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OVERVIEW OF DOE's PROGRAMS ON ALUMINUM AND MAGNESIUM FOR AUTOMOTIVE APPLICATIONS

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Abstract

The US Department of Energy will present an update and review of its programs in aluminum and magnesium for automotive and heavy-duty vehicle applications. While the main programs focused on vehicle materials are in the Office of Transportation Technologies, contributing efforts will be described in the DOE Office of Industrial Technologies and the DOE Office of Energy Research. The presentation will discuss materials for body/chassis and power train, and will highlight the considerable synergy among the efforts. The bulk of the effort is on castings, sheet, and alloys with a smaller focus on metal matrix composites. Cost reduction and energy savings are the overriding themes of the programs.

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Introduction

Because of their heavy dependence on petroleum, automotive and heavy-duty land vehicles have been foci of research and development by the Department of Energy (DOE) ever since its inception in 1979. In the 1980's DOE's main interest was on increasing the efficiencies of the power trains of such vehicles, but since the early 1990's there has also been increasing interest in light weighting (without downsizing) the body and chassis as well. This latter interest accelerated with the formation in late 1993 and early 1994 of the Partnership for a New Generation of Vehicles (PNGV), a joint effort between the U.S. Government and Chrysler (now part of Daimler Chrysler), Ford and General Motors. Aluminum and magnesium have been parts of that interest, along with polymeric- and metal-matrix composites. This paper presents an update and review of DOE's current R&D efforts in aluminum and magnesium for automotive and heavy-duty land vehicle applications. Those efforts may be divided into issues of production of primary metal, sheet formation and fabrication, casting, metal-matrix composites, recycling and basic research, and this review is subdivided accordingly.

Organization

The bulk of the R&D focused on land vehicle materials is in the DOE Office of Transportation Technologies (OTT), identified in Figure 1. OTT's primary mission is reduction of the use of imported petroleum-derived fuels and decrease in emissions from all fuel-type land vehicles.

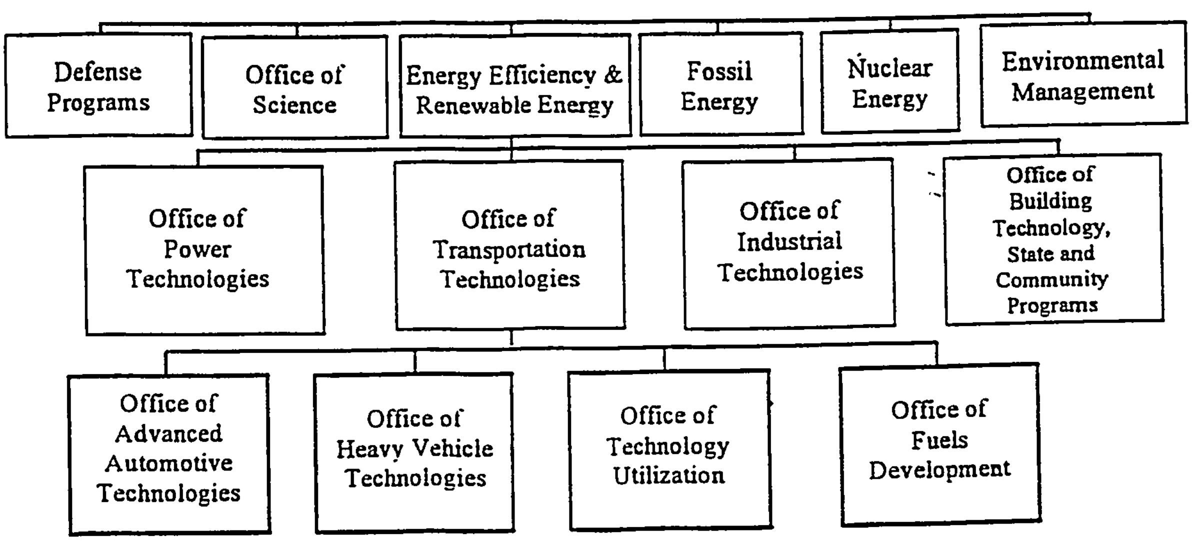

Figure 1. Simplified Organization Chart of the U.S. Dept. Of Energy.

