U.S. Department of Energy
Energy Efficiency and Renewable Energy

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

Department of Energy – Industrial Technologies
Industrial Materials of the Future Program Review

Chicago, IL
June 3rd, 2005

DOE Project DE-FC36-04GO14036

CARPENTER Powder Products

Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

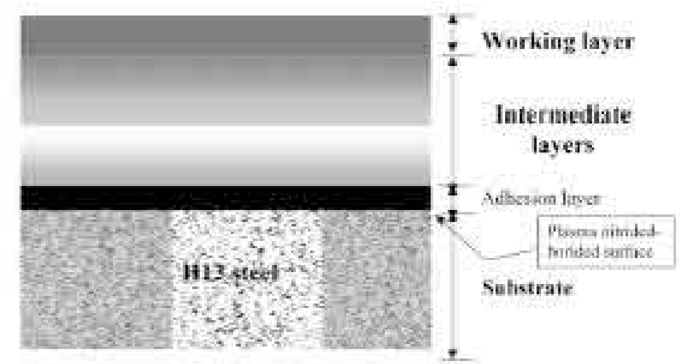
FGM for Industrial Tools & Dies (DE-FC36-04GO14036)

Goal: Development of functionally graded materials (FGM) for improved industrial process efficiencies and energy utilization.

Challenge: Development of robust FGM structures and fabrication processes that are reliable and economical to implement.

Benefits: A 120 trillion Btu/yr estimated reduction in energy consumption by 2020, and environmental emissions of over 2.3 million tons of CO_2 and 64 thousand tons of other emissions per year. Deploying FGM tooling is expected to have a $4.22 billion/yr savings to U.S. manufacturing industry.

Potential End-User Applications: Manufacturing tooling for the metal casting, glass, and forging industries.



Participants: Carpenter Powder Products, Pacific Northwest National Laboratory, South Dakota School of Mines & Technology, Metaldyne, GKN, THT Presses

FGM Project Team Members

Group	FGM Partners
Industry Participants	Carpenter Powder Products (*powder metallurgy*) Metaldyne (*forging & metal casting*) GKN Sinter Metals (*forging*) THT Presses (*metal casting*) Lancaster Glass*, Anchor Hocking* (*glass*)
University	South Dakota School of Mines & Technology
Government	Pacific Northwest National Laboratory DOE Golden Field Office

*Proposed addition in place of Techneglas

Energy Efficiency Barriers-Pathway Approach

Barriers

- Inefficient thermal management with most industrial manufacturing tools
- Historically tooling has been made from low-cost tool steels with inadequate durability

Pathways

- Development of functionally graded materials with enhanced thermal and chemical compatibility characteristics
- Prototype tooling and industry trials to validate and quantify energy savings and performance enhancements

Critical Metrics

- Durable and economical FGMs with >10x tool life enhancement
- Reduction in energy input needed for tooling and manufacturing processes

Benefits (est.)	2020
Energy Savings	120 trillion Btu
Cost Savings	$4.22 billion
Carbon Reduction	2.3 MTons

FGM Project Tasks

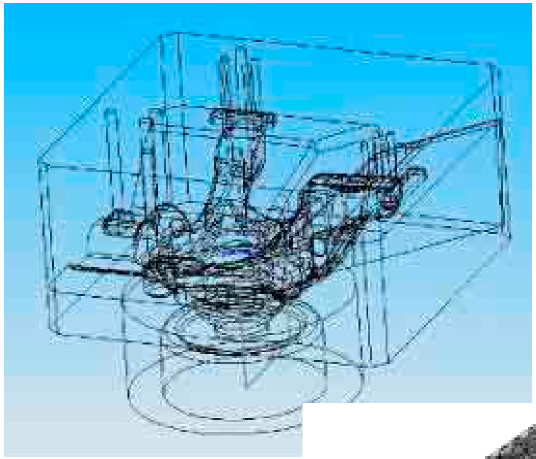
- Task I - Identify and Model Tooling Issues in Hot Forming Processes
  - Forging
  - Die Casting
  - Glass Forming
- Task II - Optimize LPD and SSDPC Processes for Manufacturing FGM Tooling
  - SSDPC Structural Analysis
  - LPD Structural Analysis
- Task III - Asses Performance of FGM Tools in an Industrial Environment
  - Manufacture FGM Tools
  - Production Trials
  - FGM Performance Assessment

