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Review

Current State of Semi-Solid Net-Shape Die Casting

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Received: 7 November 2019; Accepted: 25 November 2019; Published: 2 December 2019

Abstract: Semi-solid processing of alloys is nearing the end of its fifth decade in existence. This promising manufacturing route has undergone a number of changes over the past five decades and apart from certain successful industrial applications, it appeared that it had become a niche technology with limited applications, notably in the automotive and consumer product markets. Nevertheless, despite the strong competition of traditional casting and in particular die-casting processes, and the emergence of Additive Manufacturing (AM), there seems to be a resurgence in demand for Net-Shape Die Casting of Semi-solid alloys as testified by the high numbers of delegates at the 15th SSM Conference at Shenzhen, China in September 2018. What follows is a brief review of the historical development of the process as well as more recent developments with an eye to future prospects.

Keywords: SSM Die-casting (SSMDC); SSM feedstock; SSM applications; thixoforming; non-dendritic microstructures; industrial applications of SSMDC

1. Introduction

Semi-solid metal processing (SSP) covers all the manufacturing routes involving materials processed in their semi-solid state. These technologies are known for taking advantage of the thixotropic behavior of metal alloys (discovered by Spencer et al. [1]) to permit a liquid-like slurry filling of a die/mold resulting in improved properties of the final products. This thixotropic phenomenon is related to the agglomeration/de-agglomeration phenomena that are themselves dependent on the application of shear inputs [2]. When shear stress is applied on a material in the semi-solid state, particles separate from each other (de-agglomeration) to generate a material state consisting of a suspension of solid particles into a molten metal (liquid) matrix. Hence, this effect means a reduction of viscosity due to the change on the material structure. Once the material is left resting for enough time, the particles start generating new bonds (agglomeration) and the material ends up recovering its initial state [3–5].

SSP relies on feedstock materials that have non-dendritic microstructures and exhibit the thixotropic behavior described above, i.e., when the material is not disturbed it remains stiff, holds its shape and can be easily handled but when sheared, it experiences rapid thinning and behaves like a liquid. This behavior is the key to SSM processes where material flows as a semi-solid slurry into a die, as in conventional die-casting.

The methodologies employed to attain the necessary non-dendritic, near spheroidal microstructures that are appropriate for SSM feedstock, have been key to the commercialization success or otherwise of these group of processes. Over the years, at the Research &Development level, various routes have been developed over the years, with various degrees of success, for obtaining these necessary near spheroidal microstructures, however in successful commercial SSM applications the following routes for obtaining feedstock have been used:

(a) Continuous casting with magneto-hydrodynamic (MHD) stirring of the melt during solidification [6,7].

(b) Semi Solid Rheocasting (SSR), where a cold spinning 'finger' is inserted into the melt acting as a source of nucleation [8,9].

(c) Gas Induced Semi Solid Rheocasting (GISS) [10,11], where the nucleation is induced by fine bubbles of argon gas introduced into the melt by a perforated graphite rod.

(d) Through the SEED (Swirled Enthalpy Equilibration Device) process [12,13], where a high fraction solid slurry is obtained as liquid metal is cooled into the semi-solid temperature range.

(e) Thixomolding, an injection molding technology that uses magnesium pellets or chips that has been successfully producing commercial parts over the past four decades [14,15].

The SSR, GISS and SEED routes allow in-situ recycling and therefore offer substantial potential savings, nevertheless although the MHD typically requires a supplier of the feedstock and does not lend itself in-situ recycling, the process provides better quality products through higher consistency of feedstock quality. Thixomolding, uses magnesium pellets heated up and sheared in a plastic extrusion set-up. It is a commercially successful process, with millions of components produced each year for the automotive and consumer products/electronics markets (computer, VCR, mobile phones accessories, sports goods).

Compared to HPDC, SSM processing confers a number of advantages to the final products, such as fine, uniform and virtually free of porosity microstructures, ability for post-processing heat-treatments to increase mechanical properties, reduced energy consumption and reduced die thermal shock and therefore longer die-lives, due to the lower heat content of the semi-solid material. Higher melting point alloys, such as hypereutectic aluminum-silicon alloys with very high silicon contents (~25–40%), super alloys or steels, which cannot be die cast, may nevertheless, be processed by SSM methods.

