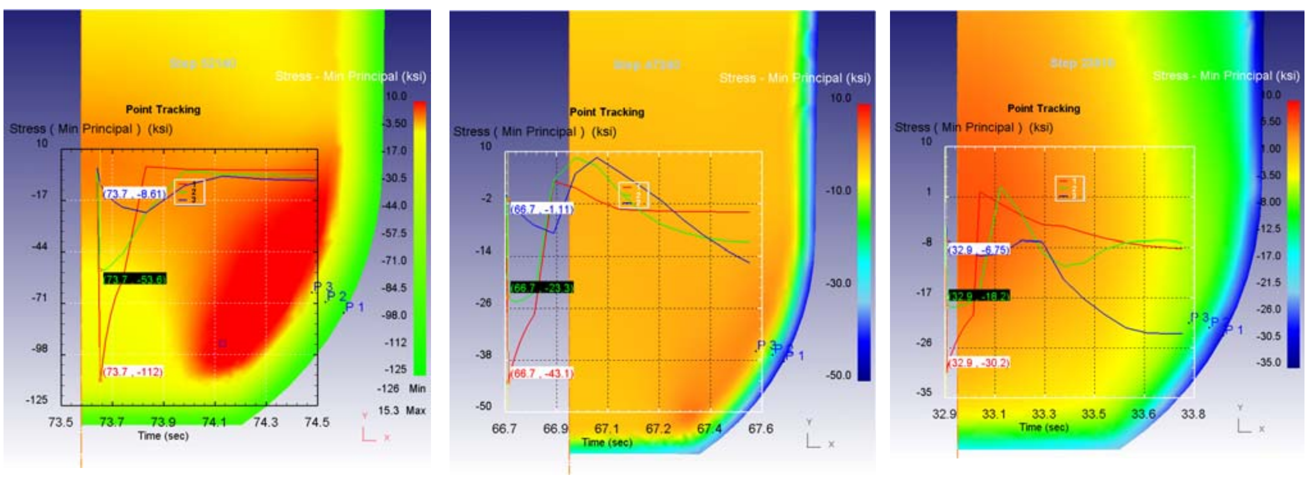
(a) Fast cooling rate (b) Medium cooling rate (c) Slow cooling rate

Figure 10: Simulated temperature variations on a punch tool as a function cooling rate.

For a medium cooling rate (Figure 10b), the surface temperature reaches 1065F, which is not much different than the high cooling rate. It does show higher interior temperatures of 1018F and 965F respectively. The overall tool temperature is much more uniform, a condition that doesn't improve the tool softening response but does decrease thermal fatigue because of smaller temperature differences between the tool core and surface.

Air cooling of the punch tool results in an extremely high surface temperature of 1946F (Figure 10c). The interior temperatures also remain elevated at 1725F and 1657F respectively, well above those in the water cooled tools. Under these conditions, a conventional tool steel would last less than 100 cycles. However, the relatively small temperature differences observed between the locations modeled would significantly reduce thermal fatigue cracking. Unfortunately no material currently available could withstand the conditions imposed by the air cool simulation.

The same cooling rates were used to simulate stress, strain and elastic/plastic deformation on the tool. Simulated stress variations are shown in Figure 11a. 11b and 11c. For all three cooling rates, stresses, strains and temperatures are higher at the surface of the tool. Stress decreases and strain increases as the cooling rate changes from fast to slow cooling at all points in the tool; i.e. from surface to interior. The simulation also shows that elastic/plastic deformation can occur and varies as a function of the cooling rate. The results show that during fast cooling, stresses exceed the yield point of H13 and produce deformation of



(a) Fast cooling rate (b) Medium cooling rate (c) Fast cooling rate

Figure 11: Simulated stress variations on a punch tool as a function of cooling rate.

the tool. While slower cooling rates decrease stresses on the tool, the surface temperatures remain higher so that the yield point of H13 is exceeded at that point. Deformation and the failure of H13 tools will occur regardless of cooling rate employed during the forging operation. Since H13's strength decreases rapidly at elevated temperatures, current practice uses pressurized water cooling and endures high stresses until the tool fails.

The modeling results indicated that use of an FGM tool with higher strengths at elevated temperatures coupled with a reduced cooling rate during the forging operation has the potential to produce much higher tool lives in this application.

Arvin Mentor – Modeling work was conducted on an H13 hollow punch used to forge truck components. It exhibited softening and thermal fatigue cracking in the chamfer area of the tool. Point tracking of the temperature in this tool for one cycle is illustrated in Figure 12 and shows a deeper heat affected zone with a longer contact time in the chamfer compared with other areas of the tool. Peak temperatures reach 1220F which results in softening of the H13 material and eventually leads to thermal fatigue cracking.

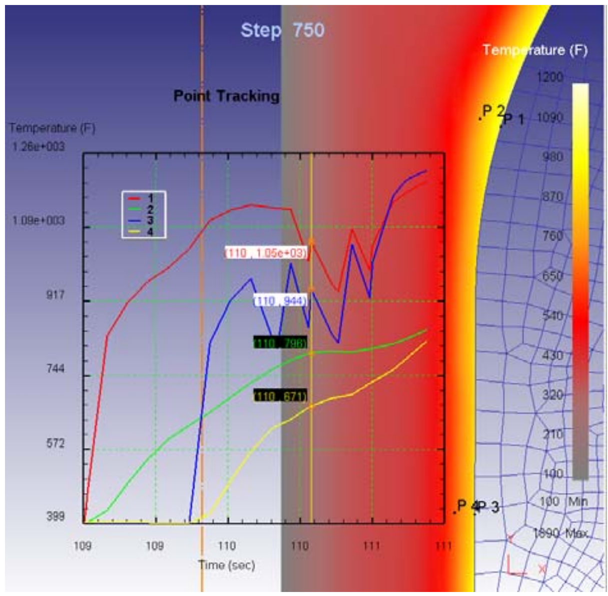


Figure 12 Temperature variations in a hollow punch tool after one cycle.

Modeling of the stresses in this tool, illustrated in Figure 13a and 13b, shows a compressive stress component of –145 ksi and an effective tensile stress of 182 ksi. Both stresses are high enough to cause local plastic deformation in H13 at the maximum temperature of 1220ºF. Stresses can be lowered through variations in cooling rate and with the use of lubrication, but they still remain high enough to cause plastic deformation. The use of FGM tooling with higher strength at elevated temperatures in this application could increase tool life considerably.

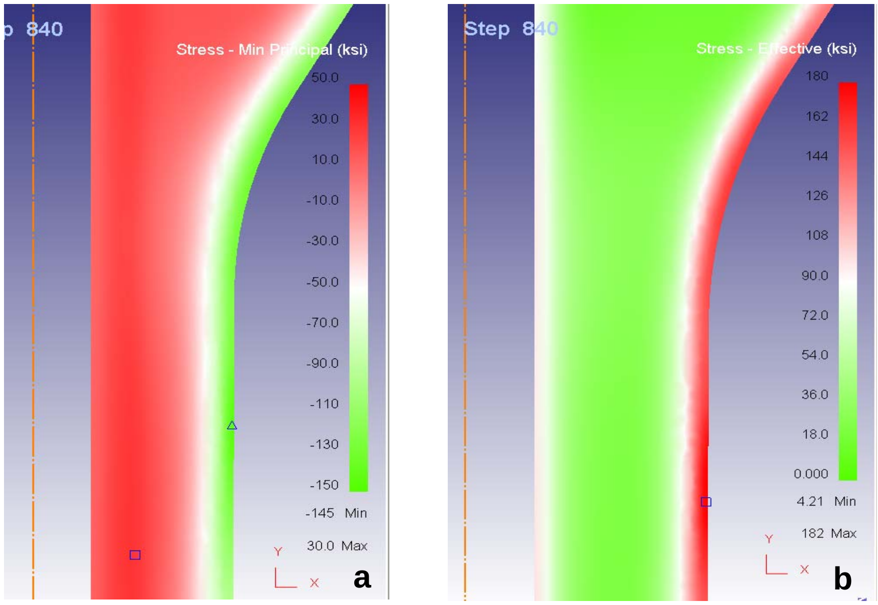


Figure 13: Stress variations in a hollow punch tool after one cycle; (a) compressive stress component, (b) effective tensile stress.

<u>THT</u> – Modeling at THT concentrated on die casting equipment and specifically on a piston head used for removal of a biscuit after a die casting shot. The piston head undergoes extreme variations in temperature, has an extremely low life and presents a formidable challenge to the adaptation of a new tooling approach. A section view of the piston head is illustrated in Figure 14 below.

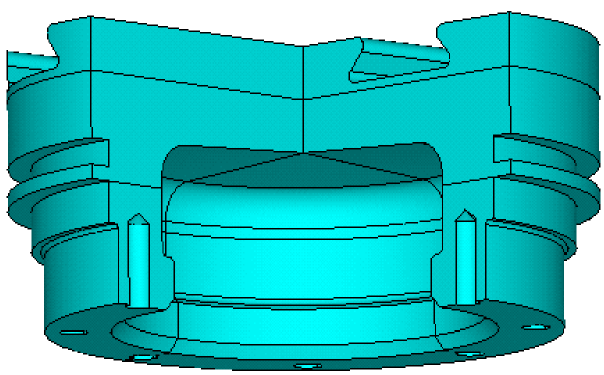


Figure 14: Cross section of shot piston in aluminum die casting equipment.

As shown in Figure 15, molten metal during the die casting of copper components exposes the piston head to a temperature of 2080˚F. The interior of the piston is cooled with 60˚F water, thereby creating extreme thermal variations and high stresses in this tooling. The pour time, shot time and biscuit removal time total 135 seconds. The delay time while getting ready for the next run is slightly under 13 minutes. The boundary conditions for the finite element modeling study included a pour temperature of 2080˚F, internal cooling of the piston head with 60˚F water and a piston head temperature of 80˚F at the end of a cycle.

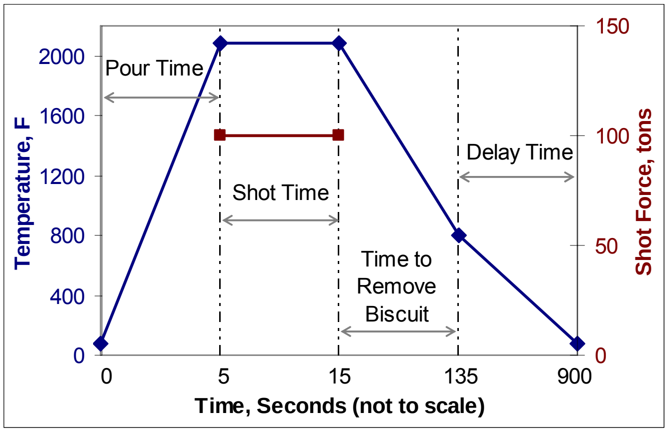


Figure 15: Timeline for once cycle in aluminum die casting operation.

Initial modeling was done on a standard H13 piston head using the aforementioned boundary conditions. The surface temperature of the piston head reaches a maximum temperature in 5 seconds, maintains that temperature for 15 seconds and then decreases with the biscuit removal at 135 seconds to approximately 800˚F. At the end of the cycle, the temperature is under 100˚F. Stress analysis showed minimal levels at 5 and 35 seconds but very high levels, as shown in Figure 16, approaching 170 ksi at 135 seconds and 217 ksi at the end of the cycle. The high stress levels occur at the base and corners of the grooves in the piston head. Modeling showed that casting load induced stresses are insignificant compared to the thermal stresses. The low internal water

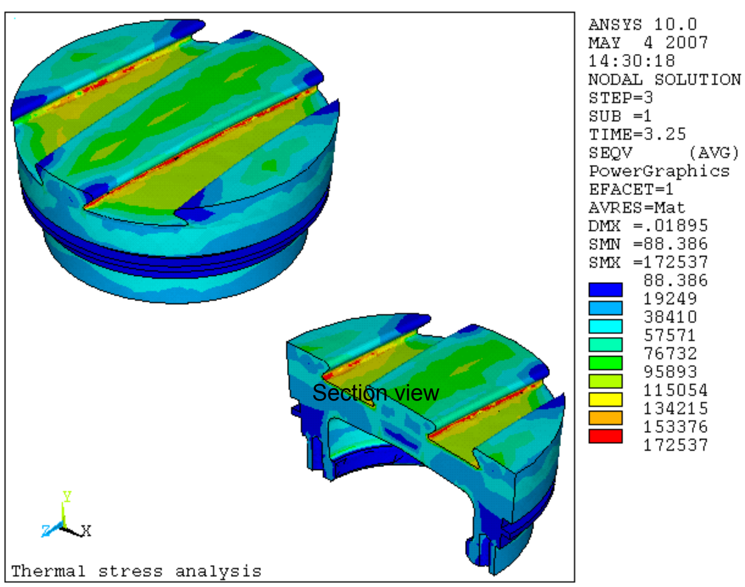


Figure 16: Stress variations in die casting piston head after one cycle.

cooling of the piston head coupled with the very high temperature of the poured metal are the primary reasons for the high thermal stresses. The amplitude of the alternating stress is greatest at the top surface layers of the piston head which causes deformation of the H13 tooling resulting in a high susceptibility for crack/failure initiation.