Benchmarking and Tool Failure Analysis

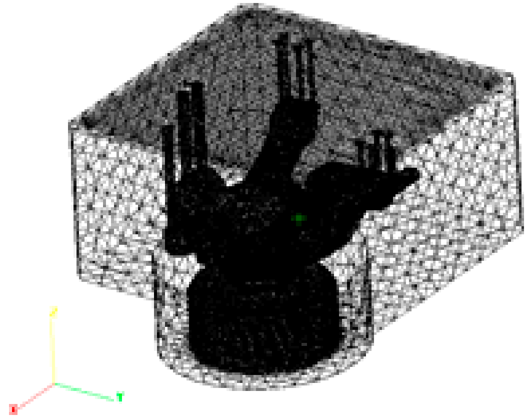
- Tooling Application Focus
  - Forging dies and punches
  - Die casting dies and shot-sleeves
  - Glass press forming dies
  - Extrusion die and mandrels
- Each application has its own unique modes of failure
  - Empirical analysis is necessary to benchmark performance and failures of current tools
  - Modeling is important for in-site into failure modes and prediction of FGM performance

Tool Failure Analysis: Casting Die Modeling

- FEA and other models
  - Die casting simulation for thermal profile prediction in die and shot-sleeve assembly
  - FEA stress analysis
  - Die and casting alloy reaction prediction via thermodynamic prediction and reaction mechanism calculations
- High production aluminum die casting dies from THT and Metaldyne currently being benchmarked