OTT's Office of Advanced Automotive Technologies (OAAT) focuses on automotive applications. Its efforts are directed at lightweight structural materials for body and chassis applications as well as materials for advanced propulsion systems. OAAT is working with the automotive industry through the PNGV and the U.S. Automotive Materials Partnership (USAMP) to develop by 2004 production-ready, mid-sized automobiles vehicles that are 40% lighter than and achieve three times the fuel economy of current vehicles while maintaining comparable performance, comfort, safety, cost and recyclability. OAAT has recently published a long range plan for its R&D (1).

OTT's Office of Heavy Vehicle Technologies (OHVT) is working with the suppliers of diesel engines and representatives of the U.S. trucking industry to develop more fuel-efficient, heavy-duty vehicles. OHVT's efforts are focused primarily on high-strength, weight reduction materials for heavy-duty trucks and materials for more efficient engines.

OTT also oversees the Northwest Alliance for Transportation Technologies (NATT), an effort managed by Battelle's Pacific Northwest National laboratory (PNNL) and aimed at increasing the presence of the automotive and truck manufacturing industry in the northwest U.S. The descriptions below of NATT's aluminum and magnesium projects are taken from a recent review (2).

DOE's Office of Industrial Technologies (OIT) works with the aluminum and magnesium industries to identify and develop improved technologies aimed at reducing the energy consumed in the production of the primary metals. Some activities are also focused on improved or alternate processing technologies which result in reduced use of energy and a corresponding reduction in emissions from that processing. The relevance of OIT's projects to land-use vehicles is mainly in reducing the costs of the primary metals.

The Office of Science (formerly the Office of Energy Research) supports R&D efforts to develop a better fundamental understanding of materials, materials properties, and the fundamental aspects of materials processing and process modeling which will contribute to the more timely applications of lightweight materials.

Primary Metal

Through the leadership of the Aluminum Association and OIT, a detailed technology roadmap (3) outlining the requirements for achieving aluminum industry goals and a focused R&D agenda has been developed. High priority research needs identified in that roadmap are currently being funded by OIT in the area of primary and secondary aluminum production, recycling and near net-shape forming processes. Several multi-partner research teams are currently working to develop inert anode and wettable cathode systems for more energy-efficient, productive and environmentally friendly primary aluminum production. One research effort is developing methods to recycle aluminum saltcake constituents. Another is developing alternative technology which will reduce or eliminate the need for saltcake in selected secondary markets. Work is also underway or planned for advanced scrap separation and remelting processes, and conversion of processing waste to useful products. Semi-solid forming is being investigated through an industry/university/national laboratory collaboration.

NATT is sponsoring two projects to reduce the cost of primary magnesium. Alcoa is developing an advanced process involving thermal reduction of calcium magnesium carbonate. This process offers the possibility of continuous slag tapping and magnesium condensation. EIMEx, L.L.C. is evaluating a novel electrolytic membrane technology previously demonstrated for production of primary forms of other metals. This effort will determine if direct reduction of MgO is feasible and, if so, at what rate the reaction will proceed.

Sheet Formation and Fabrication

One of the highest priority projects sponsored by OAAT focuses on development of low-cost, continuously-cast aluminum alloy sheet. Since aluminum sheet can find application in many body and chassis components, there is a need to implement new manufacturing processes for sheet aluminum that significantly lowers the cost compared to existing production methods. Such methods depend on the use of thin-sheet casting techniques combined with carefully controlled rolling and annealing. However, starting with thin sheets severely limits the amount of variation which can be achieved in the sheet rolling process, as compared to the breakdown of directly-cast ingots. This means that every process step must be optimized in order to achieve the best combination of sheet properties. The objective of the project is to meet quality standards for the aluminum alloy sheet product at a lower cost by optimization of the crystallographic texture. The three key components, casting, rolling, and annealing, require modeling of the physical parameters, such as fluid flow, plastic deformation and heat flow. The intent is to capture the microstructural evolution during each step into the current modeling tools. Experimental activities include casting aluminum automotive alloy sheet by belt and twin roll casting techniques, characterizing properties and structure of the sheet to gain an understanding of the relationship of structure to processing, and optimizing composition and processing of selected sheet production methods.

