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ADMINISTRATIVE INFORMATION

1. **Project Name:** Development of Functionally Graded Material for Manufacturing Tools and Dies and Industrial Processing Equipment.

2. **Lead Organization:**
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5. **Date Project Initiated:** March 31, 2004

6. **Expected Completion Date:** September 30, 2007

PROJECT RATIONALE AND STRATEGY

7. **Project Objective:** While materials currently used for tools, dies and equipment in the hot forming industries have performed adequately for many years, they represent a weak link in regards to current day objectives of increasing manufacturing efficiency and reducing energy consumption. In many hot forming applications, the use of monolithic alloyed materials have reached the limit of their usefulness. A potential solution lies in the development of functionally graded materials (FGM) that can be designed to overcome the shortcomings of existing materials used in the hot forming industries. The DOE FGM project is a unique combination of a multidisciplined team with basic science capabilities and manufacturing technology expertise. The project goal is to implement FGM solutions into manufacturing environments associated with hot forming applications in the forging, die casting and glass industries. Success will better enable these basic and mature U.S. industries to maintain or gain a competitive edge in a global market.

8. **Technical Barrier(s) Being Addressed:** Project technical barriers are associated with the lack of current materials that can withstand the high temperature, stress, corrosive and erosive environment

of many hot shape forming applications. Issues include low strength at elevated temperatures, thermal cracking and fatigue, high energy and life cycle costs and poor erosion and chemical compatibility properties. Solving these barriers requires a new approach to materials selection and the manufacturing of these materials with advanced powder metallurgy materials and processing technology.

9. **Project Pathway: Initially** two advanced powder metallurgy forming processes will be pursued to develop functionally graded materials (FGM) to meet the rigorous environment of hot forming applications and significantly reduce energy usage and manufacturing costs. This goal will be accomplished by identifying current and serious material issues with project partners from the forging, die casting and glass industries. FGM materials for tools and processing equipment will be custom designed and manufactured for testing in a commercial environment. Performance, energy usage and economics will be analyzed to determine which materials and fabrication process can be successfully implemented by the project's industrial partners.

10. **Critical Metrics:** Materials currently used for tools, dies and other processing equipment in hot forming operations have been in existence for over fifty years. The cost of energy used is high and production efficiency low because of the inadequacies of these materials. The targets for success in this project is to (1) reduce energy consumption by 25 percent, (2) increase tooling lives by a minimum of five times that of current materials and (3) provide a globally competitive edge to U.S. forging, die casting and glass manufacturing industries.

PROJECT PLANS AND PROGRESS

11. **Past Accomplishments:** Efforts to date on the project have been focused on Task I, Identification and Modeling of Tooling Issues in Hot Forming Processes, and to a limited extent on Task II, Optimization of the Laser process Deposition (LPD) and Solid State Dynamic Powder Consolidation (SSDPC) Process for Manufacturing FGM Tools. Based on team expertise, the Task I analysis of tool failures in hot forming applications has been lead by CPP, Metaldyne and GKN with significant help from PNNL. In the area of modeling, efforts have been lead by PNNL with help from industrial partners Metaldyne, GKN and THT Presses. For Task II, preliminary trials have been initiated by SDSMT and CPP to further explore the LPD and SSDPC processes and to product sample tooling for preliminary testing by Metaldyne and GKN.

    Results to date show that tool failures in hot forming processes are directly related to the boundary conditions for specific applications. Temperature, stress, wear and chemical reactivity that involve both the tooling and the hot formed component can result in premature tool failures. In addition, cycle time, lubrication and coolants can significantly affect the performance of tools in hot forming processes. Different types of failures were observed on tooling supplied by project partners Metaldyne and GKN. High speed forging of a Metaldyne wheel spindle with standard tooling resulted in tool failure by thermal fatigue and some thermal softening. Failure of a lower die in the forging of a connecting rod at GKN was due primarily to high mechanical stress and wear. A core pin used in the same GKN application failed because of thermal softening. In an aluminum die casting application at Metaldyne, tool failure was associated with chemical reactivity at the die cavity entry and with thermal fatigue and thermal softening in other parts of very complex tooling. A variation in tool failure modes was observed in other tools and that solutions to these failures will be unique for each hot forming process.

    Preliminary modeling efforts, lead by PNNL, have been initiated on the die casting and glass forming processes. THT Presses has supplied a solid model of the die casting process, which is being combined with ProCAST, a finite element casting simulation software. A coupled fluid-thermal analysis has been demonstrated. Glass forming models are available at PNNL and will be used to address internal radiation, thermal conductivity and thermal stress in glass forming operations. Preliminary modeling of hot die forging by Metaldyne and GKN is being shared with PNNL for specific applications.