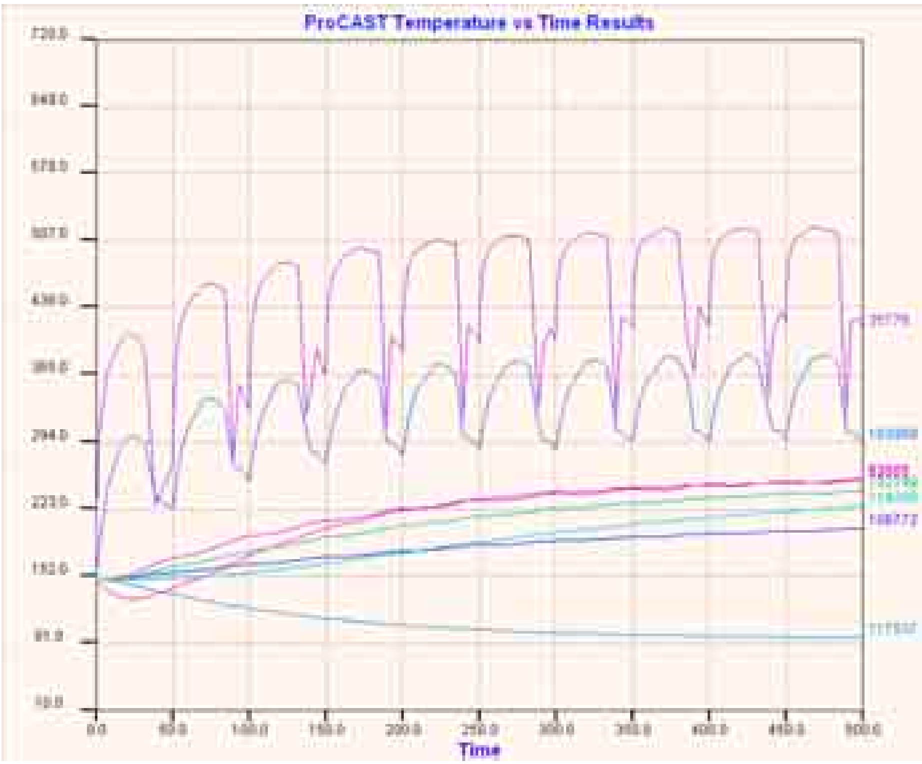


Solid Works model



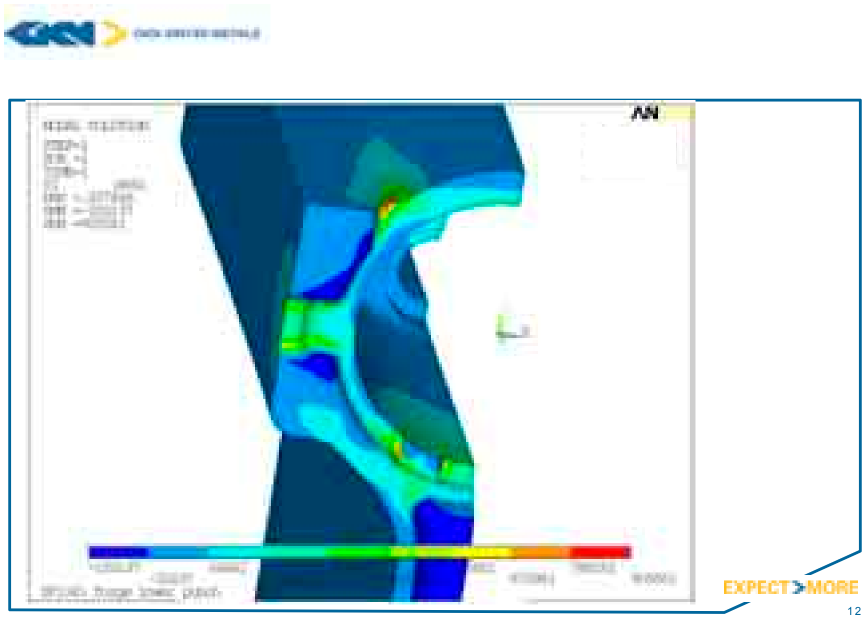
Die assembly me

Die Casting Die Surface Thermal Analysis



- Thermal die heat-up analysis
- Temperature vs. time is plotted for random sampling of nodes in the molds
- Significant temperature transients result from heat up by motel metal and rapid cool down of die surface by application of mold wash each cycle

Tool Failure Analysis: Forging Die Modeling



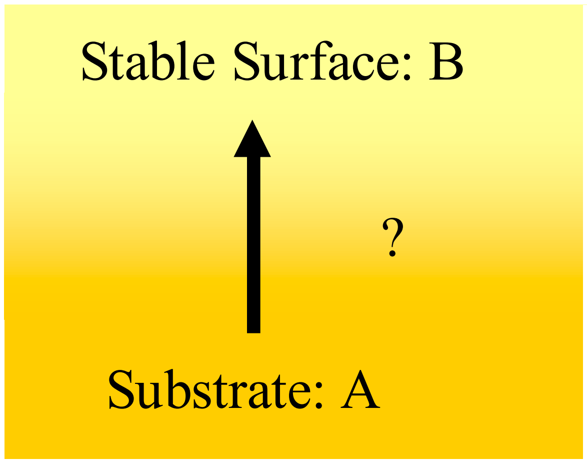
- FEA of stresses in die
- Results are used to determine high and low stressed areas, as well as indicators of potential crack initiation points
- Over-stressed and thermal softening are the primary issues with forging tools

Background on FGM Structures

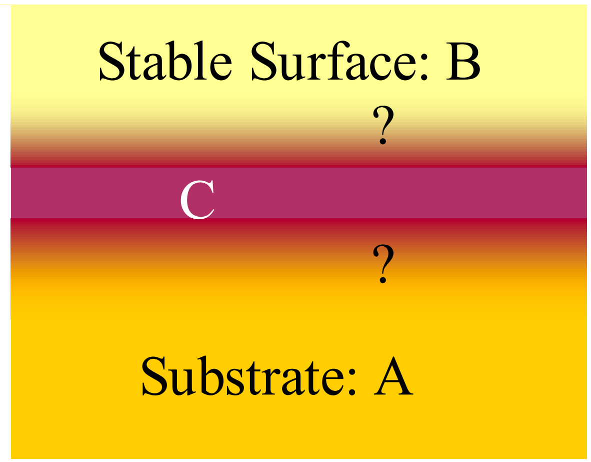
- No material has optimum properties for all tooling applications
- Monolithic materials of tool steels are typically used for most tooling applications, primarily due to low cost
- Trade-offs are typically made between, strength, hot toughness, and wear resistance
- The purpose for FGM is to create a bulk structure with optimum properties placed in localized regions where they are most needed
- Graded structure transition from one alloy or structure to another, and are selected based on operating environments

Functionally Graded Structures

Single Transition
A-B



Double Transition
A-C-B



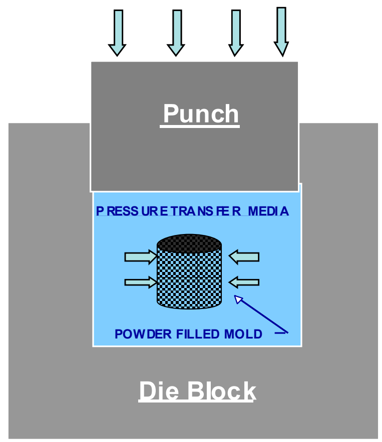
- Prediction of Graded Material Structure and Behavior
  - Existing Phase Diagrams
  - Computation and prediction of phase diagrams using ThermoCalc®
  - Non-Equilibrium alloy composition kinetic predictions using DICTRA®
  - Empirical trials