Owens Illinois – Modeling focused on a plunger tool used for a glass container manufacturing process at O-I.

A decision was made to concentrate on a high volume plunger tool. Previous evaluation of failed tools showed porosity in the coating as well as surface cracking and spalling during container manufacturing. O-I and PNNL worked together to further model this application taking into account the laser cladding of the AISI 8620 plunger substrate with a material exhibiting greater high temperature strength than the existing coating material. Instrumented mold equipment was used to compare actual operating temperatures with model predictions.

O-I and PNNL completed the work on a steady state transient cooling model for their glass bottle manufacturing system. Efforts concentrated on establishing boundary conditions to incorporate into the model. Additionally, thermal and physical properties of an AISI 8620 material laser coated with an advanced cobalt base alloy CCW Plus were determined and incorporated into the model. CPP and PNNL prepared and tested the laser coated AISI 8620, respectively. Properties determined, which will be discussed in Phase II, included thermal conductivity, specific heat, density, coefficient of expansion, Young's modulus and Poisson's ratio.

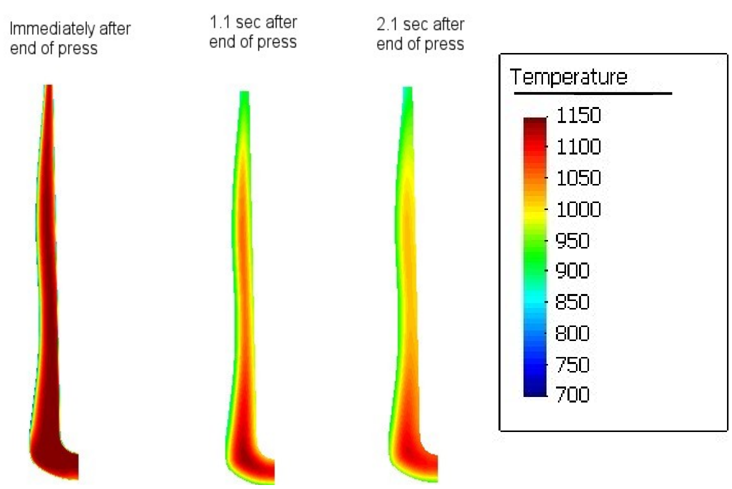


Figure 17: Temperature variations in the parison as a function of time immediately after pressing.

A high volume plunger tool used in the Narrow Neck Press and Blow (NNPB) process for manufacturing glass containers was evaluated in the project to determine if the life of this tool could be improved. The plunger is used to create a cavity in a gob of glass to form a parison which is then inverted and blown to the desired shape in a cast iron mold. A steady state model was used to predict the temperature profiles in the parison and in the plunger as a function of time. Figure 17 illustrates the temperature variations in the parison as a function of time immediately after the pressing, 1.1 seconds after the press and 2.1 seconds

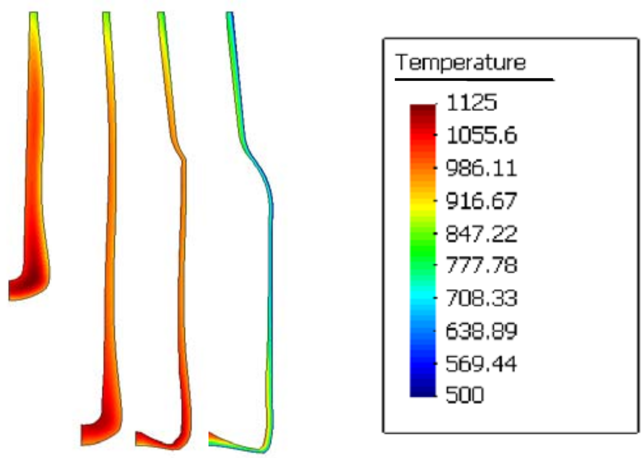


Figure 18: Simulation of inversion and blowing out of a glass container shape.

after the press. From a starting temperature of 2100F, the outside surface of the parison reaches a temperature of 1742F in 2.1 seconds. The inversion of the parison and blowing of the container's shape must be done quickly to get the elongation shown in Figure 18. The temperature variation of the plunger, which was the main focus of this project, is illustrated in Figure 19. The plunger, which forms the cavity in the glass gob, is withdrawn quickly and reaches a maximum temperature of 1100F but this can vary considerably as shown in Figure 19. It is important to keep the temperature at 1100F or below to prevent the tool from sticking to the glass. Modeling showed a temperature range of 800F to 1100F in the plunger which indicated that the material selection for this tool did not need to take into account extremely high temperature strength. However, the variation in temperature within the tool placed emphasis on spalling of the coating on this tool.

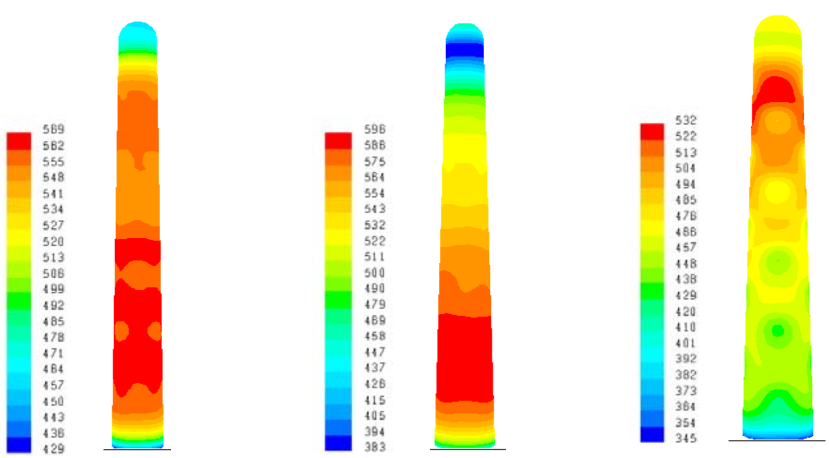


Figure 19: Simulated plunger steady state temperature distribution during glass forming.

4.2 Phase II LPD and SSDPC Tool Manufacturing Process Development

Phase II of the project, which involved optimizing the LPD and SSDPC process, manufacturing prototype FGM tools and characterizing various tooling materials and structure was comprised of three tasks. Task I involved the variation of LPD and SSDPC process parameters to insure bonding between the coating and the substrate in the LPD process and full density tooling in the SSDPC process. This task also involved the manufacturing of prototype tooling. Task II characterized the mechanical and physical properties of materials not previously used for tooling applications. Data was needed on the elevated temperature properties relative to FGM tooling design and on the physical properties for insertion into the modeling work. Task III involved some basic research of SDSMT to determine the structural compatibility of LDP refractory metal binary pairs for potential use as high temperature tooling materials.

4.2.1 Task 1 – Optimize LPD and SSDPC Processes

One of the key objectives of the project was to use two state of the art powder metallurgy processes to manufacture FGM advanced tooling materials. One approach used laser powder deposition (LPD) of various high temperature and wear resistant materials to current substrate tooling materials [Ref. 5, 6]. The second approach used a solid state dynamic powder consolidation (SSDPC) process to consolidate powder of unique nickel and cobalt based alloys into monolithic and bi-metallic tooling. One of the goals of the project was to understand and optimize key variables associated with the LPD and SSDPC processes in order to manufacture prototype FGM tooling that could be tested in the hot forming of metallic and glass components.

<u>LPD -</u> The LPD process used a YAG laser to directly clad specialized metal powders to standard tooling materials, typified by H13. Key variables such as power, speed and powder flow rates were studied to obtain full dense coatings metallurgically bonded to the substrate material. Figure 20 illustrates the

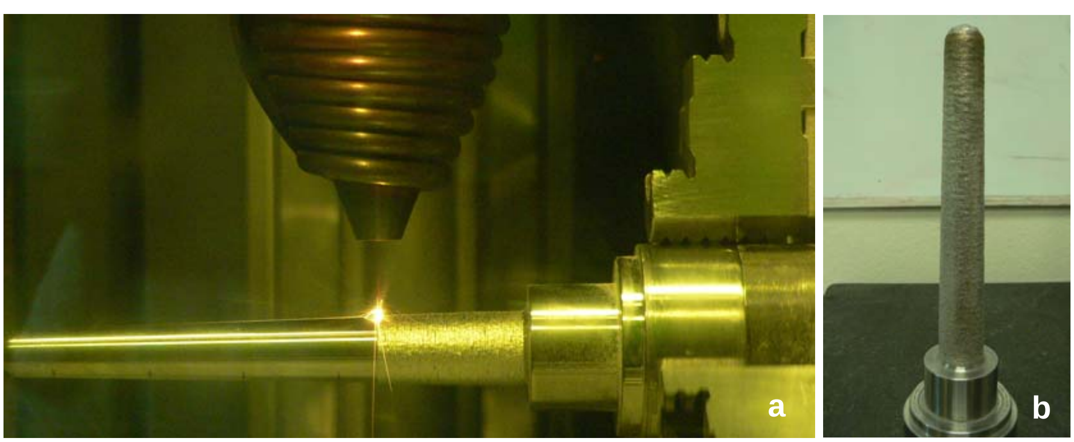
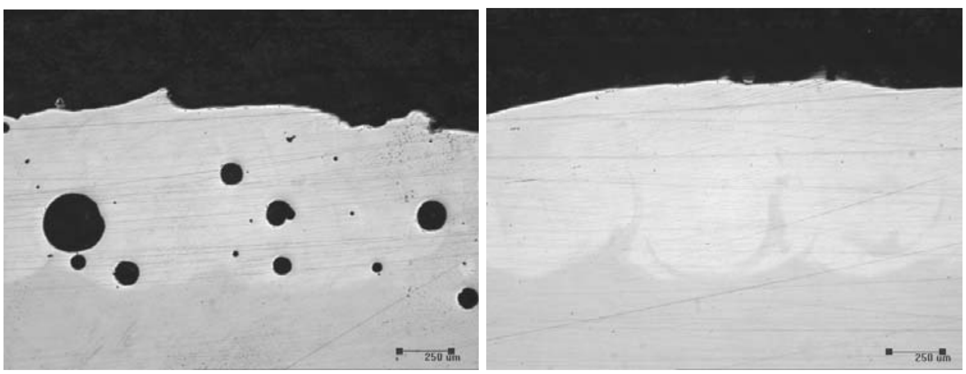


Figure 20: (a) glass plunger being laser clad and (b) after laser cladding.

cladding of a glass forming tool with a cobalt base alloy. Issues of concern included distortion of the tool during cladding and the potential for precipitation of detrimental intermetallic phases in the heat affected zone. Thermo-Calc and DICTRA phase progression studies were conducted and compared with thermal stability testing of clad tooling to ensure the absence of embrittling phases on chosen FGM materials that would be detrimental to tool life in a production environment. Clad tooling was held ten hours at 1200°F for this study. Both distortion and deleterious second phase precipitation was controlled by establishing set parameters for linear spacing, powder feed rate, coating thickness and laser power.