In another OAAT project, a team led by Alcoa is investigating technologies leading to improvements in the conventional automotive sheet forming/stamping process and to develop alternative economical forming processes and/or methods for automotive component manufacturing which offer weight reduction opportunities and enable aluminum to become more cost effective. The goal of the process/press optimization portion of the activity is to improve the aluminum stamping process through the development of a method for controlling the flow of metal into a tooling cavity during the stamping process through the application of binder load distribution techniques, active draw bead and open loop control of the process. Improved control of the forming process will expand the operating "window" of acceptable process parameters, making it more robust, reducing production problems, reducing process development time, and improving quality. A parallel activity is aimed at evaluating the economic and functional improvements in forming aluminum at elevated temperatures. Properly designed and implemented warm forming techniques have the potential to improve both the intrinsic and extrinsic formability of aluminum, permit aluminum to be substituted for many steel body components with rather minor modifications of the tooling, and increase the ability of the materials to produce more complex shapes.

The goal of another OAAT project is to optimize the alloy chemistry and processing procedures of a non-heat-treatable 5XXX aluminum alloy to meet a spectrum of requirements and, in so doing, result in a lower production cost, provide a broad supply base, and take advantage of the production experience of the beverage can market. Presently, only heat-treatable aluminum alloys are used in the automotive industry for exterior body panels, due to their high yield strength for dent resistance, and their excellent surface appearance. However, these alloys must be formed in the T-4 condition and then age hardened while the paint is curing to achieve higher in-service strength. Less expensive non-heat-treatable 5XXX aluminum alloys have been used for structural components in automobiles and for interior panels where surface appearance and dent resistance are not critical. To date several 25,000 lb. ingots of non-heat-treatable aluminum alloys have been cast and successfully processed and rolled to finished thickness for stamping trials by automotive and trucking industry suppliers. Economic models indicate that production costs for non-heat-treatable alloys would be 10% less than those for heat-treated grades.

NATT is currently funding a Cooperative Research and Development Agreement (CRADA) effort between Reynolds Metals Company and Pacific Northwest National Laboratory (PNNL) to develop aluminum tailor welded blank (TWB) technology for automotive applications. Specifically, this CRADA project focuses on the development of a comprehensive forming, performance, and durability database that will allow the automotive designer to apply aluminum tailored blanks in a cost-effective manner. Tailor welded blank technology typically involves the joining of two or more sheets of different thickness, and in some cases sheets having different alloy composition. Aluminum TWB's allow the designer to use thicker aluminum sheet in areas where it is needed (such as door hinges and lock areas), while using thinner sheet for the rest of the part to save weight and cost. In the TWB process, a continuous welding process (such as gas-tungsten arc welding, laser welding or electron beam welding) joins the different thickness sheets prior to stamping the part. In order to apply aluminum TWB's to complex parts such as inner door panels, automotive designers require significant formability, mechanical performance, and durability data in order to optimize weight, structural performance, crashworthiness, and overall cost. PNNL and Reynolds are developing the materials property and performance database for aluminum TWB's using a wide range of mechanical testing and characterization methods. Primary issues that are being addressed by the project include mechanical properties of the welded panels, corrosion behavior, and toughness characteristics and fatigue properties of the welded blanks subjected to typical forming strains and automotive paint bake cycles. Through this comprehensive testing and evaluation program, Reynolds will develop the forming limit data that will assist the design of panels and structures, and will be able to provide the performance and durability data required for introduction into high-volume automotive applications.

Casting

In order to improve the quality of aluminum castings for automotive applications, a team comprised of the USAMP, several national laboratories, universities, and suppliers to the automotive industry is collaborating on an OAAT project to develop information and technology to optimize the design and improve the product capabilities for light weight, high integrity, cast structural components. The project is focussed on the following technologies: 1.) a concise and flexible automotive application design manual useful in implementing light metal structural castings; 2.) a comprehensive light metal cast material database; 3,) math based fill and solidification models that will allow the user to model cast microstructural features that significantly influence material properties; 4.) a simulation tool that can accurately predict both tensile and cyclic material behavior of cast light metal components; and 5.) casting sensor technology which improves casting process control and the NDE capability required to ensure the high integrity of cast components. Project success will allow industry to produce castings which are lighter in weight, closer to near net shape, exhibit higher strength and ductility with a narrow spread in property variation.