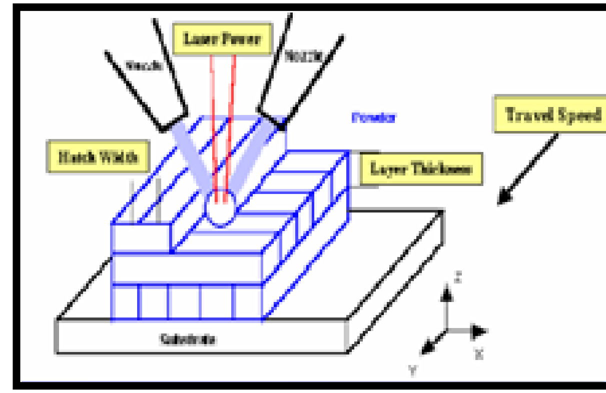
FGM Material Approach

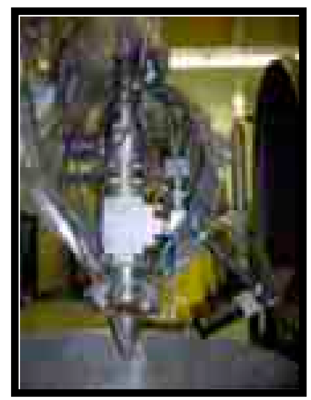
- Several material paths selected for graded structures from H13 tool steel substrate to enhanced surfaces
- Graded structures to:
  - Conventional alloys
  - Nickel based super alloys such as DM21 and Alloy 718 (High Temperature)
  - Cobalt based super alloys such as CCW & CCM+® (Chemical Resistance)
  - Individual elements and compounds, such as WC in high Ni-Cr Matrix (high surface wear resistance)

Task II: FGM Processing Methods

- Solid-State Dynamic Powder Compaction (SSDPC)







3kW Nd:YAG Laser Equipment

- Laser Powder Deposition (LPD)

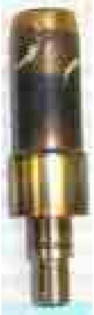
Benefits of FGM Processing Methods

- SSDPC Process Advantages
  - Produce fully dense components with minimal cycle time and cost
  - Increased strength over conventional PM processing
  - Powder and/or solid (discrete 2nd phases) combinations
  - Minimize potential debits of excessive diffusion between dissimilar metals as a result of short cycle time and high cooling rates
  - Near net shape capability
- LPD Process Advantages
  - Fabrication of true graded structures
  - Selective placement of unique structures, including structures with discrete insoluble 2nd phases
  - Ability to repair/convert existing tooling

Task I: Tool Failure Analysis Outline

- Metaldyne RO: Punch Nose, Intermediate Punch, Anvil, Shear Die
- Metaldyne Twinsburg: Aluminum Die Cast Inserts
- GKN: Connecting Rod - Open Die/Closed Die, Core Pin
- American Axle: Button Die, Button Die Holder, warm forging punch
- Chamberlain: Extrusion Tip
- S&J Technology: Glass forming mold



Tool Failure Analysis: Hot Forging Punch

wheel spindle

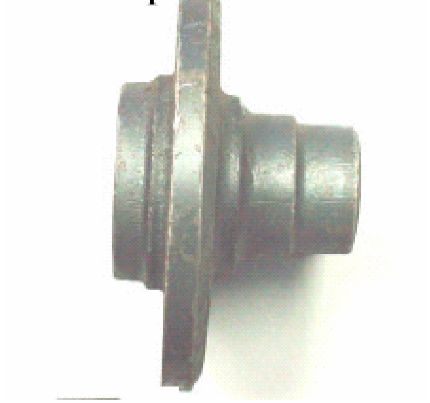
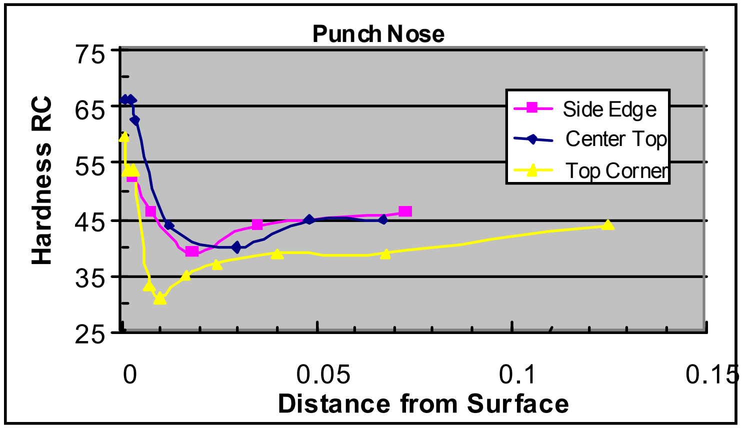