However, even though the potential of the process is clear to see and through its long history had numerous attempts to full commercialization, it has only been successfully exploited in a limited number of cases [16], using mainly conventional aluminum casting alloys of the AlSi7Mg type (A356 and 357).

2. Past SSM Processes

Despite their mixed history, SSM processes have been responsible for the production of aluminum castings is of the order of millions of tones in North America, Europe and Japan by the 1990s [17,18]. However, SSM represents only around 1% of the total in this vast market (see Figure 1), where die-casting and permanent mold casting are still overwhelmingly dominant [19]. Using aluminum 356 & 357 as the workhorse alloys for the industry, SSM products were made of consistent quality and properties, albeit at a higher premium cost than die cast parts [16].

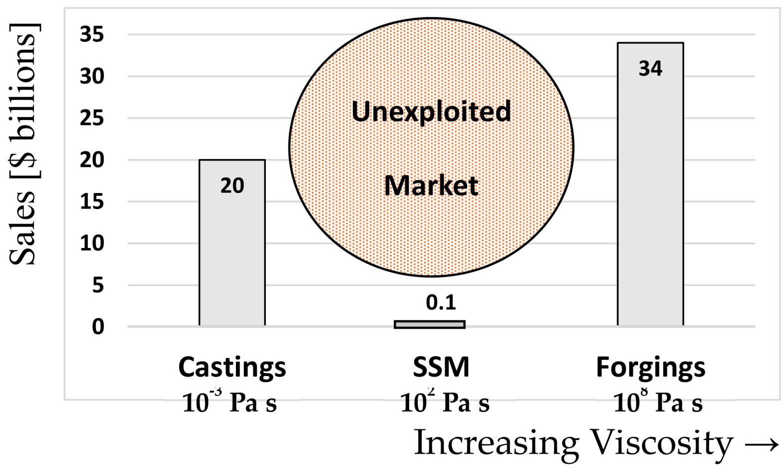


Figure 1. Semi-solid market annual US sales [19].

The early commercialization of SSM processes was undertaken by three main players, Alumax Inc. and Thixomat Inc. in the US, and Stampal SpA in Italy. Thixomat followed, and found success, via a clearly defined approach utilizing only magnesium products and focusing in the electronics and consumer products markets with some automotive applications [14,15]. Stampal SpA, via the drive of its farsighted Chairman at the time Gianluigi Chiarmetta, focused exclusively on aluminum products for the automotive market. Stampal products were technically very successful, but the commercial viability became unsustainable due to the use of MHD feedstock associated with a price premium as well as the inability of recycling post process feedstock on-site and having to send scrap back to the main feedstock provider at the time Pechiney in France [16]. These applications clearly demonstrated that SSM products had better properties than their die-cast counterparts due to the reduced gate velocities used in SSM, which resulted in uniform die filling as shown in Figure 2.