A NATT project has been initiated by a team comprised of members of the Big Three automotive producers and several national laboratories to improve the energy efficiency and cost effectiveness of large scale aluminum automotive die castings by extending die life and reducing die wear. The objective will be achieved by completing the following three primary tasks. In Task 1 the team identified and characterized the fundamental thermal, chemical, mechanical, and metallurgical mechanisms that result in die wear and die failure. The results have been summarized in a report together with a summary of related past and present efforts aimed at minimizing die wear. The goal of Task 2 is to identify, evaluate, and apply appropriate thermal models to describe the heat transfer behavior during the die casting cycle. Task 3 will focus on the identification and evaluation of surface modification, coatings, and/or base material modifications that have the potential to reduce die wear. Successful completion of the project has the potential to extend die life by a factor of two. This increased die life will have a direct effect on the cost of manufacture of aluminum components and on the quality of the components.

An OAAT project is focused on developing the materials processing and design technologies required to reduce the die development time for metal mold processes from twelve to three months. Die castings of aluminum and magnesium parts are used as example processes. This involves process development in support of rapid, net-shape die fabrication in the areas of free-form fabrication and net-shape casting. Some of the candidate technologies being investigated are: investment cast tools produced from a rapidly-prototyped pattern, rapidly machined tooling, and hot isostatically-generated tooling. A die insert fabricated using investment cast tooling fabricated by rapid prototyping methods was evaluated with a 3000 piece die casting run of an aluminum torque converter. The tooling was constructed in 7 ½ weeks, a significant reduction in lead time compared to conventional approaches, at a much reduced cost.

A major development of an advanced casting process to produce ultra-large transportation components is being supported by OHVT for the purpose of producing lower cost, lightweight vehicles. Cost benefits are realized by producing a single large component and substantially reducing the number of parts and the number of corresponding assembly steps. The process is targeted toward high-volume production, capable of yielding over 100,000 units per year from a single caster machine. The process will employ a vertical permanent mold casting machine having multiple injection ports operating at moderate pressure. Very early in the development, an inner panel of a minivan liftgate was selected as the product component to demonstrate process capability. A substantial iterative effort was conducted in developing the design. This design resulted in reduction from eleven components (current steel design) to one, while achieving approximately 35% weight reduction. Successful simulations have been used to evaluate part filling, operation of the injector system, and to resolve specification for the caster machine and the supporting hardware. The caster is currently being installed and trial casting runs are scheduled for May 1999.

With OHVT support, an industry-national laboratory team has successfully collaborated in the optimization of a new casting process called Metal Compression Forming (MCF) to produce an aluminum 356 alloy motor mount bracket. The MCF process is a variant of the squeeze casting process. The newly developed process represents a novel approach to manufacturing aluminum and MMC components, has the low cycle times of die casting and imparts near forged mechanical properties. The use of casting and solidification models of the filling of the die cavity and the solidification of the part and determination of the thermophysical properties for the alloy were crucial to the development of the optimum process parameters for the production of a sound part. Properties of prototyped parts compare favorably with those of forgings and will allow designers to specify lower cost castings over forgings. The substitution of a cast aluminum component is expected to result in a reduction of approximately 1 lb. per vehicle (compared to cast iron components) and to offer a considerable cost savings over a forged aluminum part. The process is currently being evaluated for the manufacture of metal-matrix composite (MMC) components.

The use of aluminum castings could provide significant weight reductions in automotive suspension and chassis components. However, crashworthiness and other considerations require an adequate strength material with 15% or greater ductility, and such ductility has only been demonstrated with very expensive casting processes. Semi-solid metal (SSM) forming may, with development, provide such aluminum properties at low cost. SSM forming generally employs stirring of the metal to develop a unique, spherical microstructure, which affects the rheology of the solidifying alloy and improves its mechanical properties. The resultant material consists of about 10-60 percent solid and 40-90 percent liquid and is thixotropic in that the material becomes more fluid as a shear force is applied. The thixotropic nature of the semi-solid material is exploited by using pressure to force the material into a die at reasonably high speeds.

An OAAT project has been initiated to develop SSM technology to produce thin-wall automotive components using a robust die casting process. The part produced by this method will have several advantages over traditional die casting. Because of the fact that the alloy has been heated only to its liquid solid range, SSM casting is inherently a lower temperature process. This results in lower thermal demands on the die, extending life and reducing cost. The thixotropic nature of the material results in lower fluid turbulence as the SSM is injected into the die. This means that the cavity can be designed with thinner walls and filled more uniformly without trapping gas and creating porosity in the part. Upon freezing, shrinkage during solidification is reduced because the alloy is already partly solid at the time of injection. This results in better surface finish, reduced draft angles, and improved dimensional control so that less machining is required.