Figure 1: Microhardness Profile (conv. to RC)



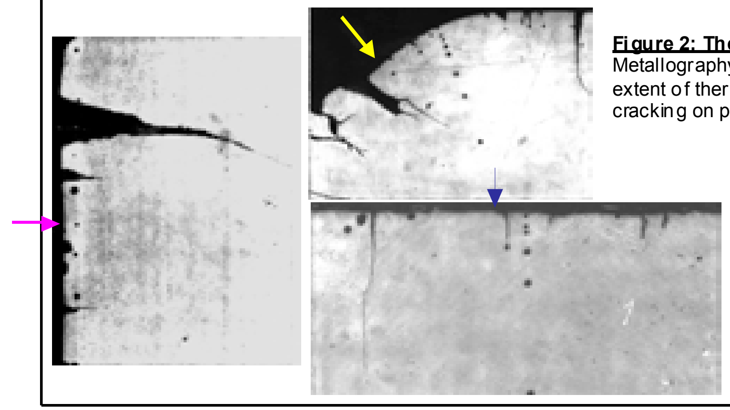


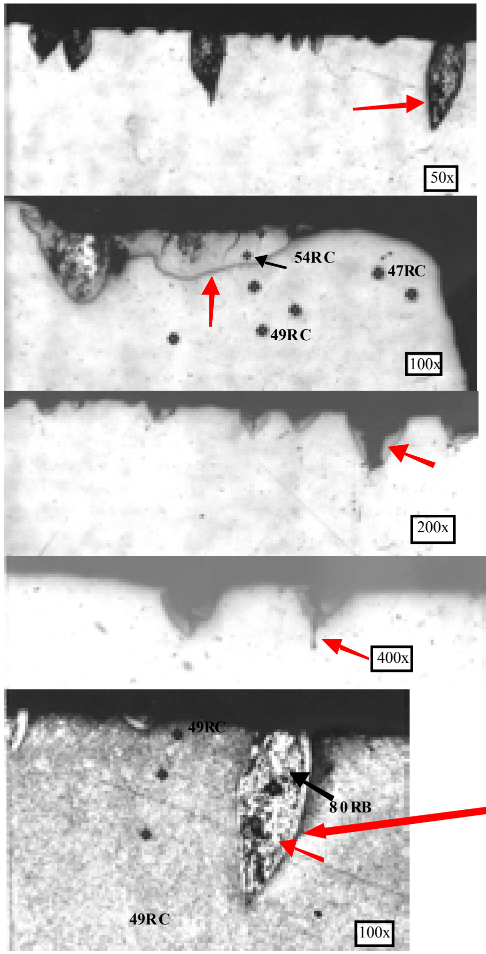
Figure 2: Thermal Fatigue
Metallography showing extent of thermal fatigue cracking on punch surface.

Tool Failure Analysis: Connecting Rod Punch

Crack Origin: OD

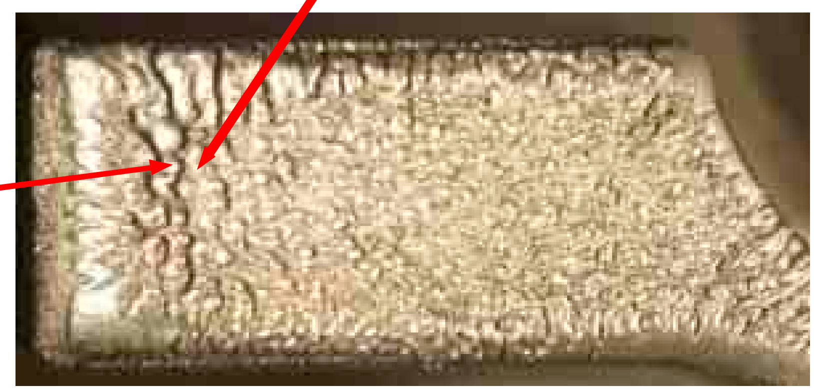
Wear lines

Tool Failure Analysis: Al Die Cast Insert



H13 Aluminum Die Cast Insert

- Metal reaction
- Brittle intermetallic phase
- Crack propagation
- Pullout/erosion



