Contemporary Magnesium Die-Casting Research and Technology: A Canadian Viewpoint

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Abstract For the last 20 years, Canada has been a world leader in magnesium die-casting research and development. The breadth of research faculty and facilities, presence of a strong industrial sector, and the participation of government funded programs and agencies have fueled significant developments. This paper provides an overview of the developments led by Canadian researchers in the field of magnesium die-casting in alloy development, property, and microstructural characterization, development of ICME models, joining and corrosion technologies, and automotive product development with focus on developments funded by large-scale government funded research programs.

Keywords Die-casting · Research and development · Canada

Introduction

The research and development ecosystem of magnesium die-casting technology in Canada is considered world leading due to the existence of involved raw metal suppliers and die-cast manufacturers, an innovative academic sector, engaging government funded agencies, and a strategic vision to fund Canada's innovation in lightweight materials. Canada is home to Alliance Magnesium, a producer of magnesium metal located in Quebec, and Meridian Lightweight technologies, a world leader in magnesium die-cast components for the automotive industry located in Southwestern Ontario. The Canada Centre for Mineral and Energy Technology (Canmet) MATERIALS (CMAT) research laboratory, a branch of Natural Resources Canada is located in Southwestern Ontario as shown in Fig. 1. CanmetMATERIALS extensive state-of-the-art laboratory equipment includes a medium tonnage cold-chamber High-Pressure Die-Cast (HPDC) machine for non-ferrous metals research installed as part of an expansion and relocation (Fig. 1). This facility is dedicated to develop

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A. Luo et al. (eds.), *Magnesium 2021*, The Minerals, Metals & Materials Series,
https://doi.org/10.1007/978-3-030-72432-0_9

Fig. 1 Natural Resources Canada CanmetMATERIALS (CMAT), located in Hamilton, Ontario, left, and CanmetMATERIALS' pilot plant HPDC machine, right (Copyright, 2019, Government of Canada, used with permissions) [1]. (Color figure online)

and deploy technologies for improved materials fabrication and production with a focus on automotive materials.

Finally, the Natural Sciences and Engineering Research Council of Canada (NSERC) and Innovation, Science and Economic Development Canada (ISED) support discovery research, and foster innovation to enhance Canada's innovation performance through various funding programs.

With these resources and Canada's strong academic sector in materials and manufacturing, Canadian researchers have demonstrated a strong insight and expertise in magnesium die-casting technology. In fact, Canada has published the second most publications in Scopus-indexed journals on magnesium die-casting per million capita in the last 20 years in the world, as shown in Fig. 2 [2]. Only Australia has a published a greater ratio of investigations on magnesium die-casting. We find then, that this

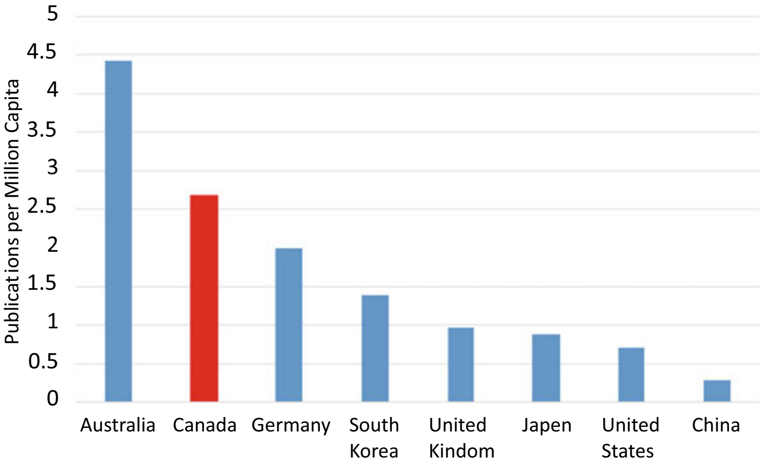

Fig. 2 Publications per million capita identified in Scopus-indexed journals since 2000 [2]. (Color figure online)

is a good opportunity to summarize and highlight the contributions that Canadian researchers have made to the development of magnesium die-casting technology. This paper strives to provide a thorough summary of Canadian-led research and development in magnesium die-casting technology. The structure of this paper is divided into different topics, including alloy development, property, or microstructural characterization of magnesium die-castings, Integrated Computational Materials Engineering (ICME) developments and modeling, joining and corrosion technology, novel products developed for the automotive industry, and large-scale research programs.

