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MAGNESIUM FRONT END RESEARCH AND DEVELOPMENT: A CANADA-CHINA-USA COLLABORATION

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Abstract

The Magnesium Front End Research & Development (MFERD) project is an effort jointly sponsored by the United States Department of Energy, the United States Automotive Materials Partnership (USAMP), the Chinese Ministry of Science and Technology and Natural Resources Canada (NRCan) to demonstrate the technical and economic feasibility of a magnesium-intensive automotive front end body structure which offers improved fuel economy and performance benefits in a multi-material automotive structure. The project examines novel magnesium automotive body applications and processes, beyond conventional die castings, including wrought components (sheet or extrusions) and high-integrity body castings. This paper outlines the scope of work and organization for the collaborative (tri-country) task teams. The project has the goals of developing key enabling technologies and knowledge base for increased magnesium automotive body applications. The MFERD project began in early 2007 by initiating R&D in the following areas: crashworthiness, NVH, fatigue and durability, corrosion and surface finishing, extrusion and forming, sheet and forming, high-integrity body casting, as well as joining and assembly. Additionally, the MFERD project is also linked to the Integrated Computational Materials Engineering (ICME) project that will investigate the processing/structure/properties relations for various magnesium alloys and manufacturing processes utilizing advanced computer-aided engineering and modeling tools.

Introduction

Increasing worldwide energy demand due, in part, to emerging economies, coupled with probable peaking of conventional petroleum production in the coming decades, are increasing the need to reduce dependence on petroleum-based fuels for transportation [1]. Vehicle lightweighting is seen as a significant strategy to improve fuel economy of vehicles with conventional gasoline internal combustion engines or alternative energy powertrains. Magnesium, the lightest structural metal, has recently emerged as a promising material for lightweighting and become a focus of research and development in North America, China and Europe [1-3]. Over the last few years, China has become the world's largest magnesium producer, supplying more than 70% of the world market in 2006. Magnesium components are routinely used by major automotive companies including General Motors (GM), Ford, Chrysler, BMW, Volkswagen and Toyota [4-11].

Despite increasing magnesium automotive applications in North America (NA), Europe and China, automotive magnesium applications remain principally at the single component level and dominated by die-casting applications. To evaluate the viability of magnesium as a major automotive structural material for vehicle mass reduction and performance improvement, a large scale magnesium development project was needed. It is also necessary to develop enabling technologies for magnesium castings and wrought products, in order to bring automotive magnesium applications from the single component level to the subsystem level.

Front end mass reduction and a near 50/50 front-to-rear mass ratio are important to vehicle fuel economy, driving and handling performance. In 2005, BMW introduced an aluminum front-end structure in its 5/6 series cars to reduce mass (about 20 kg) and achieve a near 50/50 mass distribution, at considerable cost penalty compared to steel [12]. Based on the better castability of magnesium compared to aluminum (especially in making large thin-wall castings for part consolidation) and the overall reduction in cost of the primary metal, it is anticipated that a magnesium-based, front-end structure can be designed and manufactured at significantly lower cost compared to aluminum and at near cost parity with steel.

Despite both opportunities for the automotive and magnesium industries and potential benefits to society from increased use of magnesium for automotive applications, there are many technical challenges in materials and manufacturing technologies as well as knowledge-base development. These challenges are huge and global, and require close collaboration among industries, governments and academia from many countries.

Through the efforts of many organizations and individuals, a Canada-China-USA collaborative project on Magnesium Front End Research & Development (MFERD) has been started in early 2007, to address the challenges for primary body applications of magnesium. The project is sponsored by Natural Resources Canada, the Chinese Ministry of Science and Technology, the United States Department of Energy and the United States Automotive Materials Partnership (USAMP) which is a partnership of Chrysler, Ford and GM. The goal of this project is to develop the enabling technologies in magnesium extrusion, sheet, high-integrity body casting, joining and assembly as well as the knowledge base in magnesium corrosion protection, crashworthiness, fatigue and durability, noise, vibration and harshness (NVH) performance.