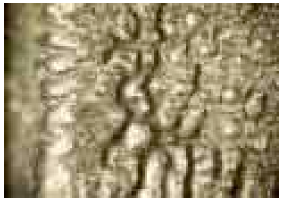
Summary: Tool Failure Analysis

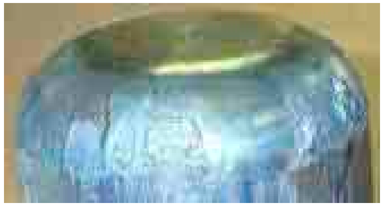
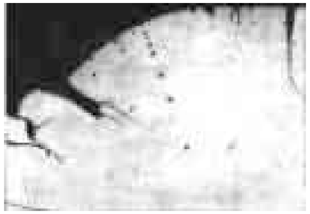
Conventional tool manufacturing processes exhibit:

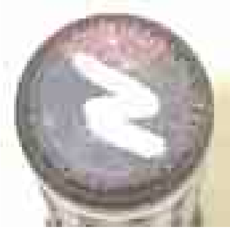
- Low material yields
- Significant machining time
- Extensive heat treatment cycles
- Long lead times
- High energy consumption

Tooling Issues:

- Heat checking
- Thermal Fatigue
- Wearing out of molds and dies
- Soldering
- Loss of hardness