Alloy Development

The most prevalent magnesium die-casting alloys used in automotive applications include AZ91D [3] primarily used in powertrain application, and AM50A/AM60B [3] primarily used in automotive applications possessing increased ductility and toughness qualities, typically used for structural applications. These alloys contain primarily aluminum, zinc, and manganese as alloying elements. However, due to the advancement of engine technologies in the 1970s, resulting in increased engine temperatures, there was a need for magnesium alloys with higher operating temperature exposure limits. Several different research groups worldwide explored various alloying elements to improve the high-temperature creep properties of die-cast magnesium alloys, while not decreasing castability, and maintaining room temperature mechanical properties. These alloying elements included rare earths and alkaline earth elements, among others. Some of these alloy formulations have successfully been utilized in automotive applications [4]. Noranda, a Quebec-based magnesium producer, began developing a magnesium die-casting alloy for high-temperature automotive applications based on alloying with Aluminum and Strontium [5–13]. This Mg–Al–Sr system takes advantage of the addition of strontium to the typical magnesium–aluminum alloy system to form Al-Sr intermetallic particles resulting in an improved thermal stability at temperatures greater than 125 °C [5]. Noranda completed extensive work documented by numerous publications describing the benefits of the alloy system for high-temperature powertrain automotive applications [5–13]. Noranda characterized the creep performance [5–12] high-temperature mechanical properties [5, 6], thermophysical properties [7, 8], castability evaluations [5, 7, 9–11], alloy composition stability through thermal cycling [12], melt protection studies [13], and recyclability evaluations in a fluxless system of the alloy system [12]. The work of Noranda resulted in the promotion of two of these compositions for high-temperature automotive applications—AJ52X and AJ62X. Figure 3 shows the microstructure of several of these AJ-series formulations.

The AJ52X composition is promoted to possess excellent creep and bolt-load retention properties up to 175 °C [5, 6, 10], a thermal conductivity that is the greatest of any magnesium die-casting alloy [7, 8], chemical consistency through a fluxless recycling process [6], and good castability characteristics, although, with a limited process window [6, 7, 9] utilizing increased metal and die temperatures and

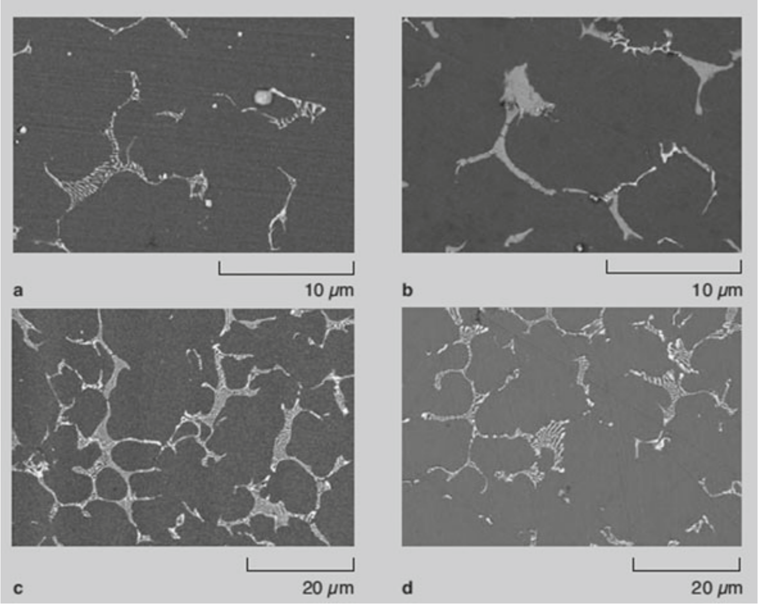

Fig. 3 SEM micrographs of Mg–Al-Sr alloy series in the as-cast condition: **a** AJ51x, **b** AJ52x, **c** AJ62x, and **d** AJ62L (Copyright TMS, 2003, used with permission) [5]

short fill times [6]. The AJ62X version was promoted as having generally similar high-temperature properties [5, 9, 10], an improved castability due to the increased aluminum content that widens the freezing range [5, 9, 10], and good corrosion resistance [5, 10]. Noranda suggests that the AJ62X alloy formulation is recommended for transmission cases and engine block components that are exposed to higher stresses at elevated temperatures [9]. The AJ62X alloy formulation was successfully implemented in a BMW aluminum–magnesium composite crankcase housing found on 3- and 6-series vehicles from 2004–2015, as shown in Fig. 4 [11].