Two attributes of this project are particularly significant:

- The focus on entire "front end" structures as the development object as opposed to individual components, thereby offering critical vehicle-level benefits in terms of mass distribution and performance, while challenging the technical community to devise materials and manufacturing approaches to permit mass production of such structures.

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- The establishment of a truly international effort bringing together scientific and engineering expertise in the field of magnesium technology from the United States, Canada and China, in what is believed to be a first-of-its-kind collaboration.

This paper describes the project goals, structure, technical tasks, progress and future prospects of this first-of-its-kind Canada-China-USA collaboration.

Project Goals and Structure

The Magnesium Front End Research and Development project is divided into the following two phases:

- Phase I. Enabling Technology Development (three years); and
- Phase II. Components Manufacturing Validation (three years).

As shown in Fig. 1, the development of enabling technologies in this project will draw product requirements from an accompanying USAMP project "Magnesium Front End Design and Development" (MFEDD) and will select target products from the front end design. In return, this project will provide critical material properties, performance (such as crash and NVH) and manufacturability data to the MFEDD design and technical cost modeling tasks.

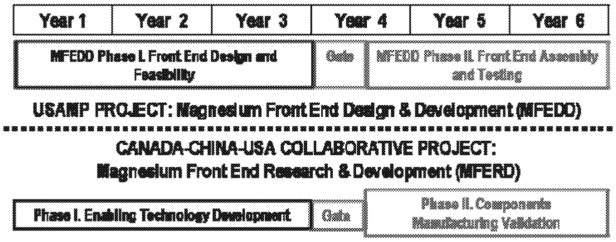
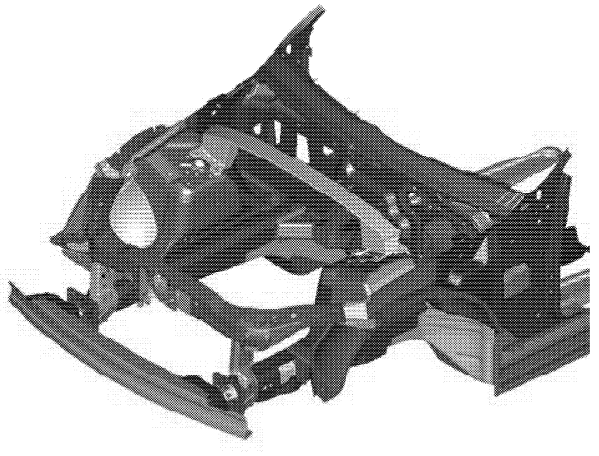


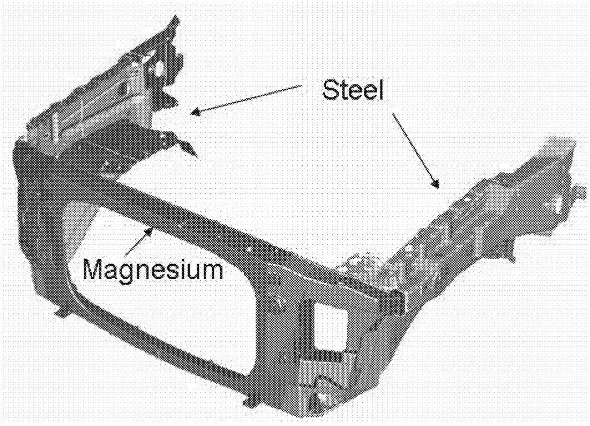
Fig. 1. Magnesium front end project structure.

This paper provides the details of the Phase I work for the first three years, with funding approved by all three countries. A decision gate is placed at the end of Phase I for both MFEDD and MFERD projects. Nonetheless, the development of the enabling technologies in MFERD Phase I would be beneficial to expanded use of magnesium in body applications. These technologies will not only enable the magnesium front end development, but also accelerate magnesium applications in automotive body structures and closures as well as other structural applications.