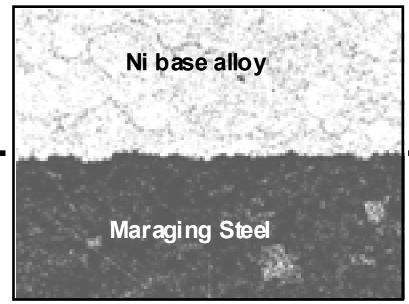



SSDPC Examples

Punch Nose



Blank

Core Pin
86,000 cycles

DM21 Nickel base alloy powder bonded to NiMark300 by SSDPC process

SSDPC Examples

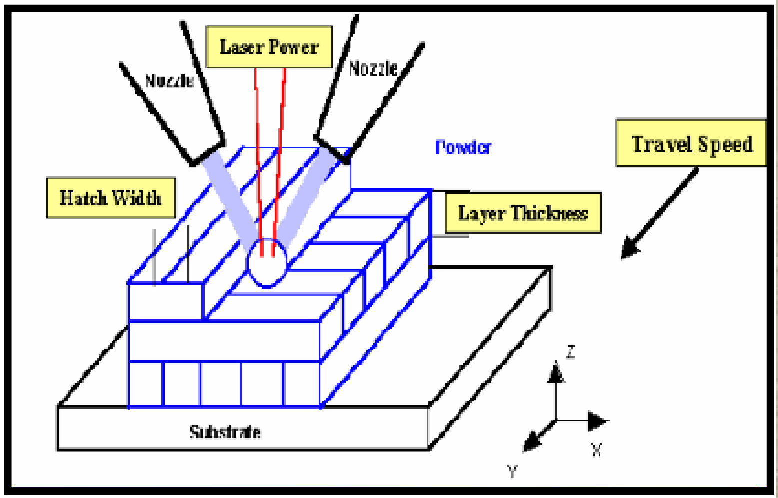
<u>Bimetal Approaches</u>

DM21 -Nickel base superalloy

CCM+ - Cobalt based superalloy

NiMark 200,300 - Maraging steel

LPD Examples

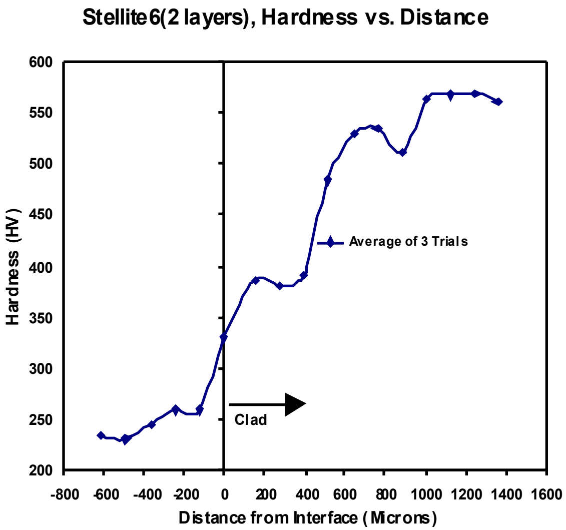


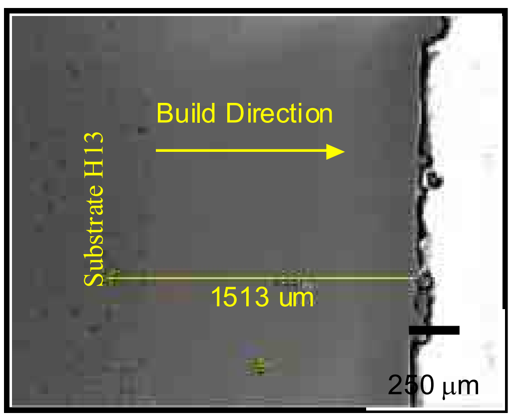
Laser Clad H13 Anvils

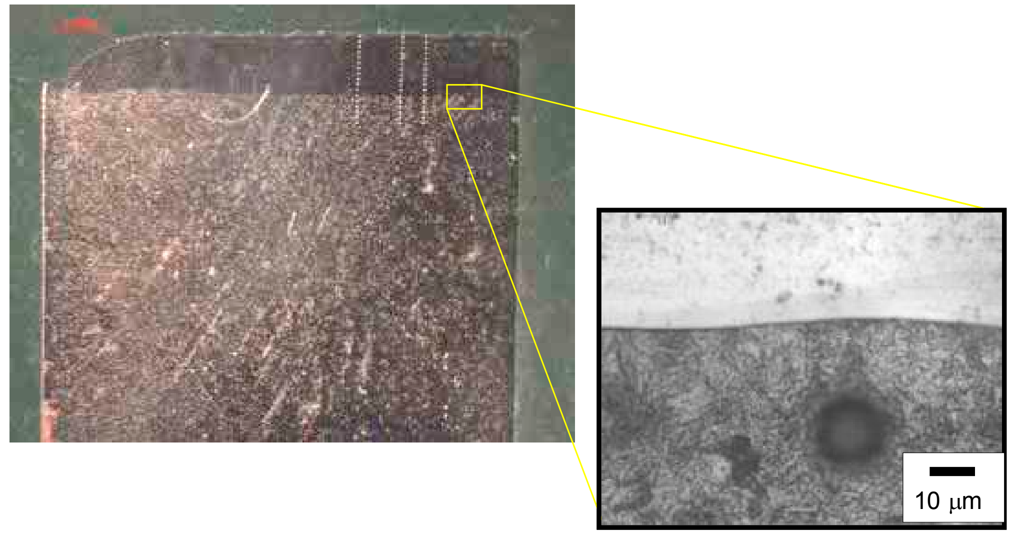
1) NiTung60 2) NiTung 60

3) DM21 3) CCW

Stellite® Alloy 6 Deposited on H13







H13/ST 6 Interface

Future Plans FY06

- Continue Monolithic Material Benchmarking Trials
  - Metaldyne Die Cast Inserts: CCM+ and Aermet
  - GKN Open/Closed Die: Aermet
- Manufacture and evaluate FGM tooling properties
- LDP FGM Fabricated Structures
  - Metaldyne Anvil: NiTung60, CCW+ DM21
- SSDPC Fabricated Tools
  - Bimetal Approaches:
    - DM21, CCM+, H13, NiMark300, NiTung60
  - Discontinuous reinforced dispersions - NiTung60
- Integrate a glass forming company into the project