Studies also showed that the LPD nozzle setup was also important in obtaining a full dense clad coating on a tooling substrate. As illustrated in Figure 21, it was determined that elimination of porosity in the clad material required the use of an annular nozzle instead of a discrete nozzle in some cases. Optimized parameters were used for cladding a variety of nickel and cobalt base alloys onto standard tooling materials typified by the much used H13 hot work tool steel.



Discrete nozzle setup Annular nozzle setup

Figure 21: Effect of Nozzle Type on porosity in LPD cladding

<u>SSDPC -</u> The SSDPC process is a powder consolation process that utilizes pressure, temperature and time to fully densify specialty alloy powder. A schematic of the process and the forging press used to consolidate the metal powder are shown in Figure 22. The process is unique and different from other consolidation processes in that it uses higher pressure, lower temperatures and short consolidation times. The higher pressures allow for shorter consolidation times and the lower consolidation temperature permit the atomized powder to retain inherent structures realized with ultra fast solidification. The basic procedure involves filling a metal container with powder, evacuating and sealing it, heating it to a consolidation temperature externally, immersing the canned powder in a liquid glass media and forging. Although each metal powder requires specific parameters, a typical cycle would involve heating the canned powder to 1950° F +/- 75°F and forging at pressures up to 120,000 psi for times of less than 60 seconds. Figure 23 shows a variation in density over a range of

parameter changes used to consolidate SSDPC tooling for this project. Key parameters are optimized to give fully dense microstructures.

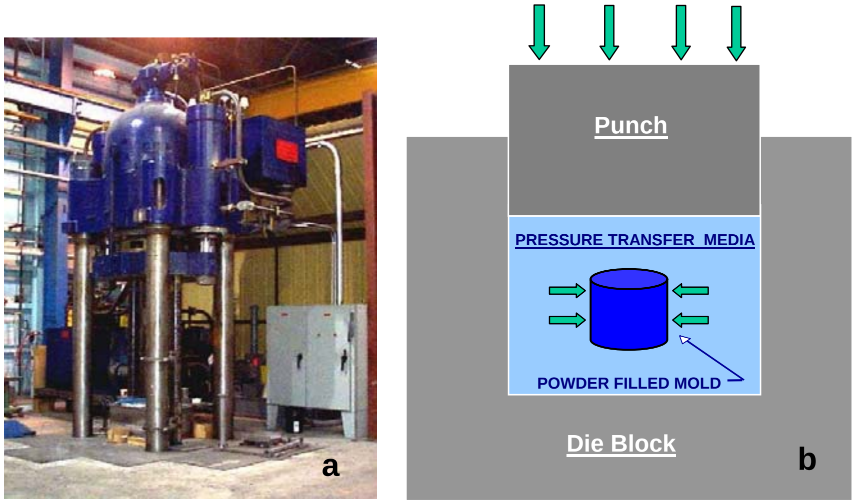
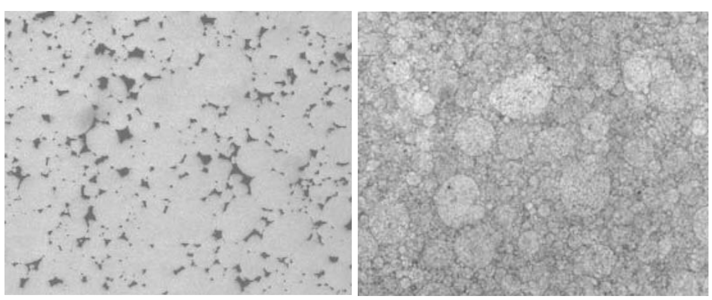


Figure 22: SSDPC process: (a) 2500 Ton hydraulic press and (b) process schematic.



Less than 100% dense Goal = 100% Dense

Figure 23: Microstructures of SSDPC process variations

4.2.2 Task 2 - Characterization of Advanced Tooling Materials

A number of the advanced tooling materials evaluated in hot forming operations were tested to determine physical and mechanical properties [Ref. 7]. The data, which was not available in the literature, was needed to assist modeling studies, to help in the design of FGM tooling, to determine the effect of thermal exposure on hardness and to assess the potential interface precipitation of phases that would be detrimental to FGM tooling. Monolithic and bimetallic SSDPC samples and LPD samples were prepared for the characterization studies.

Mechanical and physical property tests were conducted on monolithic SSDPC samples of DM21, CCM Plus, CCW Plus and Ni-Tung 60. These tooling materials included a nickel base alloy, two cobalt base alloys and a composite Ni/WC alloy. The average results of tensile testing are listed in Table 2 at temperatures up to 1400°F. Alloys DM21, CCM Plus, and CCW Plus, which

Table 2: Mechanical Properties of Monolithic SSDPC - average values

Alloy	Test Type	Temp F	.2% YS ksi	UTS ksi	E msi	RA %	EL %
DM21	Tensile	RT	189	228	34.3	7.3	5.9
	Tensile	1000	180	226		9.0	6.4
	Tensile	1200	164	207		7.4	3.9
	Tensile	1400	140	167		2.4	1.2
CCM PLUS	Tensile	RT	141	198	35.1	2.2	2.0
	Tensile	1000	106	163		6.0	2.2
	Tensile	1200	87	140		8.6	5.0
	Tensile	1400	61	79		15.8	12.6
CCW+	Tensile	RT	143	190	33.5	7.4	4.8
	Tensile	1000	95	146		10.0	2.5
	Tensile	1200	92	145		9.5	4.0
	Tensile	1400	80	92		23.2	6.5
NiTung60	Compression	RT	117	222	49.7	-	16.1
	Compression	1000	80	204			NA
	Compression	1400	62	161			NA

were designed for high temperature strength showed tensile properties that were superior to conventional tool steels such as H13. Physical properties measured on monolithic samples of materials used in this project are listed in Table 3. Distinct differences were noted among the various tooling materials tested for density, coefficient of expansion, thermal conductivity, specific heat and

Table 3: Physical Properties of Monolithic SSDPC Materials

DM21						
Temp (°C)	Density (g/cm^3)	Specific Heat (J/g-K)	Diffusivity (cm^2/s)	Diff Error (cm^2/s)	Conductivity (W/m-K)	Cond Error (W/m-K)
27	8.275	0.4364	0.0100	0.0004	3.60	0.1444
98	8.275	0.4541	0.0149	0.0001	5.60	0.0376
197	8.275	0.4789	0.0165	0.0001	6.53	0.0396
294	8.275	0.5031	0.0163	0.0002	6.77	0.0833
388	8.275	0.5268	0.0173	0.0010	7.54	0.4359
306	8.275	0.5062	0.0391	0.0036	16.39	1.4967
400	8.275	0.5297	0.0405	0.0092	17.73	4.0397
500	8.275	0.5547	0.0451	0.0021	20.70	0.9707
601	8.275	0.5800	0.0408	0.0102	19.56	4.8965
697	8.275	0.6040	0.0527	0.0032	26.33	1.6168
801	8.275	0.6300	0.0552	0.0023	28.76	1.2122
898	8.275	0.6542	0.0463	0.0027	25.04	1.4875
302	8.275	0.5052	0.0366	0.0027	15.28	1.1312

CCM Plus						
Temp (°C)	Density (g/cm3)	Specific Heat (J/g-K)	Diffusivity (cm2/s)	Diff Error (m2/s)	Conductivity (W/m-K)	Cond Error (W/m-K)
27	8.204	0.4623	0.0139	0.0012	5.25	0.4557
98	8.204	0.4801	0.0336	0.0015	13.22	0.6040
197	8.204	0.5049	0.0361	0.0016	14.94	0.6434
294	8.204	0.5291	0.0325	0.0014	14.11	0.6017
389	8.204	0.5530	0.0265	0.0073	12.04	3.2948
300	8.204	0.5306	0.0493	0.0064	21.46	2.7818
398	8.204	0.5551	0.0530	0.0044	24.14	1.9816
500	8.204	0.5806	0.0491	0.0070	23.41	3.3150
599	8.204	0.6054	0.0556	0.0007	27.59	0.3240
699	8.204	0.6304	0.0619	0.0019	32.00	0.9614
801	8.204	0.6559	0.0622	0.0019	33.47	1.0233
297	8.204	0.5299	0.0503	0.0091	21.84	3.9346

Table 3: Physical Properties of Monolithic SSDPC Materials (cont)

CCW Plus						
Temp (°C)	Density (g/cm^3)	Specific Heat (J/g-K)	Diffusivity (cm^2/s)	Diff Error (cm^2/s)	Conductivity (W/m-K)	Cond Error (W/m-K)
27	8.275	0.4500	0.0202	0.0055	7.536	2.0422
98	8.275	0.4677	0.0345	0.0007	13.352	0.2709
198	8.275	0.4926	0.0371	0.0010	15.139	0.4193
295	8.275	0.5169	0.0382	0.0010	16.321	0.4315
391	8.275	0.5409	0.0393	0.0017	17.589	0.7816
300	8.275	0.5182	0.0547	0.0039	23.466	1.6915
400	8.275	0.5432	0.0595	0.0046	26.732	2.0516
501	8.275	0.5685	0.0592	0.0015	27.863	0.7016
602	8.275	0.5937	0.0611	0.0025	30.024	1.2038
701	8.275	0.6185	0.0612	0.0008	31.298	0.4234
803	8.275	0.6440	0.0669	0.0023	35.631	1.2309
899	8.275	0.6680	0.0735	0.0045	40.607	2.5069

NT60						
Temp (°C)	Density (g/cm^3)	Specific Heat (J/g-K)	Diffusivity (cm^2/s)	Diff Error (cm^2/s)	Conductivity (W/m-K)	Cond Error (W/m-K)
27	8.275	0.3108	0.1085	0.0036	27.911	0.9303
99	8.275	0.3215	0.1203	0.0067	32.014	1.7810
198	8.275	0.3364	0.1244	0.0262	34.637	7.2794
295	8.275	0.3509	0.1213	0.0243	35.235	7.0592
391	8.275	0.3654	0.1070	0.0059	32.340	1.7863
301	8.275	0.3519	0.1124	0.0017	32.735	0.4826
401	8.275	0.3669	0.1085	0.0023	32.940	0.7117
500	8.275	0.3817	0.1041	0.0050	32.887	1.5877
599	8.275	0.3966	0.1006	0.0037	33.015	1.2001
705	8.275	0.4125	0.0874	0.0160	29.823	5.4574
302	8.275	0.3520	0.1012	0.0043	29.478	1.2496

Table 3: Physical Properties of Monolithic SSDPC Materials (cont)

Mean Coefficient of Linear Thermal Expansion				
Temp °C	CCM Plus	DM21	CCW Plus	NT60
0	1.10E-05	1.19E-05	1.53044E-05	7.65882E-06
50	1.14E-05	1.20E-05	1.48491E-05	7.73241E-06
100	1.18E-05	1.21E-05	1.44887E-05	7.82893E-06
150	1.22E-05	1.22E-05	1.42164E-05	7.94584E-06
200	1.25E-05	1.23E-05	1.40252E-05	8.08065E-06
250	1.28E-05	1.24E-05	1.39083E-05	8.23082E-06
300	1.31E-05	1.25E-05	1.38589E-05	8.39385E-06
350	1.33E-05	1.27E-05	1.387E-05	8.56723E-06
400	1.36E-05	1.28E-05	1.39349E-05	8.74844E-06
450	1.38E-05	1.29E-05	1.40465E-05	8.93496E-06
500	1.40E-05	1.31E-05	1.41981E-05	9.12429E-06
550	1.42E-05	1.33E-05	1.43829E-05	9.3139E-06
600	1.44E-05	1.35E-05	1.45938E-05	9.50129E-06
650	1.46E-05	1.37E-05	1.48241E-05	9.68394E-06
700	1.48E-05	1.39E-05	1.50669E-05	9.85934E-06
750	1.50E-05	1.42E-05	1.53154E-05	1.0025E-05
800	1.52E-05	1.45E-05	1.55625E-05	1.01783E-05
850	1.55E-05	1.48E-05	1.58016E-05	1.03169E-05
900	1.58E-05	1.52E-05	1.60257E-05	1.04381E-05

Poisson's ratio. Specific heat data presented in Figure 24 show a clustering of data for the nickel and cobalt base alloys, but significantly different data for the composite Ni/WC alloy. Conductivity differences, as illustrated by the data for DM21 and CCM Plus in Figure 25 exhibited differences among all the materials tested. This information established a database for the design and modeling of these advanced tooling materials for hot forming applications.