The development target has been set as the magnesium front end structures designed in a related USAMP project, Magnesium Front End Design and Development [13]. Two architectures, rear-wheel-drive (RWD) unibody and body-on-frame (BOF), have been selected for the USAMP magnesium front end design and feasibility study. The "donor" design target vehicle structures have been provided by GM (a RWD unibody architecture represented by Cadillac CTS) and Ford (a light truck BOF architecture represented by Ford F150). The "donor" vehicle teams have provided the baseline steel math data and the vehicle design/performance targets to the USAMP project team for design and technical cost modeling of magnesium front end structures. Fig. 2 shows the unibody front end steel baseline design [13] and the magnesium/steel upper front end design of the BOF architecture [14]. A 50-60% mass reduction goal has been set for the magnesium front end designs with equivalent performance and comparable cost (based on a technical cost modeling study) to the baseline vehicles. The critical material performance and manufacturing requirements for these magnesium structures are used as the development targets for the Canada-China-USA collaborative project on Magnesium Front End Research & Development (MFERD).



(a) Unibody front end steel baseline [13]



(b) BOF Mg/steel upper front end baseline [14]

Fig. 2. Magnesium front end development target.

Fig. 3 illustrates in "fishbone" format, how the various organizational aspects of the project contribute to the overall objective of a durable, affordable and manufacturable magnesium body structure. The project is divided into two major elements:

- Knowledge base development incorporating features of: crashworthiness (Task 1), NVH (Task 2), fatigue and durability (Task 3), and corrosion and surface treatment (Task 4); and
- Enabling technologies development including: extrusion and forming (Task 5), sheet manufacture and forming (Task 6), body castings (Task 7), and welding and joining (Task 8). Additionally, ICME (Task 9) provides an integrated computational tool to support the development of magnesium body applications.

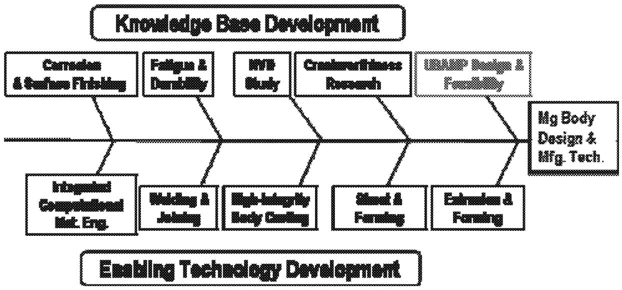


Fig. 3. Magnesium front end project "fishbone" diagram.

Project Tasks

Task 1. Crashworthiness Research

Magnesium castings have been used in many automotive components such as the instrument panel beams and radiator support structures. High-ductility AM50 or AM60 alloys are used in these applications and performed well in crash simulation and tests and many vehicles, with these magnesium components, achieved five-star crash rating. However, an entire front end structure of magnesium presents a significant challenge in vehicle crash and energy management. There is limited material performance data available for component design and crash simulation.

This task will determine the effect of high strain rates (as observed during crash tests) and anisotropic characteristics on the mechanical properties and energy absorption capability of magnesium wrought and cast alloys. The crashworthiness research includes material testing, failure characterization, CAE analyses and selected testing of prototype sections in crush (low loading rate) and crash (high loading rate) component tests. The strain rates for the material testing ranges from quasi-static, 10^{-3} sec^{-1}, through the mid rates of 10 sec^{-1}, up to 10^{3} sec^{-1} which is seen in the high deformation areas in a high speed crash. Presently, high strain rate testing is ongoing at four different labs in Canada, China and US on the common materials specified by the three-country team. Fig. 4 shows the Split Hopkinson bar test setup available to the Chinese crashworthiness team [15].

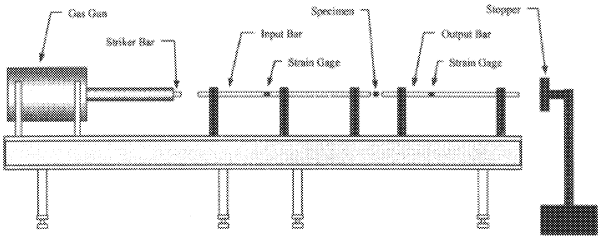


Fig. 4. Split Hopkinson bar test setup in China [15].