Characterization of Magnesium Die-Castings

The understanding of magnesium die-casting material has been an important field of research as automotive use of magnesium die-cast components has progressed into structural applications over the last 20 years. The microstructure, mechanical properties, corrosion properties, strain-rate properties, and solidification characteristics among others are important to improve the knowledge of magnesium die-casting. Canadian researchers have contributed significantly to the understanding of magnesium die-casting over the last 20 years through extensive studies focusing on the characterization of the microstructure and mechanical properties of thin-walled automotive die-cast magnesium through several different research groups [15–37]. These works primarily focus on the AM50 and AM60 magnesium alloys. From these

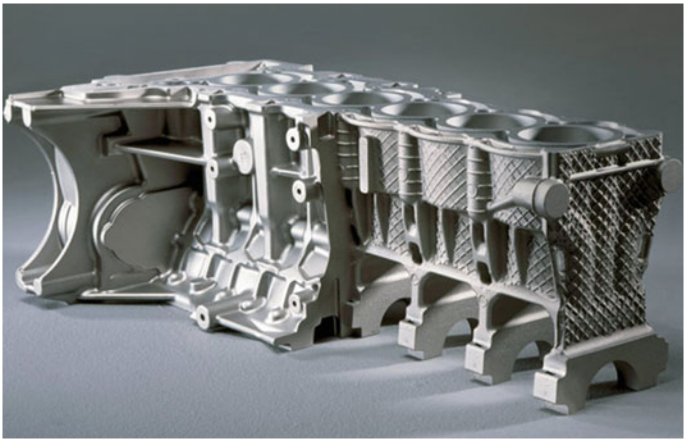

Fig. 4 The AJ62X BMW aluminum–magnesium composite crankcase housing [14]. (Color figure online)

research works, the microstructure of die-cast magnesium is described with a bimodal grain distribution [15], where a region of fine-grained grains is found close to the die surface [16], and a region of relatively coarse grains is found in the center of the cross section [17]. The microstructure of die-cast magnesium is further described as a primary magnesium matrix with relatively high aluminum concentration, containing both Mg–Al particles and Al–Mn inclusions [15, 17, 18]. This microstructure has a random texture [15] with a mean grain size in the range of tens of microns [18]. The skin region found close to the die surface resulting from faster solidification times is relatively free from porosity, and its thickness is dependent upon the local solidification conditions [16]. The core region found in the center of the casting consists of increased amounts of porosity [17], an increased amount of dendritic structures, and decreased hardness values [19]. Figure 5 shows microstructures of the skin and core region demonstrating these characteristics [20].

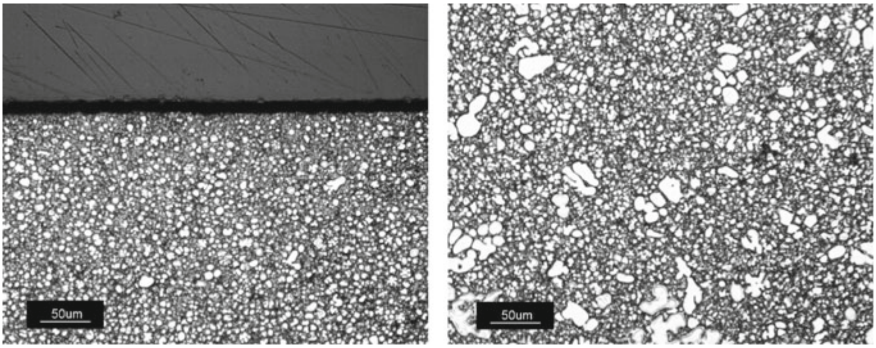

Fig. 5 Typical skin, left, and core, right, microstructures found in magnesium alloy die-castings [20]