As a result of the failure analyses conducted or standard hot die forge tooling and initial modeling studies, a series of monolithic tools were selected and manufactured to determine if the failure modes in specific applications at Metaldyne and GKN could be altered or alleviated. A tool material with significantly higher elevated temperature strength was used in the forging of the previously noted wheel spindle and provided a tool life up to 2X that of standard tooling. Better, but not meeting the project objective of 5X standard tooling. A high strength, high toughness tool material was utilized on a lower die in GKN's forging of connecting rods. The new material eliminated the cracking problems that occur with standard tooling, but did not solve the wear problem exhibited by standard tooling. In a die casting trial at Metaldyne, new materials have helped the chemical reactivity problem in this application, but failed to solve the thermal cracking problem. Each trial, however, has provided a direction toward the design of FGM materials for these applications.

Basic studies have been initiated by SDSMT and CPP to explore the variables of the LPD and SSDPC processes as a prelude to the manufacture of FGM materials. SDSMT has used the LPD process to study binary pairs and to clad iron base substrates. Bonded interfaces have been studied metallographically and by interface hardness traverses. DICTRA helped identify phases present in the interfaces and ThermoCalc was used to compute equilibrium reaction products. Results show that alloys are more easily clad and bonded to iron base alloy substrates than pure elements. CPP has studied the SSDPC process variables and established parameters for manufacturing both monolithic and FGM bi-metal tooling. As a result of the SDSMT and CPP studies, a series of sample FGM tools have been or are being manufactured for initial forging trials at Metaldyne and GKN.

12. Future Plans:

Date	Milestone/Deliverable	Partner Activities
6/30/05	Task I – Identify and Model Tooling Issues in Hot Forming Processes Identify Tool Problems & Requirement Identify FGM Systems Opportunities Model Hot Forming Applications	 CPP, PNNL, Metaldyne, GKN, THT CPP, PNNL, SDSMT PNNL, Metaldyne, GKN, THT
8/30/06	Task II – Optimize LPD and SSDPC Processes for Manufacturing FGM Tools Optimize Key LPD Variables Optimize Key SSDPC Variables Manufacturing FGM Sample Tooling Characterize FGM Structures & Properties	 SDSMT, PNNL CPP, PNNL CPP, SDSMT, PNNL CPP, SDSMT, PNNL
2/28/07	Task III – Assess FGM Tool Performance in an Industrial Environment Select and Evaluate FGM Tooling Manufacture Prototype Tools Conduct Full Scale Hot Forming Trials Assess FGM Performance for Energy/Economic Savings	 CPP, PNNL, SDSMT CP, SDSMT Metaldyne, GKN, THT CPP, PNNL

13. **Project Changes:** Techneglas, the glass-forming partner in the project withdrew from the FGM team on this DOE Cooperative Agreement. Unable to complete in the global television picture tube market, this glass forming company closed all U.S. plants associated with this market. Efforts to fill this void have been initiated in order to find another glass forming company that embraces the goals and objective of the FGM project team. Holophane, a major manufacturer of glass luminates, has been identified as a potential partner in the project. Initial discussion indicates a mutual interest in the project. Preparation of a project work statement, agreement on terms and conditions and a cost sharing agreement are underway prior to Holophane becoming an official partner of the FGM team. No other project changes or problems are foreseen at the present time.

14. **Commercialization Potential, Plans, and Activities:** The end use applications for the technology proposed in this project include tools, die and molds in hot forging metals, die casting molten metals and press forming molten glass. Current materials are a bottleneck to increasing the manufacturing efficiency in these applications. Current plans are to develop advanced FGM tooling materials for hot forging automotive steel components, die casting aluminum and magnesium parts and molding glass luminates. Two advanced powder metallurgy consolidation technologies will be used to manufacture FGM's which will be designed to meet requirements for (1) tooling for two of the largest producers of forged automotive parts in the world, (2) tooling for both a major manufacturer and user of die casting equipment and (3) molds for one of the largest glass luminate manufacturers in North America. It is expected that the FGM tool and die materials and fabrication methods developed as part of this project will be applicable to other manufacturing sectors as well. The technology will be implemented by committed project participants and disseminated throughout the U.S. industry as proven technology for reducing energy consumption and reducing manufacturing costs.

15. **Patents, Publications, Presentations:** A public relations announcement of the DOE Cooperative Agreement award DE-FC36-04GO14036 describing goals and objectives along with participating organizations was forwarded to approximately 100 trade journals and magazines during the first quarter of the project. Subsequently, Fabricating and Manufacturing magazine did an online story of the FGM project in September 2004. The article, entitled "Thinking Ahead, Meeting the Demands of Tomorrow" extolled the virtues of a federal-private partnership to develop advanced tooling that would result in a reduction of manufacturing energy costs while improving the competitiveness of American companies involved in the hot forming of metals and glass.

    One of the FGM project's principal subcontractors**,** 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 material to determine its effect on the surface shape and durability of FGM materials. An updated version of this presentation will be given a PM^{2}Tec 2005, the International Conference on Powder Metallurgy and Particulate Materials June 19-23 in Montreal, Canada.

    No patents at this point in time, have been applied for or granted as a result of this DOE Cooperative Agreement.