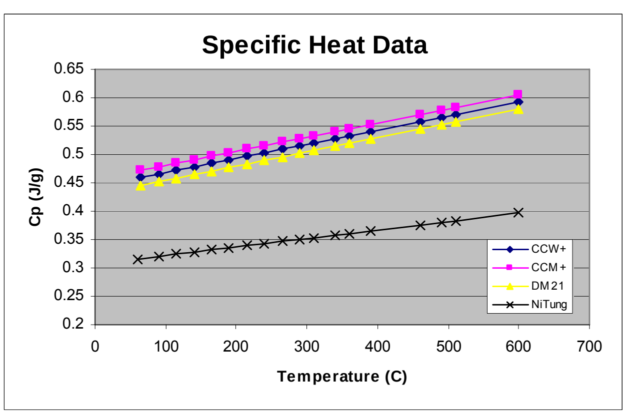


Figure 24**:** Specific Heat results for advanced tooling materials.

Bi-metallic SSDPC samples were prepared to determine the bond strength between advanced tooling and standard tooling materials such as H13 and

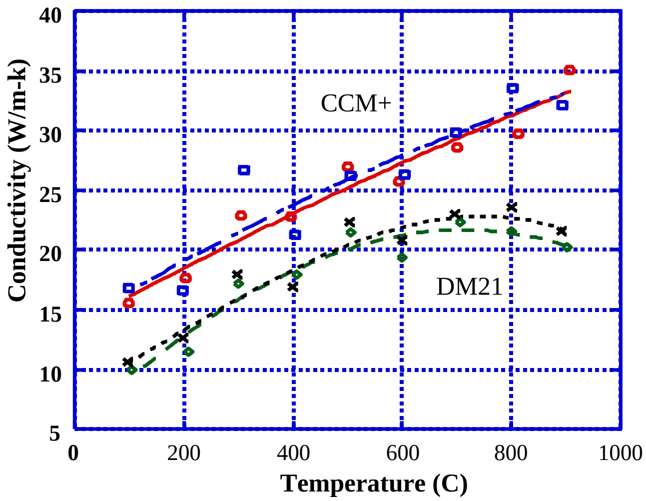


Figure 25: Thermal conductivity curves for SSDPC DM21 and CCM PLUS .

NiMark 300. The results obtained on DM21/H13 bonds and CCM Plus/NiMark 300 bonds at temperatures up to 1400°F are listed in Table 4. The DM21/H13 bonds show good strength up to 1200°F. At 1400°F the H13 loses strength rapidly and bond strength drops to very low levels.

Table 4: Mechanical Properties of Bimetallic SSDPC Materials

Alloy	Temp F	.2% YS ksi	UTS ksi	RA %	EL %	Comment
DM21/H13	RT	181.3	197.7	1.8	2.0	Failed at interface
	1000	163.8	195.6	2.4	2.3	Failed at interface
	1200	113.1	126.1	0.8	4.8	Failed at interface
	1400	13.7	25.3	96.5	75.3	Failed in the H-13
CCM PLUS/H13	RT	160.5	192.5	0.1	0.7	Failed at interface
	1000	114.3	166.6	1.3	2.5	Failed at interface
	1200	99.4	131.9	4.3	5.1	Failed at interface
	1400	15.7	25.2	96.1	80.2	Failed in the H-13
DM21/NiMark300	RT	190.0	225.4	3.1	4.0	Failed at interface
	1000	164.7	181.9	72.0	16.9	Failed in NiMark300
	1200	42.7	76.6	100.0	0.0	Failed in NiMark300
	1400	48.3	55.1	93.4	27.4	Failed in NiMark300

Table 4: Mechanical Properties of Bimetallic SSDPC Materials (cont.)

Alloy	Temp F	.2% YS ksi	UTS ksi	RA %	EL %	Comment
CCM PLUS /NiMark300	RT	161.2	169.0	0.0	0.4	Failed at interface
	1000	112.0	140.0	0.0	9.0	Failed at interface
	1200	45.1	83.9	100.0	31.9	Failed in NiMark300
	1400	26.1	48.0	5.3	0.0	Failed at interface

Similar results were obtained on the CCM Plus /NiMark 300 bonds except that the strength drops significantly at 1200°F. This means that bi-metallic tools can take advantage of the high temperature strength afforded by DM21 and CCM Plus in hot forming operation as long as the substrate materials, either H13 or NiMark 300 are kept below 1200°F.

Microstructural evaluation showed good metallurgical bonds with minimal diffusion at the interface. The CCM PLUS /NiMark 300 samples showed some minor precipitation along the bond line which had little or no effect on bond strength at any temperature. Physical properties were also determined on the bi-metallic SSDPC samples with the results listed in Table 5. Specific heat, coefficient of expansion and thermal conductivity were determined on these samples at temperatures up to 1475°F. This information provided more accurate input data for the modeling of hot forming operations using advanced alloy bi-metallic tooling.

Table 5: Physical Properties – SSDPC Bimetallic Bonds

DM21 to H13						
Temp (°C)	Density (g/cm^3)	Specific Heat (J/g-K)	Diffusivity (cm^2/s)	Diff Error (m^2/s)	Conductivity (W/m-K)	Cond Error (W/m-K)
27	8.035	0.4624	0.0220	0.0066	8.17	2.4519
97	8.035	0.4799	0.0327	0.0012	12.61	0.4627
196	8.035	0.5046	0.0342	0.0013	13.87	0.5271
292	8.035	0.5286	0.0327	0.0016	13.89	0.6796
388	8.035	0.5526	0.0339	0.0018	15.05	0.7992
317	7.952	0.5349	0.0443	0.0022	18.82	0.9560
403	7.952	0.5564	0.0442	0.0018	19.53	0.7994
502	7.952	0.5811	0.0456	0.0011	21.09	0.4930
606	7.952	0.6071	0.0524	0.0010	25.28	0.4927
702	7.952	0.6311	0.0524	0.0020	26.32	1.0039
805	7.952	0.6569	0.0612	0.0020	31.98	1.0551
295	7.952	0.5294	0.0424	0.0039	17.84	1.6610

Table 5: Physical Properties – SSDPC Bimetallic Bonds (cont.)

DM21 to NiMark300						
Temp (°C)	**Density (g/cm^3)**	**Specific Heat (J/g-K)**	**Diffusivity (cm^2/s)**	**Diff Error (cm^2/s)**	**Conductivity (W/m-K)**	**Cond Error (W/m-K)**
27	8.133	0.4624	0.0257	0.0073	9.66	2.7450
97	8.133	0.4799	0.0355	0.0005	13.85	0.1951
197	8.133	0.5049	0.0375	0.0011	15.40	0.4517
293	8.133	0.5289	0.0389	0.0012	16.73	0.5161
389	8.133	0.5529	0.0387	0.0013	17.40	0.5845
305	8.123	0.5319	0.0469	0.0003	20.26	0.1438
399	8.123	0.5554	0.0471	0.0010	21.26	0.4373
506	8.123	0.5821	0.0503	0.0008	23.79	0.3872
600	8.123	0.6056	0.0536	0.0014	26.36	0.6672
703	8.123	0.6314	0.0575	0.0014	29.49	0.6974
804	8.123	0.6566	0.0600	0.0016	32.00	0.8742
300	8.123	0.5306	0.0407	0.0019	17.55	0.8197

CCM PLUS to H13						
Temp (°C)	**Density (g/cm^3)**	**Specific Heat (J/g-K)**	**Diffusivity (cm^2/s)**	**Diff Error (cm^2/s)**	**Conductivity (W/m-K)**	**Cond Error (W/m-K)**
27	7.865	0.4624	0.0421	0.0021	15.31	0.7636
97	7.865	0.4799	0.0498	0.0070	18.79	2.6418
197	7.865	0.5049	0.0490	0.0007	19.46	0.2779
293	7.865	0.5289	0.0460	0.0019	19.13	0.7903
390	7.865	0.5531	0.0470	0.0027	20.45	1.1745
302	7.957	0.5311	0.0482	0.0009	20.38	0.3906
397	7.957	0.5549	0.0462	0.0019	20.42	0.8449
504	7.957	0.5816	0.0493	0.0005	22.83	0.2256
600	7.957	0.6056	0.0561	0.0014	27.03	0.6630
703	7.957	0.6314	0.0608	0.0019	30.56	0.9550
802	7.957	0.6561	0.0690	0.0017	36.04	0.8831
304	7.957	0.5316	0.0514	0.0028	21.76	1.1854

Table 5: Physical Properties – SSDPC Bimetallic Bonds (cont.)

CCM PLUS to NiMark300						
Temp (°C)	**Density (g/cm^3)**	**Specific Heat (J/g-K)**	**Diffusivity (cm^2/s)**	**Diff Error (cm^2/s)**	**Conductivity (W/m-K)**	**Cond Error (W/m-K)**
27	8.163	0.4624	0.0323	0.0012	12.19	0.4529
97	8.163	0.4799	0.0404	0.0004	15.82	0.1567
197	8.163	0.5049	0.0415	0.0005	17.10	0.2061
294	8.163	0.5291	0.0420	0.0017	18.14	0.7342
390	8.163	0.5531	0.0433	0.0009	19.55	0.4063
305	8.124	0.5319	0.0548	0.0014	23.67	0.6126
399	8.124	0.5554	0.0536	0.0005	24.16	0.2444
504	8.124	0.5816	0.0604	0.0065	28.53	3.0800
601	8.124	0.6059	0.0590	0.0005	29.04	0.2312
704	8.124	0.6316	0.0644	0.0012	33.04	0.6334
799	8.124	0.6554	0.0648	0.0018	34.49	0.9662
302	8.124	0.5311	0.0473	0.0078	20.40	3.3756

Tool failure analysis discussed earlier had shown that tool softening and subsequent deformation is a major cause of tool failures in many hot forming applications. To assess the softening behavior of the advanced tooling materials being evaluated in this project, SSDPC samples were exposed for extended periods of time at 1000°F, 1200°F and 1400° F. Conventionally used tooling materials such as H13, M4 and AerMet 100 were also tested. The results are listed in Table 6. The hardness of standard tooling materials which start at 50 to 60 RC drop sharply after a few hours at high temperature and reach hardness levels of 25 to 35 RC after extended time at temperature. At these hardness levels tooling in many hot forming applications deform and must be replaced with new tooling.

The advanced high temperature tooling alloys, however, maintain their strength after exposure for 25 hours at the aforementioned temperatures. DM21 starts at approximately 50 RC and maintains that hardness for extended periods of time. CCM Plus and CCW Plus start at 48 RC and 39 RC, respectively and maintain the same hardness for all exposure temperatures and time. CCM Plus actually increases several RC hardness points after 25 hours of exposure, apparently due to an aging reaction. An example of comparative hardness's of different advanced tooling materials at 1200° F is shown in Figure 26.

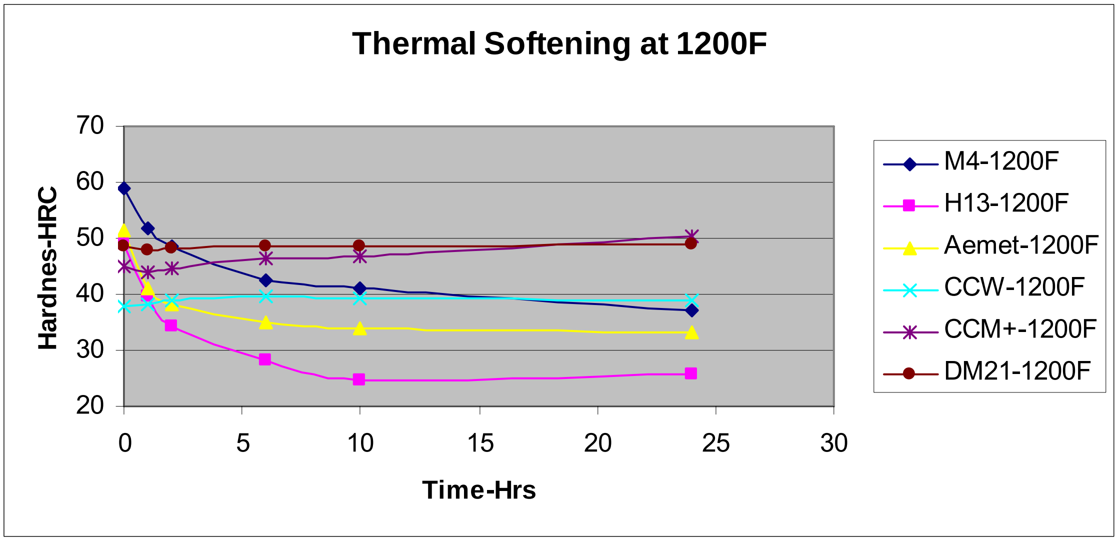


Figure 26: Effect of 1200°F aging time on hardness of tooling materials.