Task 2. Noise, Vibration and Harshness (NVH)

It is well known that magnesium has high damping capability, but this can be translated into better NHV performance only for a limited range of the sound frequency, 100-1000 Hz. The low-frequency (<100 Hz) structure-borne noise needs to be controlled by the panel stiffness between the source and receiver of the sound. The lower modulus of magnesium, compared to steel, is often compensated by the thicker gages and/or ribbing designs. For high-frequency (>1000 Hz) airborne noise, a lightweight magnesium panel would transmit significantly more noise into the occupant compartment than a steel or aluminum panel, Fig. 5 [16]. A two layer construction with an expandable low density (0.52 g/cm^3) urethane stiffening/NVH foam between the two layers of metal was used in the underbody prototype of Chrysler's magnesium-intensive body study vehicle [17].

The NVH study in this project is focused on the sound transmission characteristics of magnesium alloys used in dash panels. The task will also include analysis of sound of different frequencies (such as powertrain and airborne and white noise at audible frequencies, 20-20,000 Hz) and the effect of dash panel features on the sound transmission. This task will also compare the tested NVH properties of magnesium alloys with other materials such as aluminum and steel as well as a laminated dash panel from a typical production vehicle. While the fundamental NVH study is carried out in China and Canada, the US team is focused on the acoustic mitigation of the typical dash panel configurations and component NVH testing.

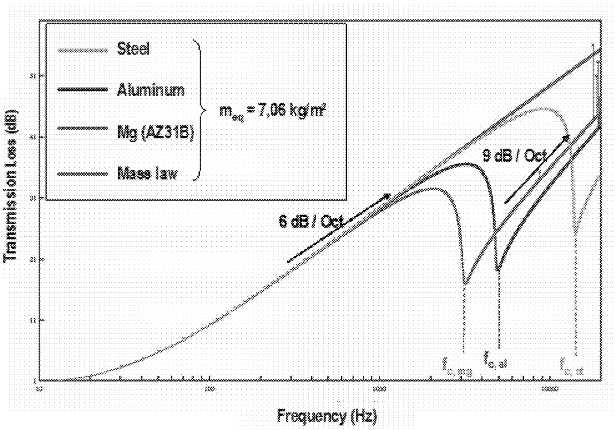


Fig. 5. Transmission loss vs. sound frequency of a magnesium panel compared to steel and aluminum [16].

Task 3. Fatigue and Durability

Fatigue and durability are critical in magnesium structural applications and there are very limited data in the literature, especially on wrought alloys. The Fatigue and Durability team has structured an international arrangement to address the fatigue behavior of magnesium castings, extrusions and stampings which have been joined into an integrated front end body structure. The effect of alloy chemistry, processing and microstructure on the fatigue characteristics of magnesium alloys will be studied. Fig. 6 is a total strain amplitude plot as a function of the number of cycles to failure for an extruded AZ31 section, generated by the fatigue team [18].

This task will study, compare and improve the fatigue predictive capability for analyzing magnesium components and sub-system behavior through better understanding the critical interactions of design, material and processing parameters that influence component microstructure and subsequent properties. Casting, extrusion and sheet products will be characterized sufficiently to establish links between microstructural features and fatigue behavior. Required monotonic and cyclic material properties for both multi-scale and traditional fatigue analysis methods will be defined, measured and made available in a final report. Preferred joining methods will be evaluated and CAE analysis parameters developed that allow accurate simulations of joints. The team will analyze magnesium front end components and sub-systems with both multi-scale and traditional methods, compare results and make recommendations that ensure component designs/sub-assemblies meets vehicle durability requirements. Functional durability of magnesium samples and typical magnesium joints will eventually be tested to validate the fatigue test and simulation results.

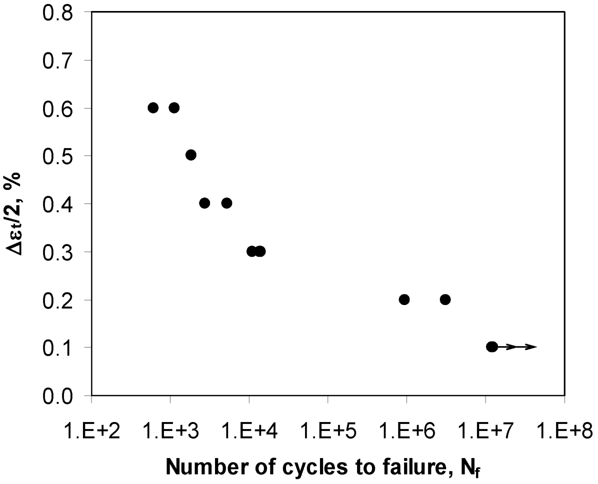


Fig. 6.Total strain amplitude as a function of the number of cycles to failure for the extruded AZ31 magnesium alloy [18].