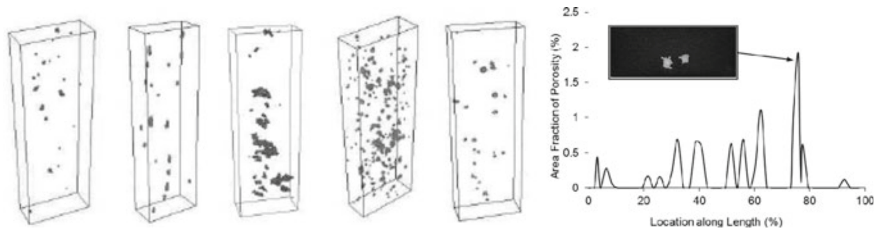

Fig. 6 Internal porosity detected by computed tomography of samples excised from regions of different solidification condition in a large magnesium die-cast component, left, and variation of areal fraction of porosity along length of coupon #4 from computed tomography data, right (Copyright Elsevier, 2005, used with permission) [25]

The properties of die-cast magnesium alloys have been found to depend upon the local microstructure [16, 17, 21–26] or casting conditions [27]. The size and location of internal porosity have demonstrated a significant effect on the tensile [17, 23–25, 28] and fatigue properties of die-cast magnesium [22]. In three separate studies completed on tensile samples with different solidification conditions, the internal porosity was characterized using x-ray tomography, as shown in Fig. 6, the evolution of porosity was described [28, 29], and the size of internal porosity was found to correlate analytically with the tensile elongations, and empirically with the fracture location in the gauge length [25, 28].

A smaller grain size in magnesium alloy die-castings results in improved creep resistance [19], a greater strain-hardening rate [24], greater tensile yield strengths [26], and improved corrosion rates compared with the core region [30]. The skin region, formed at the die walls during solidification from a rapid cooling rate forming a fine-grained microstructure, is primarily responsible for the shape of the tensile stress–strain flow curve [21] following a power-law hardening rule [15] and correlates with 4-point bending [23] and tensile flow strength [16] experimental results from different locations in a large thin-walled die-cast component. The tensile yield strength of die-cast magnesium can be accurately predicted using a modified Hall–Petch relationship developed through spherical microindentation considering both the skin and core regions [26]. At higher strain rates, the tensile yield strength [15] and compressive strength [31] were found to increase, while decreases in strain-hardening rate [15] were observed.

Several Canadian researchers have performed casting, solidification, and heat transfer studies on magnesium die-casting alloys through either die-casting experiments [27, 32, 33], simulated solidification studies [34, 35], or instrumented custom-designed equipment [36, 37]. Detailed analyses of different cooling rates of magnesium die-casting alloys have found that an increase in the cooling rate results in a larger quantity of intermetallic phases [32, 34] that also is affected by solute content [32]. The data created with these studies was also used to model the evolution of phase formation during solidification [34], and the latent heat of solidification [35]. These studies have also found that there is a strong influence of metal cleanliness on tensile elongation of die-cast magnesium [27]. Oxide contents less than 1000 ppm were found to result in very little effect on AM60B tensile properties. Researchers investigating the influence of calcium content between 0.2% and 0.8% in AM50 found that an increasing amount of calcium resulting in reduced visual appearance, affected the operation of the die-cast cell, resulted in more dross, and decreased mechanical properties [33]. Finally, in a set of studies completed to determine the heat flow capability of different cooling devices, it was found that copper rods are capable of transferring heat with a rate of 435.5 BTU/hr [36], while isobars were found to result in 14% improved cooling capability when compared with copper rods [37], demonstrating their effectiveness.