Table 6: Thermal Softening – 1000F, 1200F, 1400F

1000F							
Hours	**M4**	**H13**	**AerMet**	**CCW**	**CCW+**	**CCM PLUS**	**DM21**
0	59	49.1	51.5	38	42.2	44.9	48.5
1	58.5	50	46.4	37.1	42.6	43.7	48.5
6	58.5	49.2	44.4	38.6	42.6	45.5	48.5
10	57.6	47.7	43.8	37.7	42.2	44.8	47.1
24	59.2	48	44.3	38.5	42.7	44.9	48.9

1200F							
Hours	**M4**	**H13**	**AerMet**	**CCW**	**CCW+**	**CCM PLUS**	**DM21**
0	59	49.1	51.5	38	42.2	44.9	48.5
1	51.8	39.6	41.1	38.1	42.5	43.8	48
2	48.7	34.2	38.1	38.9	42.6	44.6	48.3
6	42.4	28.1	35	39.5	42.6	46.3	48.5
10	41.1	24.8	34	39.3	42.5	46.9	48.5
24	37.3	25.6	33.2	38.9	42.9	50.2	48.8

1400F							
Hours	**M4**	**H13**	**AerMet**	**CCW**	**CCW+**	**CCM Plus**	**DM21**
0	59	49.1	51.5	38	42.2	44.9	48.5
1	33.1	23.5	45.7	38	42.9	49	49.2
2	31.8	19.8	45.7	39.2	42.8	52.4	47.8
6	30.1	21.3	43.5	39	42.9	51.7	47.5
10	29.2	18	46.2	38.4	44.7	51.9	48.9
24	28.5	14.2	45.4	38.8	47.2	51.7	48

4.2.3 Task 3 - Basic Research on Refractory Metal Binary Pairs

Some basic research was also conducted by SDSMT to determine high temperature refractory metal candidates for graded material depositions with the LPD process. Fundamental studies were conducted on pure refractory metal binary pairs that exhibit complete solid solubility [Ref. 8]. Additionally, refractory metals such as Mo, Nb, Ta and V were laser deposited on H13 tool steel and 4340 alloy steel. The purpose of this effort was to characterize the interface of binary pairs as a preclude to developing future FGM materials with higher temperature capabilities. Particular attention was accorded to bonding issues, diffusion of one metal into another and the formation of brittle intermetallic phases. Binary pair studies included metallographic and SEM analyses and hardness testing across the interface.

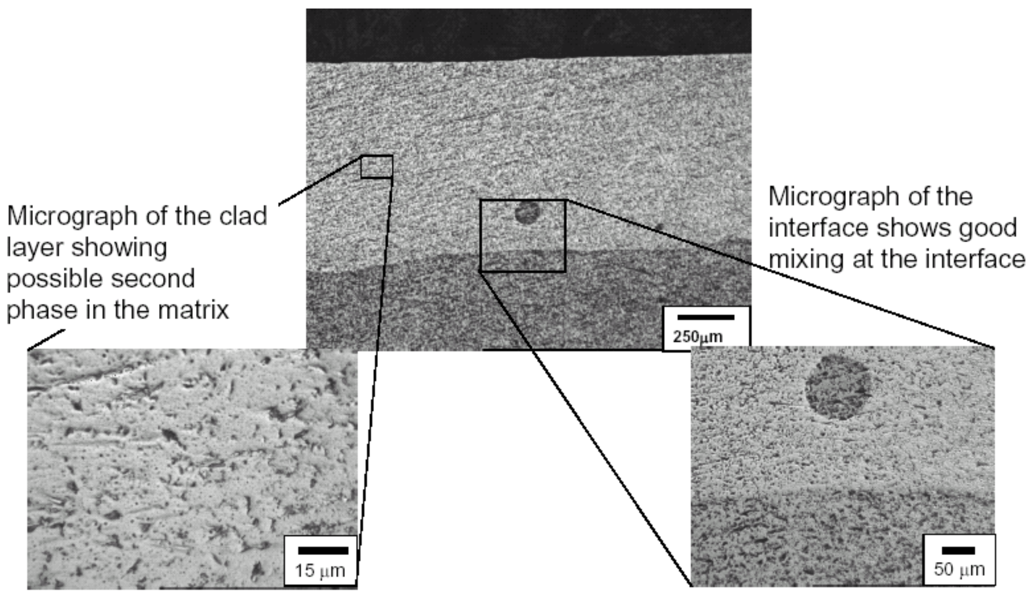


Figure 27: Microstructures of an LPD V-Nb binary.

Results varied for the binary pairs studied, and showed a variety of structural conditions including intermetallic phase formation, interface cracking, abrupt hardness changes at the interfaces and in some instances, porosity. A better understanding of the microstructure was achieved through SEM analyses which established compositional variations which when combined with DICTRA identified phases present at the cracked boundaries. Thermo-Calc was also used to compute equilibrium reaction products between the surface layers and the substrate. Of all the binary refractory pairs studied, the Nb-Ta and V-Nb pairs showed good mixing and good bonds.

Figure 27 shows a micrograph of the V-Nb binary pair. Poor results were obtained on the W, Nb and Ta binary pairs. Except for V, cladding of refractory metals to iron base tool steels was not successful. Overall, the results showed good adherence of V to H13 with the LPD process.

Figure 28 shows an excellent microstructural bond and hardness traverse across the V/H13 bond interface. The interface transition is very good and no softening or hardening is observed for either the substrate or clad material. However, chemical analysis of the bond showed that the V is embedded approximately 70% into the H13 substrate as opposed to a desired result of 10% to 20%. Further work adjusting laser parameters can probably reduce the dilution. Nevertheless, this basic work on binary pairs shows the greatest potential for cladding a tooling material with a high temperature refractory element can be achieved with V as opposed to the other refractory elements studied.

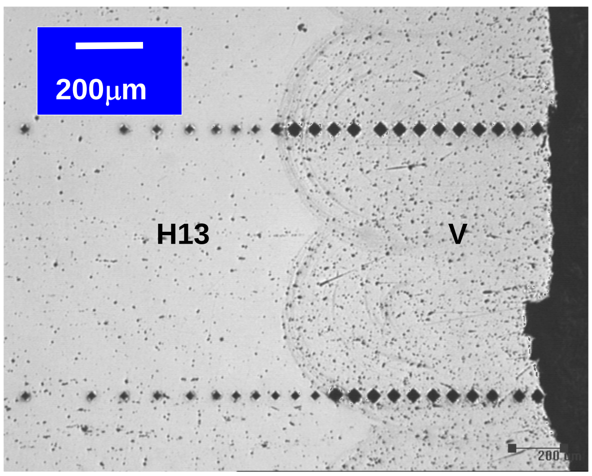


Figure 28: LPD H13/V binary pair showing microstructural bond and uniform hardness in coating.

4.3 Phase III Industrial Performance of FGM Tooling

Phase III involved an assessment of the industrial performance of FGM tooling. Task I established the robustness of the LPD and SSDPC processes and the manufacturing of a variety of tools for commercial testing by companies engaged in the hot forming industry. Task II assessed the performance of FGM tooling in a variety of applications in terms of economic savings and reduced energy consumption.

4.3.1 Task 1 – Industrial Trials

GKN Sinter Metals - GKN Sinter Metals forges large quantities of connecting rods for the automotive industry. Three tools from the hot forging system were selected for the trials of advanced SSDPC tooling; a lower punch and die which exhibit low life due to cracking and a core pin which exhibits softening and wear due to exposure at high temperature. AerMet 100, a high toughness tooling material, was selected as a replacement tooling material for the lower punch and die since analysis showed that temperature was not a problem with this part of the tool set. Initial trials on this lower die showed no advantage over standard H13 tooling which is usually pulled for cracking at 10,000 cycles. Figure 29 illustrates cracking observed on the AerMet 100 tool after 10,081 cycles in essentially the same location as exhibited by standard tooling. Figure 29a shows a finish machined AerMet 100 lower punch die. Figure 29b shows the location of the cracking and Figure 29c shows how the high stresses in this die caused the cracks in two separate areas to propagate and join in the center of the die. Testing of another lower punch resulted in the AerMet 100 tooling being pulled after 7932 cycles. No major cracking was observed but the surface of the tool showed a wear pattern and minor surface cracks which resulted in a part quality

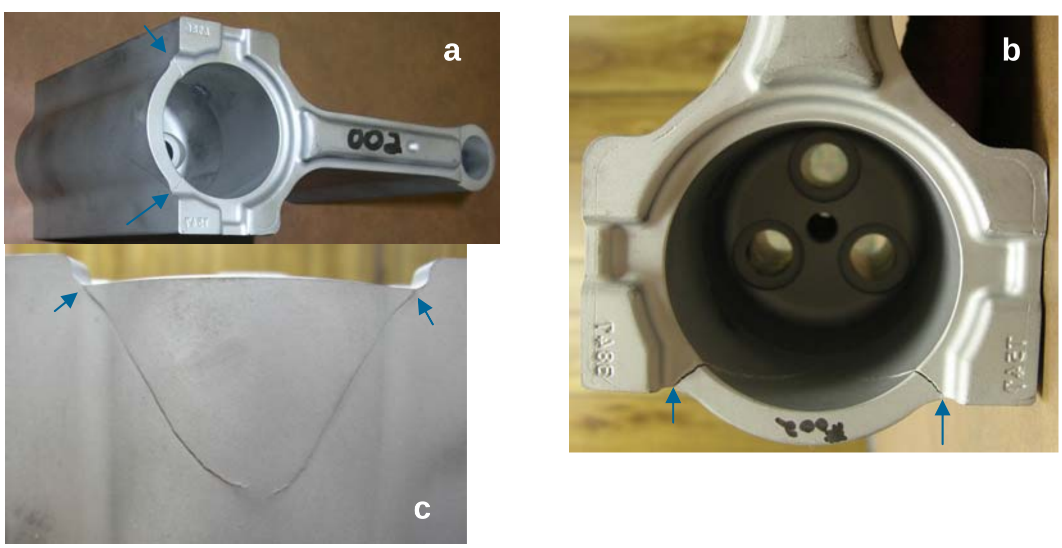


Figure 29: Cracks observed in AerMet 100 connecting rod punch after 10,081 cycles; a) overall part, b) crack initiation – arrows and c) crack progression.

problem. As described in the modeling section of the report and shown in Figure 9, both parts exhibited stress levels in the cracked areas of these tools that no known tooling material could withstand. The ultimate solution to the cracking problems in both the lower die and punch lies in a redesign of the tooling.

High temperature exposure on the working surface of a core pin at GKN results in softening and wear, which necessitates replacement after 11,000 to 28,000 cycles. As a potential replacement, a series of SSDPC bi-metallic tooling

Blank

Core Pin
86,000 cycles

Figure 30: DM21/NiMark300 SSDPC bimetallic core pin blank and finished tool.

consisting of DM21/Marging steel and CCM Plus /Maraging steel pairs, as illustrated in Figure 30, were tested and evaluated. Overall results showed results that SSDPC tools had lives 2x to 4x that of standard tooling. Only one out of twenty tests showed a tool tip failure and that was for scoring. The working tips of these tools showed no softening or excessive wear which occurred in over 50% of the failures for standard tooling. For the DM21/Maraging steel bi-metallic tools, 8 out of 10 failed in the maraging steel threads and 2 failed in the chamfer area. For the CCM Plus /Maraging steel tool, one failed by scoring with the remainder breaking in the shoulder or hex area of the tool. The CCM Plus /Maraging steel tools exhibited good high temperature strength but did not have the toughness exhibited by the DM21/Maraging steel tools.