Task 4. Corrosion and Surface Finishing

A major challenge in this project is to establish the surface finishing processes required for the intended front end application. The challenge is twofold in the sense that surface treatments to magnesium play roles in both manufacturing processes (e.g. adhesive bonding) as well as the use phase of the product life cycle demanding corrosion resistance. Furthermore, the current manufacturing paradigm for steel-intensive body structures employs chemistries in the paint shop that are corrosive to magnesium and are additionally aggravated by galvanic couples, primarily steel fasteners.

The project will explore novel coating and surface treatment technologies that have been developed in the U.S., China and Canada [19, 20]. These include novel pretreatments such as micro-arc anodizing, non-chromated conversion coatings, and "cold" metal spraying of aluminum onto aluminum surfaces. Fig. 7 shows the protective capability for a selectively cold-sprayed region in the vicinity of a steel fastener on a magnesium coupon [20]. Since most studies of corrosion protection and pre-treatment of magnesium have focused on die castings, the behaviors of sheet, extrusion and high-integrity castings will be explored for process compatibility.

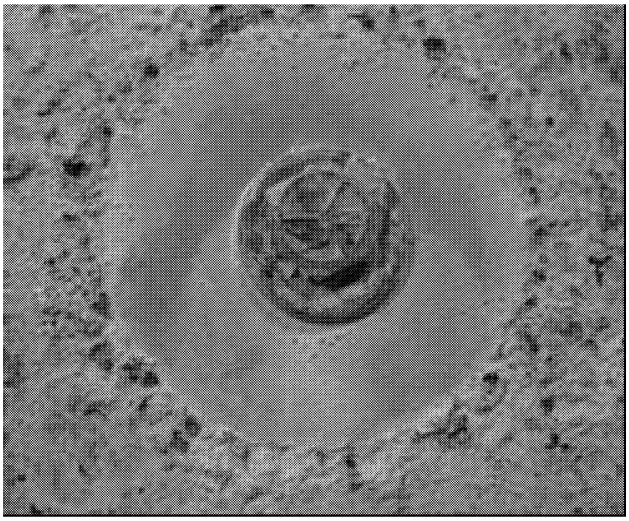


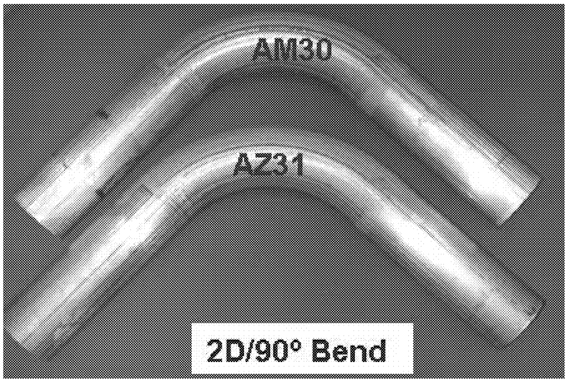
Fig. 7. Magnesium alloy AM60 plate, where the area surrounding the fastener was selectively cold sprayed with aluminum, after 1000 hours corrosion test, as per ASTM B117 [20].

While teams from all three countries will develop joint testing protocols and round-robin comparisons, there will also be opportunities for specializations inherent to the originating countries – e.g. U.S.- manufacturing processes, selection and system testing; Canada – environmentally-assisted corrosion and cold-spraying; China – novel surface treatment processes and testing.