Cast aluminum alloys have been used to reduce the weight of internal combustion engine blocks. An innovative process which uses a high-intensity infrared (IR) heat source to fuse wear-enhancing additives into a surface in a matter of seconds is being developed in another OAAT project to produce uniform wear-resistant coatings for aluminum engine block cylinder bores. During fiscal year 1999, material compositions which are most likely to provide wear resistance, frictional behavior, compatibility with engine lubricants, and manufacturability will be selected based on discussions between automotive industry materials engineers and senior tribology and infrared processing staff at the Oak Ridge National Laboratory.

Performance requirements for engine and transmission components include operation at temperatures of 120° to 150° C and stresses of 50 to 150 MPa. The creep rate of currently available die casting alloys are sufficiently high that distortion and stress relaxation can occur. Development of magnesium alloys with improved creep resistance or the demonstration of manufacturing technologies for existing creep-resistant alloys is necessary. Definite needs include modification of creep-resistant alloys for die casting, semi-solid molding or lost foam casting technology, or process variations that yield creep resistance in conventional alloys.

A new OAAT project has been initiated to develop a die-cast magnesium alloy that will have a balance of strength, ductility, castability, creep resistance, corrosion resistance and recyclability at an acceptable cost. The project will be divided into phases. In Phase I the most promising approaches that are likely to lead to satisfactory alloys will be evaluated., An alloy matrix from the list of elements most likely to produce a creep-resistant microstructure will be developed based on established statistical and alloy development processes. Room temperature and elevated temperature (150° and 200° C) tests will be conducted on specimens with die-cast microstructure produced under well controlled conditions. Phase I will establish promising alloys for detailed evaluation and optimization, and demonstrate/justify commercialization potential based on creep, castability and cost. In Phase II, promising alloy families will be optimized and evaluated in detail (including corrosion and recyclability). Die-cast components will be produced from optimized alloys by suppliers and evaluated. Phase III will result in an alloy that meets stated objectives and prototype automotive components that meet automotive targets.

NATT is working with the Thixomat, Inc. (Ann Arbor, MI) to evaluate the moldability and creep strength of several magnesium alloys. Thixomat will utilize the Thixomolding process to semi-solid mold these alloys. This process has the advantage of lower operating temperatures than die casting, which in turn increases the number of alloys that can be molded. Other advantages include lower porosity, improved part tolerance and increased die life relative to die casting of magnesium alloys. Alloys that utilize precipitation hardening or dispersoids to stabilize dislocation structure and impart creep strength will be evaluated.

Metal-Matrix Composites

A team composed of the USAMP, several national laboratories, universities and suppliers has initiated an OAAT project to assist in the development of two new low-cost powder metallurgy technologies for production of particle-reinforced aluminum components. The project is designed to develop, transfer and implement press-and-sinter and direct powder forging to provide cost-effective, lightweight powder metallurgy particle-reinforced aluminum (PMPRA) automotive components. Team members will identify wear mechanisms and design apparatus and tests to evaluate components; establish a validated cost model for the processes and identify major cost drivers and feasibility of meeting the targets; develop novel sintering cycles, powder fabrication concepts, develop low cost alternative reinforcements, and characterize powder and compacts; and develop process models and process design guidelines. Interim results have demonstrated new processing technology for the fabrication of pump components, using particulate-reinforced alloys, resulting in ½ pound weight savings and increase in performance of the pump. This will potentially result in an overall weight reduction in the pumping system of 4-5 pounds and a potential 20% reduction in the input power needed for the pumping system.

OAAT is jointly sponsoring a project with the Electric Power Research Institute (EPRI) to investigate aluminum metal-matrix composites (MMC's) reinforced with flyash from coal-burning electric power plants. Participants include ECK Industries, Thompson Aluminum Casting and the University of Wisconsin at Milwaukee. The flyash is supplied by Wisconsin Electric. The point of the effort is to show that such flyash-reinforced MMC's can be produced with properties equal to or better than unreinforced aluminum but at lower cost on a weight basis as the flyash is essentially free. Work to date has indeed shown that aluminum with one type of flyash is acceptable and automotive components are being cast to demonstrate potential commercial feasibility.