The next set of trials was to include a redesign of the thread area in this tooling and rerun the bi-metallic DM21/Maraging steel tools. These trials were not completed because GKN Sinter Metals closed this plant for business reasons.

Metaldyne/FormTech **–**The Royal Oak plant of Metaldyne/FormTech is a major supplier of hot forged automotive components such as spindles and wheel hubs. A four station Hatebur forging machine is used to manufacture parts at the rate of 60-70 per minute. This machine, a part of which is shown in Figure 31, uses high pressure water cooling in order to maintain a manageable tooling life in the

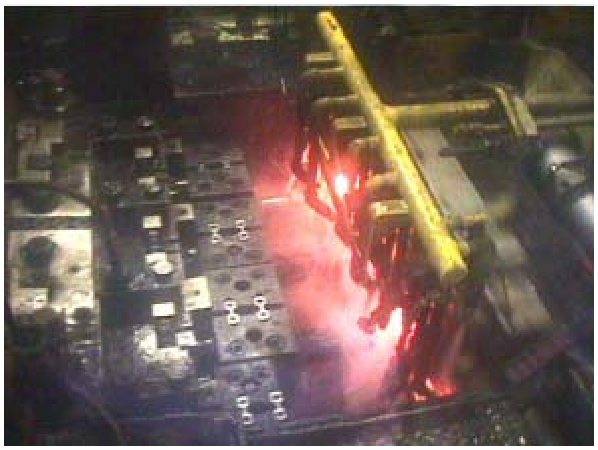


Figure 31: Four station Hatebur forging machine.

forging system. Nevertheless tooling must be changed every 20-45 minutes because of tool failures that would result in scraped or defective parts if not replaced. Standard H13 tools give an average life of 7,000 cycles. Initial trials on an SSDPC DM21 intermediate punch showed no improvement over standard tooling in terms of tool life. However, the DM21 tool did not fail because of softening and wear but rather by large cracks, as shown in Figure 32, which were caused by severe thermal cracking due to the high pressure water cooling. Subsequent testing of SSDPC DM21 and CCM Plus punch nose tooling showed a slight improvement of 1.5x to 2x. over standard tooling for the DM21 but no improvement with the CCM Plus tooling. Testing of an AerMet 100 punch nose failed at ½ the life of standard tooling material. The higher toughness of AerMet 100 was of no advantage in this application because of its poor high temperature strength.

Anvils, the third tooling component addressed in the Hatebur forging system,

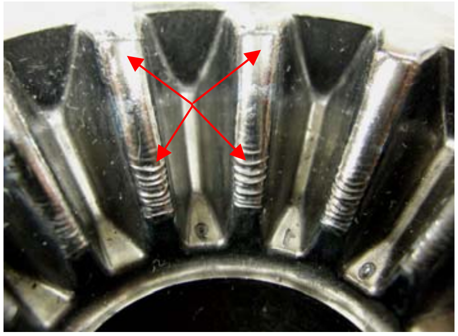
CCM+ DM21

Figure 32: Large cracks on SSDPC CCM+ and DM21 tooling.

were manufactured by LPD coating and H13 substrates with CCW Plus, a high temperature cobalt base alloy, NiTung 60, a nickel/WC composite and DM21, a high temperature nickel base alloy. Results showed comparable lives to standard tooling for the DM21 and NiTung60 coated H13 substrate. The CCW Plus coated tooling slightly exceeded standard tooling. A decision was made to continue with LPD CCW Plus coated tools using a variation in LPD coating parameters to ensure a more uniform and dense coating. Production tests on these tools have a tooling life 2x to 3x that of standard tooling. A subsequent sale of Metaldyne to FormTech resulted in a reduction of resources and production time for running trials at the Royal Oak plant. No further work was conducted at this forging facility. A cost analysis indicated that a 3x life on FGM tooling would be marginal from an economic view. This view is attributed to the high cost of the alloying elements in the FGM tooling at that time.

Efforts at the Metaldyne/FormTech, Fort Wayne plant focused on a knockout punch, a gear die and a spline die. Forging operations at this plant were less severe in terms of cooling and used lower forging temperatures. A SSDPC CCM Plus tooling was used to replace standard H13 tooling for the knockout punch. When testing was completed, the CCM Plus tooling performed exceptionally well and exceeded by 300X the standard tooling life of 7,000 cycles. CCM Plus tooling has been adopted as bill of material for this application. Testing of an SSDPC DM21 gear die also showed good results when compared to standard H13 tooling. The DM21 gear die was pulled after 10,000 cycles, a 5x improvement over standard tooling, due to a bore failure unrelated to DM21. The gear teeth, where failure usually occurs, showed no wear or deformation in this gear die.

A comparison between standard material and the DM21 tool is illustrated in Figure 33. Testing of the SSDPC DM21 spline die at Fort Wayne showed no improvement over standard tooling. The high temperature capabilities of DM21 could not be taken advantage of as the high forging loads resulted in slight yielding of the punch. Since the tolerances of the spline die are very tight, the minor yielding put the part dimensions out of specification and the die was pulled.



Current Die material at ~2,000cycles

SSDPC DM21 Die at ~10,000 cycles

Figure 33: Gear die comparisons of conventional ferrous based and SSDPC DM21 tooling after forging.

Metaldyne/AsahiTec - Metaldyne/AsahiTec manufactures large complex aluminum die castings for the automotive industry in large volumes. The process uses segmented dies that encounter varying conditions during the die casting of these aluminum parts. Die segments at the gate see higher temperatures, chemical erosion and cracking. Die segments in other parts of the die exhibit thermal fatigue cracking. These issues were addressed by different SSDPC material. The use of CCM Plus was directed at the gate area and AerMet 100 was used further away from the gate. A normal life for many of the segments in this aluminum die casting die is two months. Both materials exceeded the goal by achieving a 5x life of that of standard H13 tooling. The CCM Plus tooling in the gate area resisted chemical erosion and soldering extremely well. The AerMet 100 has performed very well further into the die relative to heat checking. The full extent of the improvements are not known because of the withdrawal of the operation from the project when AsahiTec purchased this facility. Nevertheless, both CCM Plus and AerMet 100 have become bill of materials for this aluminum die casting operation.

Arvin Meritor - Arvin Meritor is a major supplier of hot forged automotive and truck components and became a contributing partner to the FGM project. Tooling problems centered around softening and deformation, heat checking and cracking. Initial tests were conducted on a punch tool which showed failure in a chamfer area due to softening and cracking. Modeling confirmed that the chamfer area of the tool reached and maintained a temperature high enough to soften H13. A series of punches were LPD coated with CCW Plus and finish machined as illustrated in Figure 34 by Arvin Meritor. Manufacturing trials showed a punch tool life 3x to 4x that of standard H13 tooling. The trials, using a coating of the of the high temperature high strength CCW Plus alloy confirmed anticipated results. Subsequent testing of additional LPD coated punch tools confirmed the improvement in tool life for this application.

In another application at Arvin Meritor, a gear die was experiencing severe deformation and cracking in the teeth that limited the life to 2000 cycles. Normally this gear die which is manufactured from H13 cannot be reworked and is scrapped. A series of SSDPC DM21 tool blanks were made and tested at Arvin Meritor. Tool life tests showed a 3x improvement in life for this tool over standard tooling. The die showed a minor amount of wear on the teeth but no cracking or

Figure 34: Punch tool before (a) and after (b) LPD cladding with CCW Plus.

deformation. More importantly, the tool can be reburned to correct the small amount of wear that occurred during testing and reused a second and perhaps a third time. Arvin Meritor is assessing the economics for both the punch tool and gear die to help determine the justification for using the LPD and SSDPC tools tested in their manufacturing operations.

Owens Illinois - Owens Illinois (O-I), one of the world's largest manufacturers of glass containers, joined the project after the withdrawal of Techneglas due to financial problems. O-I identified a plunger tool as a major problem in their narrow neck press and blow process (NNPB) for manufacturing small neck glass containers. As previously described, these tools, which are manufactured by HVOF coating on AISE 8620 steel, failed because of porosity, cracking and spalling. Modeling of the process helped understanding of the thermal behavior of a plunger and established the maximum allowable temperature so as to avoid sticking during formation of the cavity in the viscous glass by the plunger. After a number of LPD process parameter variations were conducted to eliminate porosity in the coating, production trials were tried on LPD CCW Plus coated tools at O-I's manufacturing operations. Results showed no improvement over the standard tooling. While the failure issues associated with standard tooling, porosity, cracking and spalling, were eliminated, the LPD CCW Plus tooling did not have the wear resistance to maintain dimensional requirements and contributed to low impact strength in the container by contamination and scratching the glass.

In an effort to increase wear resistance of the plunger tool, NiTung60, a nickel/tungsten carbide composite, was used to LPD coat another series of plunger tools. Figure 35 shows the AISI 8620 steel being LPD coated and shows the appearance of the plunger after cladding. These tools were finished machined by O-I and tested in their manufacturing facilities on a standard production line. Results showed an improvement over LPD CCW Plus clad tooling but no better than standard AISI 8620 HVOF coated plungers. Again these tests demonstrated higher than desired wear on the plunger tool which showed an improved but unacceptable defect rate in the glass containers. A modification of the amount and size of the tungsten carbide in the NiTung 60 composite has been made and additional plungers manufactured. O-I will continue testing even though the FGM project has been officially completed.

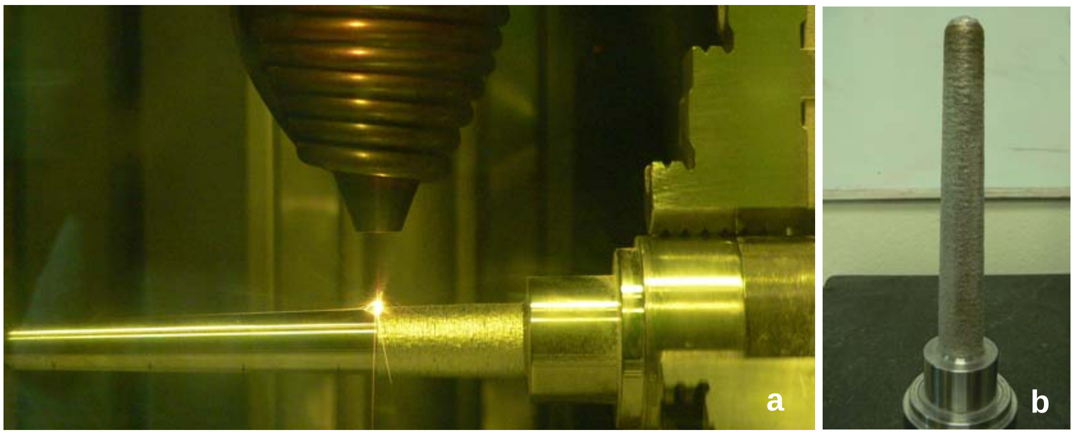


Figure 35: Glass plunger being laser clad (a) and after LPD cladding (b).

THT Presses – THT Presses manufactures die casting equipment with an emphasis on machines that produce aluminum bronze and copper components. The piston head on this equipment, which is used to remove the biscuit head upon completion of a die casting cycle, exhibits an extremely low life. This tooling, currently made from H13, typically fails in 10 to 20 cycles. Failure analysis and modeling showed that failure occurred by thermal softening of the tool combined with high alternating stresses due to internal water cooling of the tool. Since the proposed FGM tooling material for this application has much better high temperature strength, its use should decrease the susceptibility for crack/failure in this application

Modeling indicated that a material capable of maintaining high temperature strength could improve the performance of this tool. A SSDPC CCM Plus /H13 bimetallic tool was selected for evaluation in this application. The starting blank and the finished tool are shown in Figure 36. Trials were conducted on a 100 ton die casting machine manufacturing aluminum bronze components. Initial tests showed some minor cracks on the tooling after doubling the life of standard tooling when using a casting temperature of 2100F. Further examination showed no deformation or collapse of the dove tail which is observed in standard tooling.