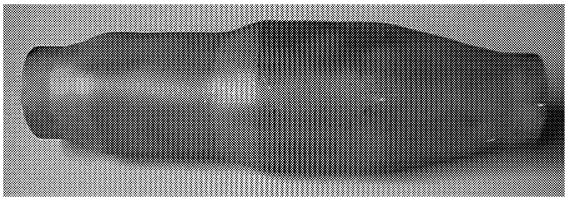
Task 5. Low-Cost Extrusions and Forming Techniques

While high-pressure die casting is the dominant process for current magnesium automotive applications, wrought magnesium alloys and their manufacturing processes are receiving increasing attention from academia and industry. As magnesium is expanding into critical automotive body applications, there is a great need for developing magnesium extrusions and sheet products and manufacturing processes to provide improved mechanical and physical properties, crash performance and corrosion resistance. The primary reason that magnesium extrusions are not used in automotive applications is the low extrusion speeds. For example, the maximum extrusion speed of the workhorse commercial magnesium wrought alloy AZ31 is only about a half of that of aluminum extrusion alloy 6063, which makes magnesium extrusions much more expensive largely due to the higher material and processing costs [21]. Mg-Al-Mn based AM alloys are excellent die cast alloys which offer higher ductility compared to Mg-Al-Zn based AZ alloys. Recently, AM30 (Mg-3%Al-0.4%Mn) alloy was found to have about 20% faster extrusion speed than AZ31 (Mg-3%Al-1%Zn), with similar strength and slightly improved ductility at room temperature and elevated temperatures up to 200°C [22].

The key in this extrusion task is to develop/select magnesium extrusion alloys (AM30, AZ31, AZ61, etc.) with high extrusion speeds and improved mechanical properties. The extrusion process needs to be optimized for high speed (low cost) and better microstructure. New extrusion alloys and grain-refining techniques [23] will also be exploited for improved mechanical properties and extrudability. Extruded magnesium tubes will need to be bent to form structural parts in the front end. Rotary draw bending [24] and stretch bending processes will be investigated for magnesium tube bending. Moderate temperature bending might be needed. Gas forming [25] of magnesium tubes will be used to evaluate the tube formability. Fig. 8 illustrates the examples of magnesium tube bending and warm gas forming. Efforts are also directed to develop the simulation capability for magnesium extrusion and process-structure-property relationships in support of the integrated computational materials engineering (ICME) task.



(a) Magnesium tube bending [24]



(b) Warm gas forming of magnesium tube [25]

Fig. 8. Magnesium tube bending and warm gas forming.

Task 6. Low-Cost Sheet and Forming Processes

Sheet is usually the last product form that comes to mind when considering magnesium automotive components. This is because of the high-cost and low formability of current magnesium sheet. Recent developments in the twin-roll strip casting of magnesium sheet are promising in terms of potential for low-cost, as supported by a recent USDOE sponsored cost modeling study [26]. In addition, magnesium ductility/formability has been shown to increase rapidly above about 230°C, Fig. 9 [27]. It has been demonstrated that magnesium sheet can be formed by warm stamping or superplastic forming [28, 29].

A major goal of the sheet and forming task is to procure, select and develop low-cost magnesium sheet based on the twin-roll continuous casting (CC) process, with formability and mechanical properties comparable or better than those of the current, high-cost sheet produced by the direct-chill (DC) ingot process. Sheet materials will be procured from several DC and CC sources, as well as developed by our collaborators in China and Canada. A few new sheet alloys, other than the current staple AZ31, will also be explored. The materials will be evaluated for microstructure, texture, warm formability and post-form mechanical properties. Research is also carried out to establish the process-structure-property relationships of magnesium sheet in support of the ICME efforts.

Task 7. High-Integrity Body Casting Development

Magnesium automotive components are mainly produced by high pressure die casting (HPDC). HPDC is a near-net shape manufacturing process in which molten metal is injected into a metal mold at high speed and allowed to solidify. This process, however, creates inherent defects, typically gas porosity in the castings due to the entrapment of air in the molten metal as a consequence of the high speed injection of the molten metal into the die cavity. The presence of gas porosity in castings is detrimental to their mechanical properties and pressure tightness. In addition, the formed pores, particularly those located adjacent to the casting surface, tend to expand during heat treatment, leading to the formation of blisters on the casting surface. The full potential of magnesium alloys and castings is, therefore, not realized.