Development of ICME Framework for Magnesium Die-Castings

The development of Integrated Computational Materials Engineering (ICME) tools for magnesium die-cast components is a very important research field with the advancement of automotive applications into more structural components, such as instrument panels and liftgate inners, among others. The designer of a magnesium die-cast component requires confidence that the material properties being represented by a material card in FE (finite element) simulations of the performance provide both an accurate and robust representation of the material in order to optimize the design. Further, new applications for magnesium die-casting will necessitate alloy compositions designed with specific properties to meet the requirements. Canadian researchers have contributed significantly to developing tools to optimize the alloy design process through thermodynamic databases [38], computationally developing predictive behavior of the solidification process of magnesium die-castings [39–41], developing models predicting process-structure-property relationships of magnesium die-cast alloys [29, 42–48], and applying process-structure-property relationships into material codes to predict the structural behavior of magnesium die-cast components [49–51]. Thermodynamic software and database packages, such as FactSage™, are routinely used to model phase diagrams and phase equilibria in alloy systems to predict freezing ranges and phase formations for magnesium die-cast alloys, among other data [38]. Canadian researchers have developed an optimization algorithm that searches these databases for the optimal conditions of multicomponent alloy systems to meet given criteria. The example of optimizing corrosion resistance of an existing magnesium alloy while maintaining existing properties is given, resulting in a complex composition [38]. Several Canadian researchers have developed computational and empirical models that predict the complicated solidification process during high-pressure die-casting of magnesium alloys considering directional solidification and precipitation of hydrogen gas over the entire solidification range [39], and the governing equations for fluid, solid, and mushy regions [40] both to predict shrinkage porosity, and the simulated local volumetric flow rate over the filling process to predict poor metal front conditions [41]. Figure 7 shows the

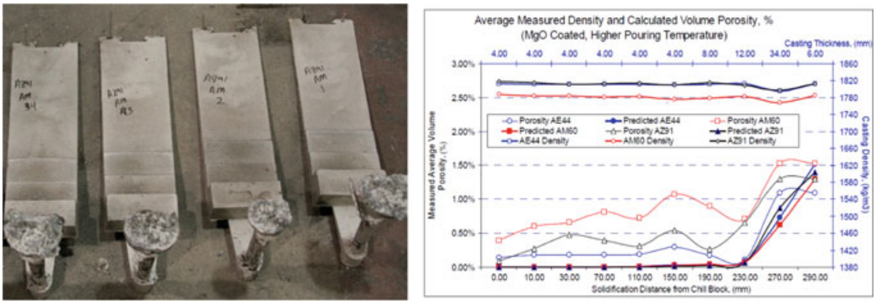

Fig. 7 Castings produced, left, and measured versus predicted volumetric porosity for three different alloys as part of the development of a computational model to predict porosity in magnesium die-castings. (Color figure online) (Copyright TMS, 2008, used with permission) [39]

castings produced and predicted and measured levels of volumetric porosity from a Canadian research group's work in developing a computational model to predict porosity [39].

Further, other groups have developed empirical relationships to predict the average local grain size for cooling rates typical of both sand- and die-cast processes [44], and the skin thickness in magnesium die-castings using heat transfer equations and predictive equations of the local grain size from cooling rates [42]. The local yield strength of magnesium die-castings has been predicted using a modified Hall–Petch relationship originally developed using spherical microindentation cyclic load–unload experiments on samples of varying average grain size [26]. This method, which utilizes the average grain sizes and relative thicknesses of the skin and core regions, was originally developed for the AM60B alloy and has shown validity for yield strengths of tensile coupons excised from an alternative AM60B cast component [42], from AZ91D, AE44, and AM60 gravity castings, and AZ91D and AE44 die-cast test plates [43–45]. The prediction of local tensile properties in a large die-cast component—ultimate tensile strength and elongation—has been predicted using a critical strain model and knowledge of the local porosity conditions [25]. The framework of the critical strain model was improved with additional investigations [43, 47, 48] to consider a strain concentration factor and the spatial location of the porosity in the cross-sectional area within the casting. These improvements simplified the input required and improved the predictions. The failure model predicts a maximum condition for porosity found centered in the cross-sectional area, and a reduced elongation as the porosity is located closer to the cast surface, reaching a minimum prediction using the thickness of the skin region [44]. This model was found to accurately predict the range of tensile elongations of coupons excised from AM60B cast components [42], and extended to AM60, AE44, and AZ91 gravity castings, and AE44 and AZ91 die-castings [46]. Figure 8 demonstrates the range of predicted tensile ductility of AM60B magnesium alloy from the location of the porosity in the cross-sectional area compared with experimental data of the size and location of porosity and the associated fracture strains [25, 42–44, 47, 48].