MC-21, Inc. (Metallic Composites for the 21st Century, San Diego, CA) in conjunction with NATT, is working to lower the cost of producing high-performance aluminum MMC's. Besides the costs of the raw materials, processing and machining costs have been identified as the two most significant barriers to widespread commercial use of such materials. Analysis of the stir-casting process projected that it should be possible to produce high-quality MMC's for a processing cost of no more than 15-30 cents per pound. So, NATT established a cost-sharing project with MC-21 to design and construct a high-efficiency, cost-effective MMC stir-caster. A pilot stir-casting system has now been designed and assembled, and is now operational. Initial runs on 5, 10, 20, and 30 vol % silicon carbide (SiC) in aluminum have confirmed that complete mixing can be accomplished in times ranging down to only a few minutes. The elements allowing such rapid ceramic incorporation include a novel impeller design and powder injection system.

The other major issue that inhibits the production of low-cost MMC automotive components is machining. Single-point diamond tools are currently used to machine MMC's, but these tools are costly, fragile, short-lived, and require resharpening to control the cost. The objective of another part of the MC-21 project is to develop tools from low-cost rotating metal wheels to which inexpensive, sharp, diamond particles are affixed. Machining of MMC surfaces is accomplished by contact with these many rotating diamond points. MC-21 has worked with commercial tool makers to design and manufacture rotary tools having different diamond particle sizes and concentrations. These tools are currently being used to machine MMC samples. Metal removal rate, surface finish, and tool life are being studied. Early indications are that high removal rates and long tool lives are possible.

Recycling

The acceptance of aluminum- and magnesium-intensive vehicles of the future may depend upon whether they can be cost-effectively recycled. The Argonne National Laboratory is currently developing a long-range plan for OAAT to address R&D needed to insure this. An initial plan should be available sometime in 1999.

The DOE Albany (Oregon) Research Center is working on a way of separating cast and wrought aluminum alloys. Previous work has shown that cast aluminum alloys become brittle at high temperatures owing to intergranular melting. The solidus for cast alloys is typically in the 520° to 580° C range, while that for wrought alloys is typically in excess of 600° C. Thus, when a mixture of cast and wrought aluminum is heated to this range and subjected to crushing, the cast material fragments while the wrought merely deforms but stays intact. The cast fragments can then be separated from the wrought by simple sizing.

Cost reductions in magnesium alloys can also be realized by increasing its recyclability. Currently, there is little recycling of magnesium from used automobiles because of the low volume available. However, as more magnesium is utilized in automobiles, recycling will help meet cost reduction goals. NATT is working with Case Western Reserve University and Garfield Alloys to evaluate and develop recycled magnesium with properties equal to virgin material. The methods being evaluated to remove impurities include: 1) filtering, 2) sludging and 3) evaporation. Both Class I and Class II scrap will be evaluated in this project.

Basic Research

Basic or fundamental research principally in understanding deformation of aluminum alloys is supported by the Division of Materials Sciences in the DOE Office of Science. Much of the work in deformation is under the auspices of the Center for Excellence in the Synthesis and Processing of Advanced Materials (CSP) Project on Metal Forming. The scientific objective of this center project, which coordinates individual efforts at six national laboratories and two universities with industrial and international collaborators, is to further atomistic understanding relating to the forming of aluminum alloys for industrial and particularly automotive applications. The long-term goal is to develop constitutive equations for metal forming with a fundamental basis. Aspects of the work will treat recrystallization, texture, hardening and dynamic recovery. Recent highlights of the work include: demonstrating that general scaling relationships exist which control the dislocation structure as a function of plastic deformation for different metals, different deformation modes and different plastic strains; developing techniques for measuring initial and hot deformation textures and applying them to a 5182 aluminum alloy (relevant to study of dynamic recrystallization); and demonstrating high superplasticity (deformations up to 600% at a strain rate of $1x10^{-4}$/s and greater than 300% at rates of 0.01/s) in a relatively low-cost Al-Mg alloy similar to commercial 5083.

Additional work in aluminum considers issues related to the welding or joining of aluminum through a second CSP project; fatigue, corrosion or stress corrosion of aluminum; adhesion to aluminum;

and efforts to predict the thermodynamic properties of aluminum alloys. Additional information may be found at the Division of Materials Sciences web site (4). Total funding of aluminum related work across a variety of projects is estimated at $3.5 million in FY 1999.

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