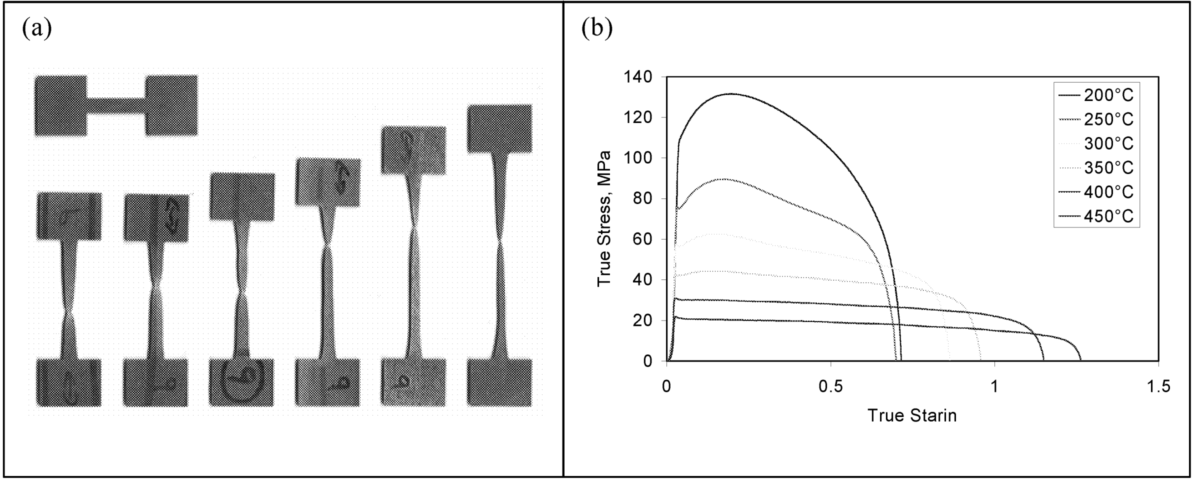


Fig. 9. Tensile test results of AZ31-H24 sheet material (2 mm gage) under constant speed pulling with initial strain rate of $1x10^{-2}$ s^{-1} (a) failed tensile bars, (b) true stress-strain curves at temperatures from 200 – 450°C [27].

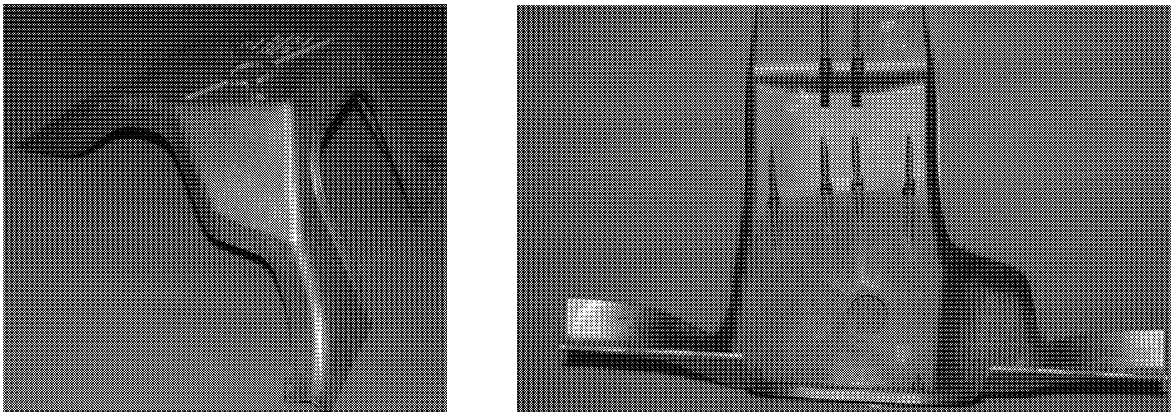


Fig. 10. Super-vacuum die casting magnesium shock tower [30].

Current aluminum body castings (about 3-5 mm wall) use special alloys and licensed vacuum die casting processes. These castings are very expensive due to the dedicated alloys and processes. The focus of this task is to develop high-integrity vacuum die casting processes for magnesium alloys to produce cost-effective magnesium castings that are heat-treatable and weldable. Porosity reduction and ductility improvement and thin-wall capability (about 2-2.5 mm) are some of the technical challenges.