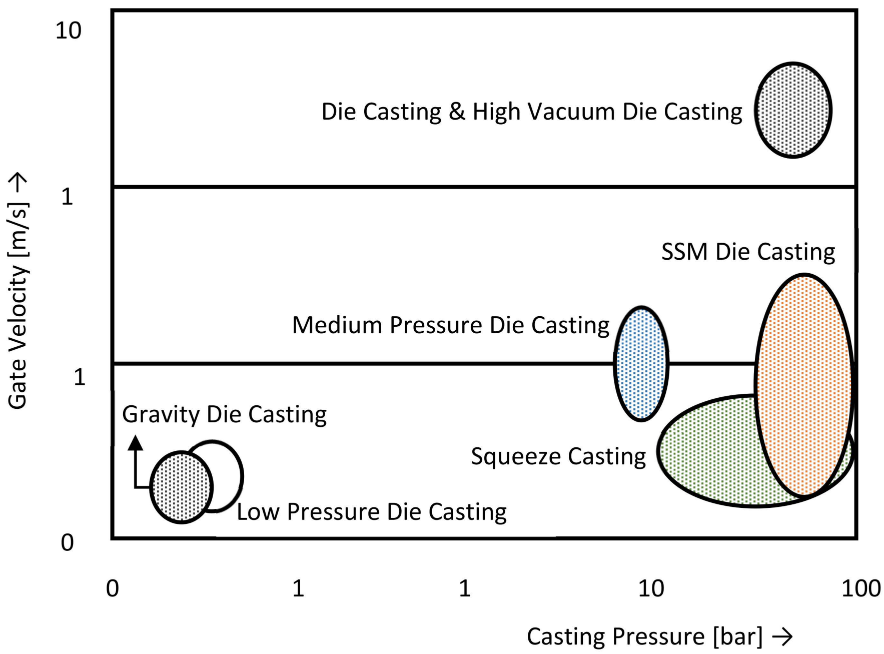


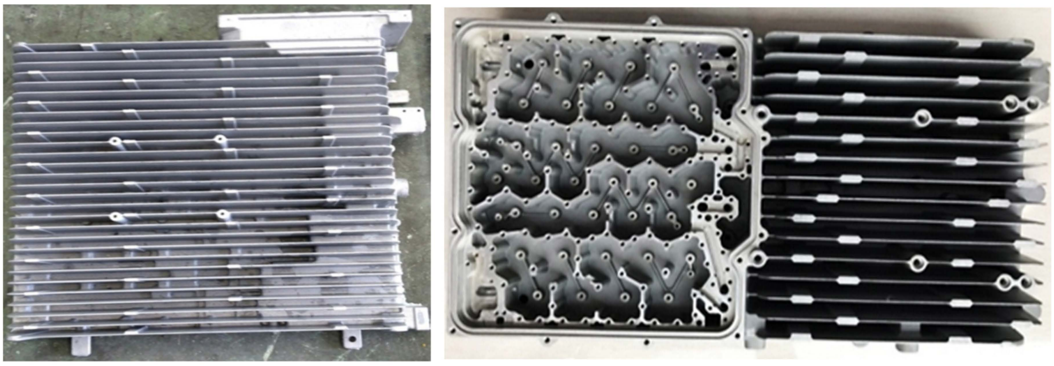
Figure 2. Relation between Casting Pressure and Velocity of the metal at the Gate [20].

The absence of recycling feedstock encouraged Ube in Japan to seek an alternative route of producing feedstock but this particular process failed to succeed due to patent infringements [21]. Following these early attempts, the die-casting press manufacturer Buhler in Switzerland became involved, as well as a second European feedstock manufacturer SAG in Austria [22,23], providing another successful series of automotive and consumer market SSM products. Nevertheless, despite these successful commercialization attempts, the European market seemed to go into reverse, and one by one, the applications faded from the forefront of commercial manufacturing. Interest in SSM processing continued mainly on R&D level with few commercial successes such as Vforge in the US [24]. One particular R&D application took place at the University of Liege [25], and as part of a European collaboration the work showed a promising way towards SSM of high melting point alloys such as steels [26,27], only to be stymied by the economic recession of 2008.

3. Present SSM Processes

More recently, there has been a revival of interest in SSM manufacturing processes with feedstock that can be recycled in situ, such as SSR, GISS and SEED. Applications appeared in Europe, US but predominantly China, who currently appears to be the main driver behind the resurgence of SSM processes as testified by the well-attended SSM Conference in Shenzhen in September 2018 [28]. Semi-solid processing of metals to date has been commercially successful with aluminum and magnesium products [7,15] and typically employing high fraction solid routes [24] or high fraction liquid routes [8,10]. Currently similar processing trends appear to be followed in the commercialization of the SSM Die-casting [28–32].

Applications utilizing heavy-duty automotive as well as marine parts in Europe and telecommunication parts in China employing high fraction liquid processes by Rheometal^{TM} appear to demonstrate complexity of parts with thick and thin walls, good fatigue performance under dynamic load applications, part weight reductions, higher product yield and reduced die wear and soldering [29]. The two components shown in Figure 3 are made in Al-8%Si, have resulted in reductions of fin thicknesses from 1.6 mm to 0.9 mm in the case of the heat sink (left), and removal of any subsequent machining, a weight reduction of 0.7 kg per piece and increase of thermal conductivity from 100 to 150 W/m K. The combination heat sink and RF filter part (right) allowed a fin thickness reduction from 1.6 to 1.1 mm with a 0.4 kg weigh reduction [33].