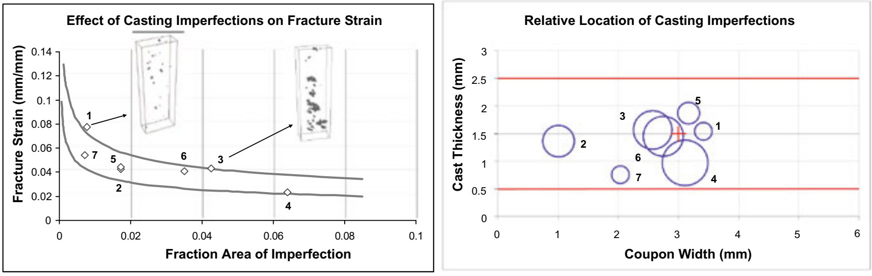

Fig. 8 Predicted range of tensile ductility from an analytical failure model, left, compared with experimental data considering both size and location of porosity, shown on right. (Color figure online) (Adapted from [43])

Canadian researchers have developed ICME tools for FE simulations of structural performance based on either material data obtained from coupon testing [49], reverse engineering a flow curve with a conservative failure prediction [50], or incorporating process-structure-property relationships into property predictions [51]. An FE material card was developed for AM50A die-cast magnesium alloy based upon coupon test results and fit to a Johnson–Cook constitutive model accounting for effects of strain and strain rate [49]. The validation of the material card was completed using static and dynamic testing of steering wheel armature cast components. From this study, it was determined that the largest error in the prediction of component performance was due to the non-homogeneous microstructure in the casting [49]. An alternative approach was taken by Alain et al. [50] who developed a material card for AM60B magnesium alloy by reverse engineering component performance coupled with a conservative failure criterion based on empirical data. The results of this work find a statistical conservative prediction of component performance failure, however, these authors state that a better understanding of structure–property relationships for large die-cast components is required [50]. This statistical conservative approach was refined in work completed more recently [51] where process-structure-property relationships were integrated into an FE material model to predict the performance of component bench testing. Figure 9 demonstrates the methodology. Local property variability and robustness were incorporated into FE performance simulations with the use of

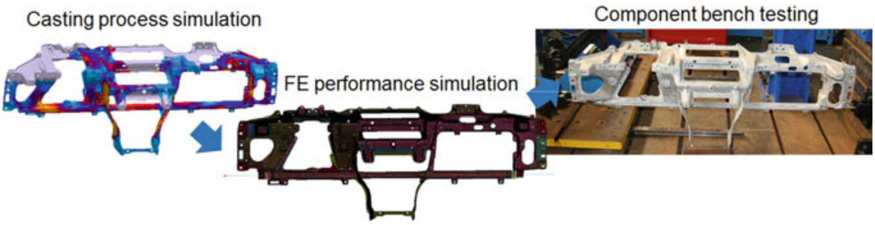

Fig. 9 Methodology presented to predict component performance incorporating process-structure-property relationships in FE models. (Color figure online) (adapted from [51])

casting process simulation results to calculate a unique material response for each FE element based upon its simulated process history. Validation of this approach shows excellent prediction of force–displacement characteristics and statistically conservative failure prediction to experimental results [51].

Joining and Corrosion Technologies for Magnesium Die-Castings

In a study completed by the United State Automotive Materials Partnership (USAMP), it was reported that joining and corrosion concerns were two of the major technology challenges to more magnesium usage in North American vehicles [52]. These are two of the areas of key research and development work by Canadian researchers for furthering magnesium die-casting implementation in the automotive industry. Canadian researchers have contributed to the research areas of joining and corrosion by developing a set of guidelines for utilizing self-threading fasteners with magnesium die-cast components [53, 54], and by developing design considerations and research into corrosion solutions and coatings for corrosion mitigation for magnesium die-castings [55–58]. A design for assembly using self-threaded fasteners is presented describing the approach to designing the hole diameter and tolerances to provide a sufficient torque assembly window for cast holes in die-cast magnesium components [53, 54]. These works further describe the effects of hole diameters, draft angles, and lengths of engagement upon the prevailing and failure torques and failure method of self-threaded fastened joints in magnesium die-castings. Design guidelines for magnesium die-cast components in automotive exterior applications are developed by Canadian researchers highlighting the considerations for sub-assembly processes with magnesium die-castings and mitigation methods for galvanic corrosion [55]. Canadian researchers investigate the severity of various accelerated cyclic corrosion test procedures to cosmetic and galvanic corrosion of die-cast magnesium and compare with in-field underbody exposure [56]. These comparisons find that each lab exposure results in a range of results, however, a more severe condition for cosmetic and galvanic corrosion than the 5 years of underbody exposure, providing validation of these exposures for a conservative magnesium die-cast product development. Further, Canadian researchers complete detailed electrochemistry investigations into various magnesium alloys, including a die-cast alloy, calculating breakdown, and repassivation potentials [57]. These researchers find that there is a difference in cyclic potentiodynamic curves between exposures to the skin and core regions of the die-cast magnesium alloy. Canadian researchers have also investigated developing low-energy plasma electrolytic coatings for die-cast magnesium alloys to reduce voltage and energy costs of these coating processes [58]. One particular study investigates a novel electrolyte solution and different exposure times to change the growth behavior of the resulting coating, as shown in Fig. 10 [58].