Four different casting processes, vacuum die casting, squeeze casting, low pressure die casting and thixomolding, are being evaluated for their ability to produce high integrity magnesium castings. Fig. 10 shows a magnesium shock tower successfully cast at Contech using a super-vacuum process developed by the US casting team [30]. In addition, the heat treatment process will be studied to improve the mechanical properties further. As part of the task, the process-structure-property relationships of magnesium castings are being studied to achieve the ICME goals.

Task 8. Welding and Joining

Welding and joining is the very important final step in assembling the front end module from the cast and wrought magnesium components and to join the module to the steel body-in-white. There is a wide range of joining techniques that can be potentially used in for Mg-to-Mg and Mg-to-Al joining [31-34]. Fig. 11 shows a friction stir weld of AZ31B-H24 sheet with limited hardness drop and grain size increase in the weld and the heat-affected zones [34]. However, there have been no welded magnesium structures in automotive applications. The Welding and Joining team has structured an international arrangement to address multiple joining issues and technologies for Mg-to-Mg, Mg-to-Al, and Mg-to-Steel joining. Tasks have been divided between countries as follows:

- Canada: Laser welding, resistance spot welding (RSW), friction stir welding (FSW), and RSW weld bonding.
- China: Arc-welding (TIG, MIG, Plasma arc, A-TIG), Laser/TIG hybrid, and laser weld bonding.
- US: Surface pretreatment, adhesive bonding, self-piercing rivets (SPR) (including riv-bonding), Mechanical fasteners (threaded fasteners, blind rivets), and FSW.

All countries are also planning to include identification and/or development of nondestructive evaluation (NDE) methods suitable for determining the integrity of the joints produced by the respective joining technologies.

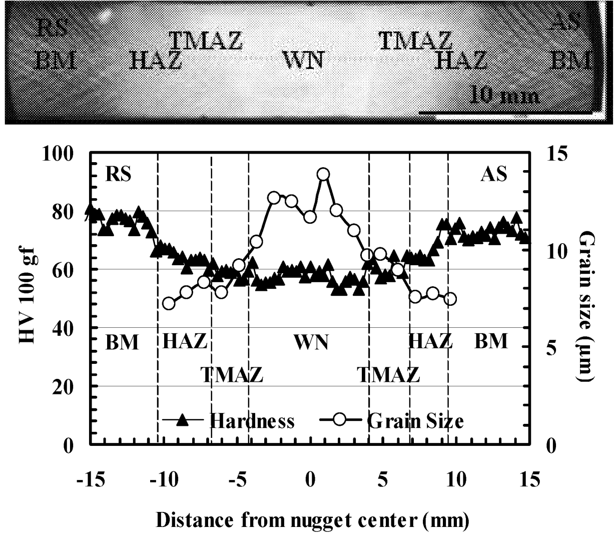


Fig. 11. Friction stir welding of AZ31B-H24 sheet showing limited hardness drop and grain size increase in the weld and the heat-affected zones [34].

Task 9. Integrated Computational Materials Engineering

Integrated Computational Materials Engineering (ICME), a new paradigm within the materials profession, offers a means to unify analysis of manufacturing, design and materials into a holistic system. A central component of ICME is the development and utilization of advanced material models which capture our quantitative knowledge of processing-structure-property relationships in a form which can be used by the broader engineering community. The goal of this task is to develop this key enabling technology for advanced lightweight magnesium processes and alloys for body structure and other body applications. This task is carried out in an accompanying Canada-China-USA collaborative project described in detail in another publication [35].

Summary

The first-of-its-kind Canada-China-USA collaborative project "Magnesium Front End Research and Development" has been formalized and launched in early 2007. The project seeks to explore emerging technologies and conduct fundamental research in the materials, manufacturing and performance of structures. This project brings together a unique team of international scope, from the United States, China and Canada to explore certain enabling technologies which could, if successful, permit the integration of magnesium-based subsystems into optimized assemblies for vehicle body structure applications using the front end structures as a test bed.

Acknowledgments

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