The same tooling was retested and removed for examination after a life of four times that of H13 tooling. The SSDPC CCM Plus /H13 tooling again showed no deformation of the dovetail and no additional propagation of the initial cracking observed in this tool. THT will determine whether the increased number of cycles, four times standard tooling, can justify the higher acquisition costs for the SSDPC CCM Plus /H13 bimetallic tooling.

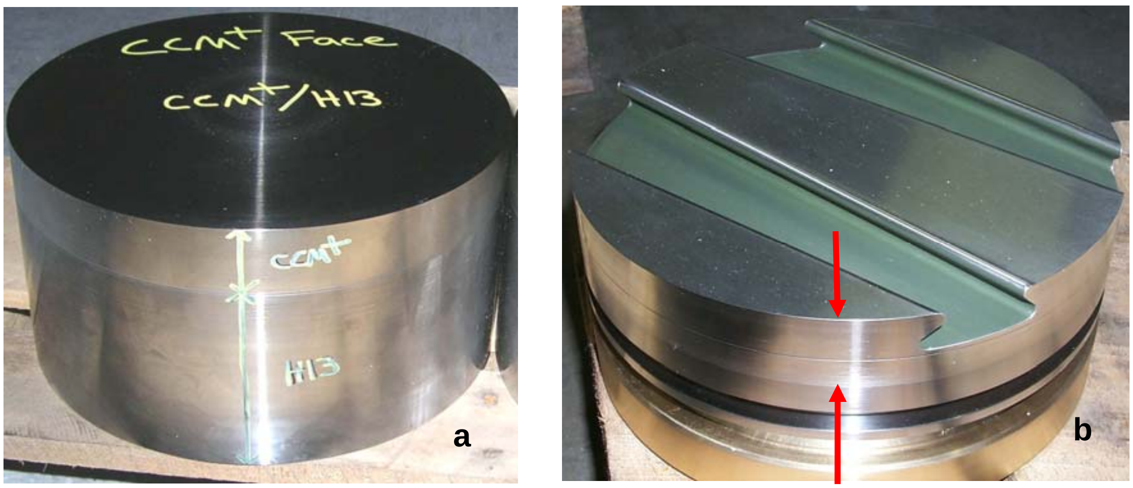


Figure 36: CCM Plus/H13 bi-metallic piston head blank (a) and finish machined tool (b).

Other Manufacturing Companies - Interest in SSDPC and LPD tooling using advanced high temperature material by non project partners developed as a result of project presentations and papers or through direct commercial tie contacts. Tooling problems at a number of companies were evaluated, failure mechanisms identified and recommendations made as to the type of FGM tooling that could have a beneficial effect on selected applications. A summary of manufacturing trials at these companies, all of whom used hot forming processes follows:

Chamberlain Manufacturing – This company, which manufactures DOD related components, was having difficulty with an extrusion punch that barely lasted more than 50 cycles. In this hot forming operation, the tool experiences a rapid surface expansion that creates high compressive stresses when combined with restraint caused by water cooling of the punch core. After hot forming the part, the tool is oil quenched and the high surface stresses are reversed. The stresses combined with thermal softening of the H13 tooling exceeds the yield strength of this material resulting in deformation and thermal fatigue cracking.

Modeling suggested that tool life could be improved by minimizing or eliminating the water cooling in the punch core, minimizing the quench after the part has been formed and by using a tooling material with high temperature strength. SSDPC DM21/H13 and CCM Plus/H13 bimetallic tooling were manufactured for initial production trials. Both materials addressed the need for greater elevated temperature strength In this application. Neither of the tools succeeded in improving the tool life in this application. While no deformation of the tools was observed, they did develop large cracks do to the severe alternating stress situation encountered in this application.

Subsequently a series of LPD CCW Plus/H13 tools were produced for testing in this application. These tests on the LPD tools showed a 1.5 to 2 times improvement in life over standard H13 tooling. The LPD tool, as illustrated in Figure 37, showed slight bulging on the tip of the tool but no thermal fatigue cracking. The bulging was apparently due to softening of the H13 substrate. The tools also showed some sidewall craze cracking but this was traced to LPD porosity in the tool blank and was subsequently corrected by changing the nozzle setup during the laser coating application. While the use of a material with higher temperature capabilities increased tool life, it was clear that the unaltered parameters of water cooling the core and rapidly quenching the tool after hot forming the component, prevented any further improvement in tool life. Because of manufacturing production quotas and a potential risk to equipment, Chamberlain decided not to implement FGM tooling.

H13 CCW Plus LPD on H13

Figure 37: Comparison of H13 tooling and with CCW Plus LPD clad on H13.

Dynamic Machine Works – This company, a manufacturer of components using a hot extrusion process was experiencing low tool lives when extruding difficult high temperature alloys with standard H13 tooling. The H13 tooling was softening, deforming and required replacement after 50 extrusion cycles. Samples of SSDPC DM21/niMark and CCM Plus/NiMark bimetallic tooling were manufactured for initial testing. These tests showed a tool life of 10 times and 6 times that of H13 for the DM21/NiMark and CCM Plus /NiMark tooling respectively. An additional set of 4 DM21/NiMark and 4 CCM Plus/NiMark tools were manufactured to verify initial results. These tools combined with some minor variation in the extrusion process result in a cycle life 38 times that of the standard H13 tooling. Dynamic Machine Works has made this FGM tooling a standard bill of material for this application.

Accellent Manufacturing – Attempts to hot forge a specialty F75 cobalt base medical alloy to near net shapes resulted in a punch tool failure after less than 50 cycles. This robotic hot forging operation used H13 tooling that softened and deformed quickly due to a high forging temperature and the high strength exhibited by the F75 material at elevated temperatures. Initial tests on SSDPC DM21 and CCM Plus punch and die blanks showed a significant improvement in tooling life. The DM21 tooling performed best with a life 5 times that of the H13 tooling. Figure 38 illustrates SSDPC DM21 die blanks supplied for this application. Examination of used DM21 tooling shows only a slight deformation in critical areas and no cracking. Re-machining of these tools further extended their life to 20 times of standard H13 tooling. Accellent has made DM21 a bill of material for both the punch and die in this application.

Figure 38: SSDPC DM21 blanks ready for machining.

American Axle/Detroit Forge Plant – This company, one of the biggest automotive parts manufacturers in the world, was experiencing problems with a button die used to hot forge stabilizer bar ends. Examination of the standard H13 die showed softening with hardness's as low as 25RC and severe deformation after 2000 cycles. This tooling failure resulted in significant downtime throughout the day to install new tooling. An SSDPC DM21 button die was supplied for testing in this application. Initial tests showed a 10 times improvement of the DM21 over the H13 button die. Examination of the DM21 as illustrated in Figure 39, showed only minor deformation after 24,000 cycles. Remachining of the DM21 after a series of hot forging runs extended the life of this tool to 100,000 or 50 times the originally used H13 button die. American Axle has made DM21 the bill of material for this application.

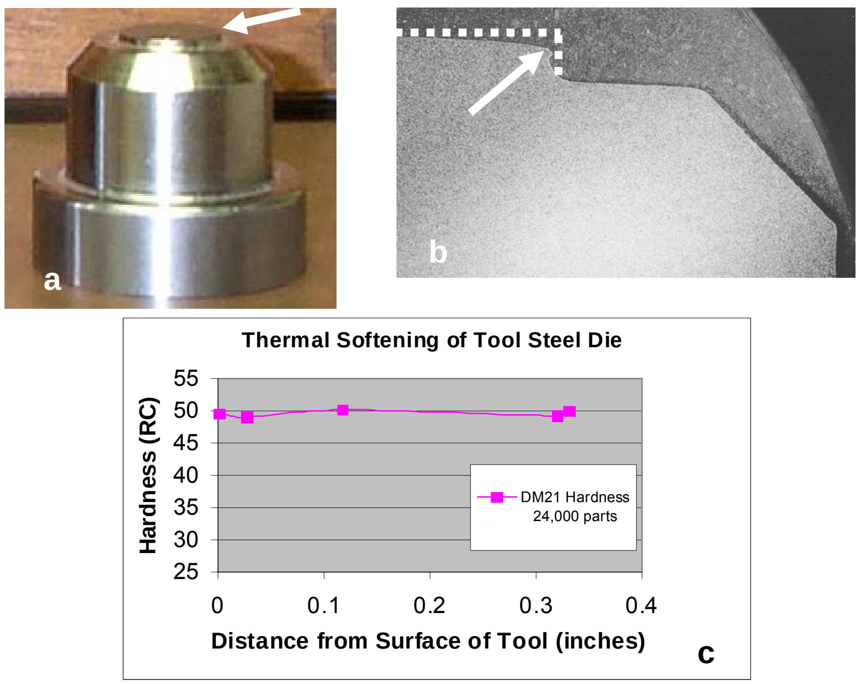


Figure 39: Machined SSDPC DM21 die (a) showing retention of shape (b) and hardness after 24,000 cycles (c).

4.3.2 Task 2 – Performance Assessment

A summary of the industrial production trials conducted on SSDPC and LPD tooling at various major manufacturing companies who were FGM project partners is listed in Table 7. The table lists the company conducting the trials, the hot forming process, the specific tools tested, the tool lives obtained and the status of the FGM tool relative to commercial use. The results show that FGM tooling meets or exceeds currently used tooling on trials involving hot forming in the forging and die casting industries. The FGM glass forming plunger is still being pursued and is in testing. The ejector pin at the FormTech Fort Wayne plant and aluminum die inserts at AsahiTec have become bill of material for those applications. The application for the core pin with a 5x life improvement at GKN disappeared with the closing of their Romulus plant. Other applications showing improved life with FGM tooling have not yet been implemented. FGM tooling, because of its higher acquisition costs, can at times offer no economic benefit when compared to standard tooling and manufacturers are reluctant to change materials or suppliers in such a situation. They will continue to work around the inefficiencies of current tooling materials.

Table 7: Supplier Trials – FGM Project Partners

Company	Operation	Tool	DOE-FGM Process	Relative Life	Commercial Use
GKN Sinter Metals	Hot Forging	Core Pin	SSDPC	5x	No
		Upper Die	SSDPC	1x	No
FormTech/Metaldyne (Royal Oak)	Hot Forging	Punch	LPD,SSDPC	3x	No
FormTech/Metaldyne (Fort Wayne)	Hot Forging	Knockout pin	SSDPC	150x	Yes
		Side Gear Die	SSDPC	5x	No
		Spline Die	SSDPC	1x	No
Metaldyne/AsahiTec	Al Die Casting	Mold Inserts	SSDPC	3x	Yes
Arvin Meritor	Hot Forging	Gear Die	SSDPC	3x	No
		Punch	LPD	2x	No
THT Presses	Die Casting	Piston Head	SSDPC	2x	No
Owens-Illinois	Glass Forming	Plunger	LPD	In Test	In Test

While it is clear that advanced materials with superior high temperature strength can significantly improve tool life, reduce costs and save energy, each application is unique and other hot forming factors can have significant effects on the performance of these tools. While superior tooling is desirable for hot forming processes, other technical factors such as lubrication, cooling and process speed can have a significant effect on manufacturing efficiency. In some cases manufacturers are reluctant or cannot make changes in their hot forming processes in order to take full advantage of FGM tooling.

Table 8 lists the results obtained on manufacturing trials with a series of non-project partners who participated in the evaluation of FGM tooling throughout the project. Results of 10x to 20x that of existing tooling were observed at Accellent, Dynamic Flowform and American Axle. All have made FGM tooling bill of material for their applications. The limited performance observed at Chamberlain could have been improved significantly, as shown by modeling work, if the interior water cooling of the extrusion punch was eliminated or minimized. Authorization for such a change could not be obtained.