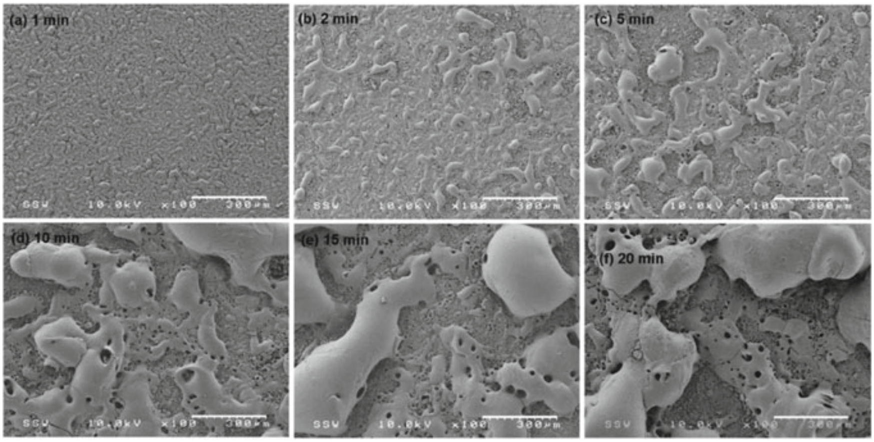

Fig. 10 SEM images of the different surface morphologies of PEO coating developed on AM50 for different durations from 1 to 20 min (Copyright 2019 Elsevier, used with permission) [58]

Development of Automotive Applications for Magnesium Die-Castings

Traditional application of magnesium die-casting in the automotive industry include transfer cases, brackets, and cross-car beams. However, more recently, new applications have been developed including roof frames, liftgate inners, door inners, and engine cradles [59]. Canadian researchers have been instrumental in leading the development of new automotive applications for magnesium die-castings and solving technical challenges to ensure successful products. These applications include developments to improve cross-car beams [60–62], front-end carriers [63, 64], and closure inners [61, 65, 66]. Canadian researchers have developed cross-car beams for numerous automobile manufacturers in the last 20 years, including General Motors [59], Mercedes Benz [60], Jaguar Land Rover [62], and Honda [61]. The performance-led design process [67], typical of these types of structural applications, resulted in significant weight reductions and part consolidation. These researchers developed products that, in one case, resulted in a weight reduction of 3.4 kg and a consolidation of 28 components into a single die-casting compared to an aluminum design [61]. An excellent example of the potential of magnesium die-castings in automotive applications is given in Ref. [62], where a platform-wide development for a cross-car beam was completed. The automobile manufacturer, in this case, improved attachment points and inefficiencies in attaching components to the cross-car beam to reduce mass, enable a dual-cavity die-cast tool, and eliminate all machining operations in the design [62]. Canadian researchers have also contributed to the development of front-end carriers through flexible design strategies for both welding-in and clip-on assembly methods [63, 64]. These designs have incorporated such features as headlamp locations and attachments, radiator mountings, and the hood latch [63]