FGM Project Task Status & Finance Details Supplementary Slides

FGM Project Task Status

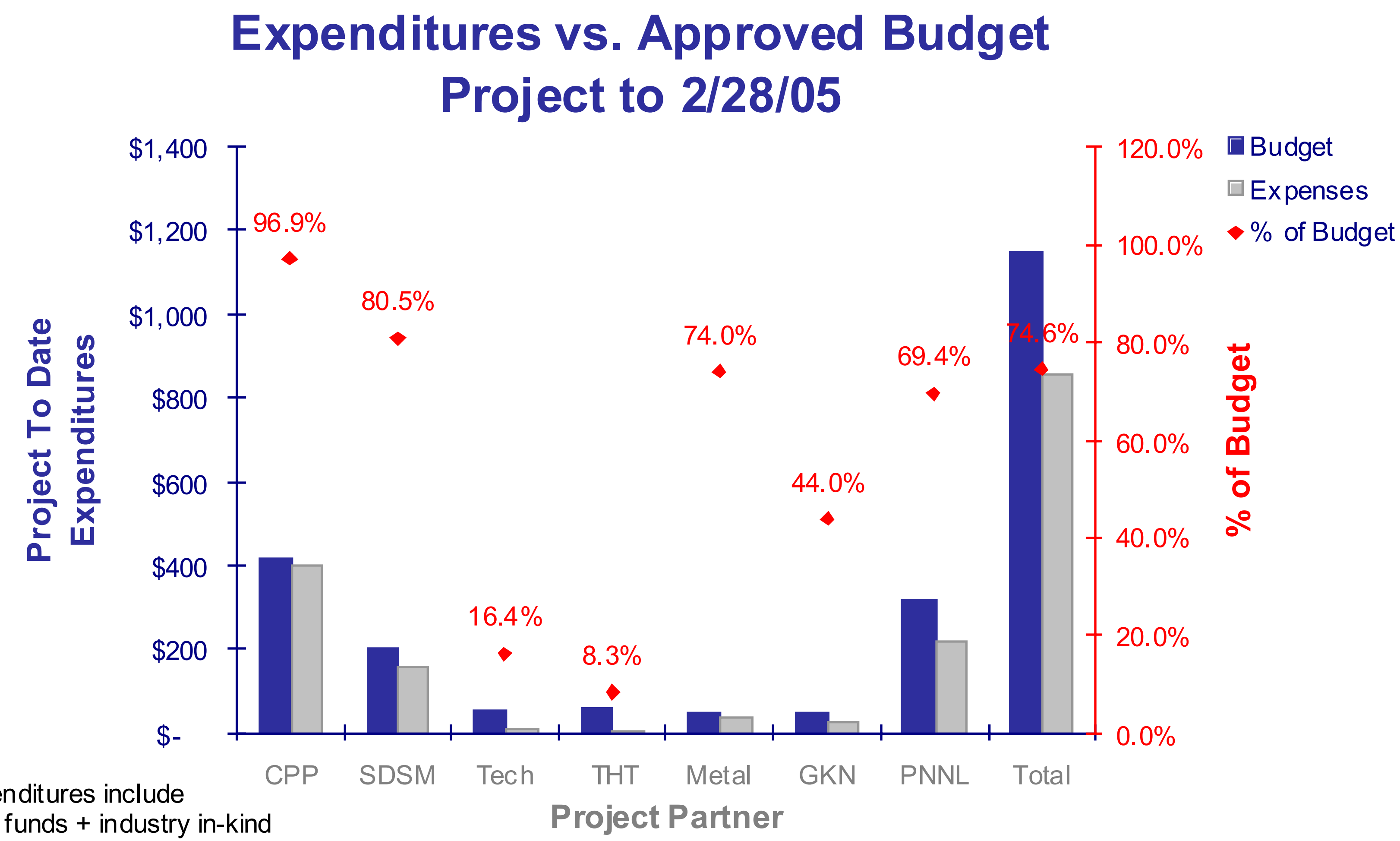
Task	Milestones	Start Date	Completion Date	Status
I	**Identify and Model Tooling Issues in Hot Forming Processes**	3/1/04	6/30/05	60%
	1) Identify Tool Problems			
	a) Review hot forming tooling requirements	3/1/04	8/31/04	100%
	b) Identify FGM systems opportunities	5/31/04	3/31/05	65%
	2) Model Hot Forming Operations			
	a) Forging & Die Casting	5/31/04	6/30/05	30%
	b) Glass Press Forming	7/30/04	6/30/05	0%
II	**Optimize LPD and SSDPC Processes for Manufacturing FGM Tooling**	4/30/04	6/30/06	5%
	1) LPD			
	a) Use LPD to produce FGM tooling	7/30/04	8/31/05	15%
	2) SSDPC			
	a) Optimize key variables of process	4/30/04	12/31/05	15%
	b) Characterize SSDPC FGM properties and structures	2/28/05	6/30/06	0%
III	**Assess Performance of FGM Tools in an Industrial Environment**	7/31/04	2/28/07	2%
	1) Evaluate FGM materials			
	a) Establish robustness of LPD and SSDPC Processes	6/30/05	6/30/06	0%
	2) Industry Prototyping			
	a) Manufacture Prototype tools			
	b) Assess FGM materials performance for economic and	7/31/04	12/31/06	10%
	energy savings	6/30/05	2/28/07	0%

FGM Project Financial Review – DOE Funds

Year	Requested* Budget	Approved* Funding	Project Spending
3/1/04 to 2/28/05	$760k	$591k	$616k
3/1/05 to 2/28/06	$910k	$705k	---------
3/1/06 to 2/28/07	$780k	---------	---------
Totals	$2450k	$1296k	$616k

*Fiscal Year (Oct.-Sept.)

FGM Project Financial Review



*Expenditures include DOE funds + industry in-kind

FGM Project Financial Review