Table 8: Supplier Trials – Non Project Partners

Company	Operation	Tool	DOE-FGM Process	Relative Life	Commercial Use
Chamberlain	Hot Forging	Extrusion Punch	LPD, SSDPC	1.4x	No
Accellent	Hot Forging	Punch	SSDPC	20x	Yes
		Die	SSDPC	10x	Yes
Dynamic Flowform	Hot Forging	Extrusion Punch	SSDPC	20x	Yes
Detroit Forge	Hot Forging	Button Die	SSDPC	10x	Yes
		Bender Bar punch	SSDPC	Not tested	No

Table 9 shows the results of limited FGM tooling tests at a number of companies. Most of the initial tests, with the exception of tests at SPS, show no or marginal improvement over existing tooling. The SPS bolt die has become bill of material for this application. Since testing at these manufacturers has been limited, CPP, as part of their commercialization plan, will continue to study these applications and provide FGM tooling where appropriate.

Table 9: Supplier Trials – Limited FGM Testing

Company	Operation	Tool	DOE-FGM Process	Relative Life	Commercial Use
SPS	Hot Forging	Bolt Die	SSDPC	5x	Yes
Colfor	Hot Forging	Extrusion Die	SSDPC	1.5x	No
Net Forge	Hot Forging	Punch	SSDPC	1x	No
Mint Tool	Warm Forging	Punch	SSDPC	1x	No
		Die	SSDPC	5x	No
PBR Columbia	Al Die Casting	Insert	SSDPC	1x	No
Holophane	Glass Forming	Plunger	SSDPC	Not tested	No
		Knockout punch	SSDPC	Not tested	No

5.0 Conclusions

1. Tooling in contact with either hot/molten metal or glass deteriorates quickly as a function of time and the environment.

2. Modes of failure include thermal softening, thermal fatigue, high stresses, chemical erosion, wear and soldering.

3. Modeling of specific applications identifies critical parameters in the hot forming that can help define the design and material choice for tooling.

4. The LPD and SSDPC tool manufacturing processes in conjunction with materials demonstrating high temperature strength can produce superior tooling for a number of hot forming processes.

5. Production testing of FGM tooling demonstrated significant increases in tooling life that ranged from 3 times to 300 times that of standard hot work tool steels for a number of applications.

6. FGM tooling showed little or no improvement over standard tooling in environments using a high volume of water or ones experiencing extremely high stresses.

7. Increased tool life can result in significant operating cost savings due to lower overall tooling acquisition costs, increased uptime (productivity) and reduced scrap.

8. Less energy is consumed in manufacturing a reduced number of tools and energy is saved because longer production runs with less down time reduces the heating requirements for the hot forming process.

9. Although not specifically quantifiable, it is estimated that energy savings meet or exceed the project goal if the new tooling materials are fully implemented.

6.0 Accomplishments and Recommendations

The objective of the project was to design and manufacture FGM tooling through powder metallurgy technology that could:

- Increase tool life by a factor of five
- Reduce energy consumption 25% by 2032
- Increase manufacturing efficiency to provide a globally competitive edge to U.S. forging, die casting and glass forming companies.

Accomplishments related to these objectives vary by the specific hot forming processes investigated and the specific applications within those processes. Specific accomplishments related to the goals of the project are as follows:

- Increased tool life – The project demonstrated the feasibility of manufacturing LPD and SSDPC tooling and established the robustness of the processes. The processes were adaptable to advanced tooling materials selected because of their superior strength at elevated temperatures. In the worst cases, demonstrated tooling lives were equal to current tooling materials, but in the many other specific hot forming processes tooling lives were superior by factors ranging from 5x to 20x. More applications could exhibit superior tool performance if other variables in the hot forming processes could be changed. Successes were achieved by clearly understanding the tooling application, failure mode of the tools and the boundary conditions associated with the process. Modeling of the hot forming processes demonstrated material and process limitations that needed to be addressed to improve tooling lives. Commercial production testing demonstrated that tooling lives can be significantly improved with new tool manufacturing processes, new tooling material and specific process boundary conditions associated with the process.

- Energy reduction – Although not quantifiable, an energy consumption 25% less than that used on current tooling materials is estimated to be possible by 2032. With longer tooling lives, equipment production time is increased, overtime can be minimized or eliminated and both electrical and gas consumption in these hot forming industries can be reduced. Longer tool lives mean less energy is consumed to manufacture tools and dies when fewer tools are required. Less scrap is created by eroded or damaged tools, which means that there will be less scrap to remelt. Energy is saved by not having to initially melt the tooling alloy or recycle the alloy after use. Longer manufacturing runs also means more energy savings since heating equipment does not remain idle while tooling changes are made. Additional energy savings are also realized by not having to redress tooling as often.

- Competitive advantage – Economic benefits attributable to FGM tooling could provide a manufacturing cost benefit. Increased tool lives mean less upfront tooling acquisition costs. Longer tooling lives result in increased productivity (uptime). Superior FGM tooling can significantly reduce quality costs, particularly when quality problems cannot be immediately detected and long runs are completed before the problem is discovered. Increased productivity may also reduce overtime and in some cases may postpone or eliminate large Capital investments when capacity increases are needed. All of these economic benefits are available to potential users of FGM tooling.

- Publications, conference proceedings and technical society presentations involving various aspects of the project are listed in the references.

The tool manufacturing processes and the tooling materials developed on this project are non-proprietary and available for technology transfer. LPD technology can be obtained from SDSMT and can be used by other manufacturers who have laser cladding capabilities. SSDPC tooling products can be obtained from CPP. CPP has established full scale production facilities for manufacturing SSDPC tooling and supplies on a continuing basis project partners who have made FGM tooling a bill of material for their applications. CPP has integrated SSDPC tooling into their list of products marketed to the tool and die industry.

It is recommended that the manufacturers involved in the hot forming of components, metal or glass, critically review tooling used in these applications to determine the potential offered by FGM tooling. While FGM is not always beneficial in all applications, it has been demonstrated that manufacturing efficiency, energy savings and cost reductions are possible for many applications. The use of FGM tooling requires a willingness to change and understanding that tooling acquisition costs are not as important as the net tooling cost per component manufactured. Long term CPP will expand both the volume and size of SSDPC tooling that will be required by market demands. Those manufacturers having LPD capabilities should take advantage of the potential for FGM tooling in the hot forming component industries.

7.0 Project Publications / Presentations

1. October, 2007 – "A New Generation of PM Tool Materials", by D.J. Novotnak and L.W. Lherbier. Euro PM 2007 Toulouse, France, October 15-18, 2007.

2. February, 2005 – South Dakota School of Mines and Technology presented a paper entitled "Development of Functionally Graded Materials for Tool and Dies and Industrial Processing Equipment" at the Minerals Metals Materials Society's annual meeting on February 13-17, 2005 in San Francisco. The presentation discussed the application of the Laser Deposition Process (LDP) to tooling materials and to its effect on the surface, shape and durability of FGM materials.

3. June, 2005 – South Dakota School of Mines & Technology presented a paper entitled "Development of Functionally Graded Materials for the Tooling and Die Industry by Laser Powder Deposition" at PM^2 Tec 2005, an International Conference on Powder Metallurgy and Particular Materials June 19-23 in Montreal Canada. The presentation was an update of a similar entitled paper presented at the Minerals and Metals Society meeting in San Francisco in February 2005. The presentation discussed the application of the Laser Powder Deposition process (LDP) to tooling materials and its effect on the roughness, surface shape and durability of FGM materials.

4. February, 2006 – A presentation by J. W. Sears et al, entitled "Improving the High Temperature Wear Characteristics of Industrial Tools and Dies Using Functionally Graded Refractory Metals" was published in the proceedings of the 2006 International Conference on Tungsten, Refractory and Hardmetals VI, which was held in Orlando, Florida, February 8, 2006.

5. March, 2006 – Two presentations by SDSMT personnel were made at the 2006 TMS Annual Meeting and Exhibition held in San Antonio, Texas on March 12-16, 2006. The two presentations were entitled "Investigating Functionally Graded Materials to Improve the High Temperature Operating Characteristics of Industrial Tools and Dies and Processing Equipment" and "Thermal Stability of Various Alloys Clad on H13 Tool Steel by Laser Powder Deposition.

7.0 Project Publications / Presentations (cont.)

6. April, 2006 – “Laser Applications in Additive Manufacturing: Spanning Microns to Meters”, Sears, J. (Invited Plenary Talk) Presented and Published at the 2nd Pacific International Conference on Lasers and Optics, (PICALO), Melbourne, Australia, 5 April 2006.

7. May, 2006 – “Fabrication and Repair with High Temperature Materials by Laser Powder Deposition”, Sears, J. W., Presented at AeroMat, Seattle, WA. 15-18 May 2006.

8. June, 2006 – “Developments in Hard Metal Surfaces for Industrial Applications through Laser Powder Deposition”, Sears, J.W., Costello, A., Miller, S., and Wolff, M., Presented & Published at the PowderMet 2006, the MPIF International Conference on Powder Metallurgy & Particulate Materials, San Diego, CA, June 2006.

9. September, 2006 – “Material solutions for the Improvement of High temperature Wear Characteristics of Industrial Tools and Dies by Laser Powder Deposition”, Roalstad, J., Bhattacharya, S. Howard, S.M. Costello, A., and Sear, J. W., Presented and Published a the 2006 Advanced Laser Applications Conference & Exposition (ALAC 2006), Novi, MI, 18-21 September 2006.

10. “Hard, Wear Resistant Metal Surfaces for Industrial Applications through Laser Powder Deposition”, Miller, S., Wolff, M., Costello, A., and Sears, J. W., Presented and Published at the 2006 Powder Metallurgy World Congress and Exhibition, Busan, Korea, 24-28 September 2006.

11. October, 2006 – “Improving Metal Forming Tools and Dies through Additive Manufacturing” Sears, J. W., Costello, A., Roalstad. J., Bhattacharya, S. and Howard, S., Presented at the Material Science & Technology 2006 Conference and Exhibition (MS&T ’06) Cincinnati, OH 15-19 October 2006.

12. November, 2006 – “Hard, Wear Resistant Metal Surfaces for Industrial Applications through Laser Powder Deposition”, Sears, J. W., Costello, A., Roalstad, J., Bhattacharya, S. and Howard, S., at the 2006 International Conference on Applications in Lasers and Electro-Optics (ICALEO), Scottsdale, AZ, October 30 – November 2, 2006.

7.0 Project Publications / Presentations (cont.)

13. January, 2007 – "Characterization of A Cobalt-Based Powder Alloy Laser Deposited on H-13 Hot Die Forging Tools", by Sudip Bhattacharya, Jerrod Roalstad, Stanley M. Howard, Aaron Costello, and James W. Sears, presented at the 2007 TMS Annual Meeting, Orlando, FL.

14. September, 2007 – "Issues Related to Laser Powder Deposition for Surface Modification of Industrial Tools and Dies". Advanced Laser Applications Conference (ALAC) Boston, MA, September 24-26, 2007.

8.0 References

1. Bhattacharya, S., et.al., "Improving the High Temperature Wear Characteristics of Industrial Tools and Dies using Functionally Graded Refractory Metals", Proceedings of the 2006 International Conference on Powder Metallurgy and Particulate Materials, San Diego, CA June 2006.

2. Bhattacharya, S., Costello, Howard A. S., and Sears, J.W., "*Development of Functionally Graded Materials for the Tooling and Die Industry by Laser Powder Deposition"*, Proceedings of the 2005 Conference on Powder Metallurgy and Particulate Materials, $PM^2TEC2005$, Montreal, Canada, June 2005,

3. J.W. Sears, "Direct Laser Powder Deposition - State of the Art", Powder Materials: Current Research and Industrial Practices, Proceedings of the 1999 Fall TMS Meeting, ed. by F.D.S. Marquis, November 1999, pp. 213-226.

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5. M. T. Ensz, et.al., "Critical Issues For Functionally Graded Material Deposition by Laser Engineered Net Shaping (LENS™)", Proc. of the 2002 Int. Conf. on Metal Powder Deposition for Rapid Manufacturing, San Antonio, TX, April 8-10, 2002. Ed. by MPIF, pp. 195-202.

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8. Wei Wei, et. al., "Microstructure Evolution and Stability of WC-18 wt.% Co under LENS™ Deposition", 2002 International Conference on Metal Powder Deposition for Rapid Manufacturing, San Antonio, TX, April 8-10, 2002, Published by Metal Powders Industry Federation (MPIF), pp 180-187.