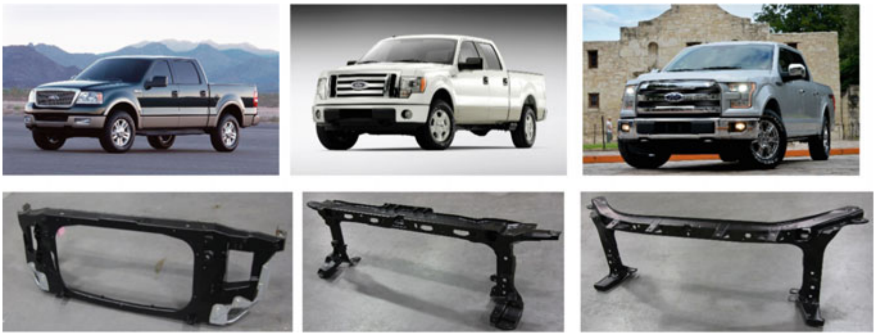

Fig. 11 Generations of magnesium radiator supports found on F-150 full-sized trucks, MY 2004, left, MY 2009, center, and MY 2015, right. (Color figure online) (Copyright 2017, IMA, Used with permissions) [64]

resulting in 8–9 kg of mass savings and a 16 component reduction compared with steel designs [63, 64]. An excellent example of design strategy evolution is provided in Ref. [64], where three generations of a magnesium radiator support casting for Ford F-150 full-sized trucks are summarized, and shown in Fig. 11. The design and corrosion mitigation evolution is detailed resulting in successive mass savings over the first generation magnesium design of nearly 60%, and 70%, respectively [64], while the improved design allowed for dual-cavity die-cast tools for the second and third generation designs. Canadian researchers have also been instrumental in developing closure inners for automotive applications, for both side doors [66] and rear liftgates [61, 65, 66]. These applications presented significant technical developments that required solutions for structural adhesives, coatings, corrosion, fastening, sealing, and sub-assembly, among others [65]. The magnesium die-casting liftgate inners in vehicle production resulted in mass savings of at least 40%, with a part reduction of at least 4 [61, 65, 66].

Key Canadian Magnesium Die-Casting R&D Programs

With a strong magnesium industry, as well as well-organized funding programs for automotive research, several different key R&D programs have been undertaken by Canadian researchers over the past 20 years. Two key programs that have been completed using federally funded R&D are the Canadian Lightweight Materials Research Initiative (CLiMRI) and Auto 21 Network of Centres of Excellence [68]. The Auto 21 R&D program was a 15 year Canadian program focusing upon automotive research and developing strong academic–industry connections [69]. Auto 21 was launched in 2001 at the University of Windsor, and coordinated and funded research programs through 48 academic institutions and academic partners focusing upon developing an improved Canadian automotive industry [69]. Successfully funded projects ranged from materials and manufacturing through social sciences and humanities, including a project focusing on developing, mapping, and correlation mechanical properties with microstructure in complex magnesium die-cast components [68]. A project funded by Automotive Partnerships Canada (APC) and four Canadian companies contributed to reducing vehicle weight by up to 40% by using lightweight materials, including magnesium [70]. This project focused upon multi-material aspects in the automobile, including dissimilar metal corrosion, joining technologies, durability, computer modeling, crash modeling, and die-casting. A key component to this project is the high-pressure die-cast infrastructure developed at the CanmetMATERIALS laboratory in Hamilton, Ontario [70]. Further, a collaborative project completed by Meridian Lightweight Technologies, General Motors, and The Ohio State University focused on developing an integrated die-casting process for large thin-walled structural magnesium alloy panels [71]. This project was designed to improve the energy productivity of traditional steel stamping and joining processes by up to 50% and focused on developing new technologies for magnesium die-cast tooling, super vacuum, new alloy formulations, overcasting technology, and advanced process simulation tools [71]. Figure 12 shows the resulting side door assembly featuring the magnesium die-cast inner structure. Finally, in an international collaborative project between China, Canada, and the US, sponsored by Natural Resources Canada, magnesium as a major automotive structural material for a subsystem level material was evaluated [72]. Enabling technologies such as NVH, crashworthiness, corrosion and surface treatments, and joining and fastening technologies were researcher with the goal of creating and entire front-end structure with 50–60% mass savings [72].

Fig. 12 Side door assembly featuring a die-cast magnesium inner resulting from collaborative project completed by Meridian, General Motors, and The Ohio State University. (Color figure online) (Copyright, 2018, IMA, Used with permission) [71]

Conclusions

This paper endeavors to provide a thorough summary of the Canadian-led research and development of magnesium die-casting technology over the last 20 years. The work published in technological areas of alloy development, characterization of magnesium die-castings, ICME development for magnesium die-casting, corrosion and joining technologies, product development, and large-scale R&D programs was summarized by demonstrating the significant contribution to the field from Canadian researchers.

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