(**a**) (**b**)

Figure 3. (**a**) 4G (fourth generation of mobile phone technology) base station cooling shell, Size: 474 × 455 × 92 mm, fin thickness: 1 mm; (**b**) 4G filter shell, Size: 448 × 242 × 66 mm, fin thickness: 1 mm [33]. (Courtesy of Mingfan Qi, School of Materials Science and Engineering, University of Science and Technology Beijing).

These rheo-HPDC products were produced by the Zhuhai Runxingtai electric appliance co. Ltd. and the technology research and development was completed by the research team at the University of Science and Technology Beijing. Technology development included slurry preparation, slurry delivery, die optimization and Rheo-HPDC process integration and automation. At present, there are 18 Rheo-HPDC production lines at Zhuhai, with supporting die-casting machines ranging from 800 tons to 4000 tons. The maximum size of the product can reach 1020 mm × 765 mm × 126 mm with a minimum wall thickness of 1 mm. The products are for communication manufacturers such as Huawei, ZTE, Samsung, as well as some automotive customers. Zhuhai Runxingtai Ltd. now produces around 3 million rheo-die-castings annually. These applications have demonstrated the ability of SSM Die-casting to overcome the problem of large thickness variations that make conventional HPDC difficult if not impossible. Filling across fins of various thicknesses at long distances is another challenge that appears to be alleviated by SSM die-casting. LED housings, heatsinks, are now produced by Rheo-diecasting with improved properties as well as cost savings when compared to conventional HPDC. Two European applications, one of a marine winch housing using Magismal 59 and heavy-duty auto parts for AV and Volvo trucks in Sweden have shown reduced costs, reduced die soldering as well as excellent fatigue performance in dynamic applications [29].

Moving on to applications utilizing high fraction solid feedstock via the SEED process [12], shown schematically in Figure 4, a number of automotive parts have been produced, see Figure 5. The component on the left, shown in Figure 5, is aluminum 319S at T6 condition, which has replaced a steel part resulting in a weight reduction of 65%, while the one next to it has replaced a steel part with a 71% weight saving [34].

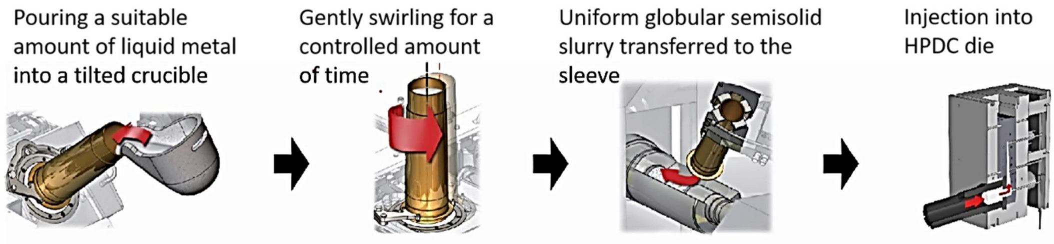


Figure 4. Schematic of the SEED (Swirled Enthalpy Equilibration Device) Rheocasting Process [12] (Courtesy Pascal Côté, STAS).

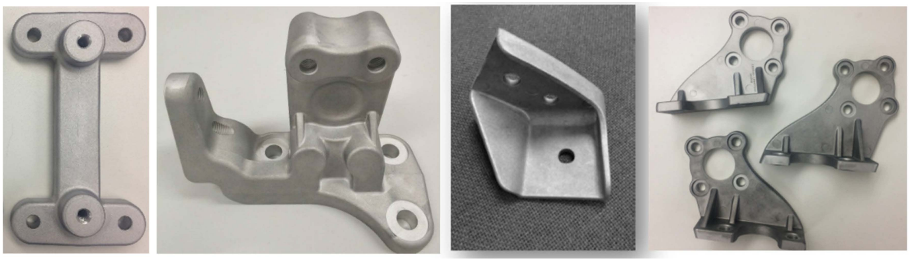


Figure 5. Automotive parts currently mass-produced in China [34] (Courtesy of Courtesy Qiang Zhu, GRINM).

A recent comparison between SSM Die-casting and Squeeze casting using the main bearing cap of an engine block as the comparative product has demonstrated that the combination of slurry flow and resulting microstructures have a significant effect on the resulting properties, with SSM products exhibiting finer grain sizes as well as a doubling in E% [35]. In summary, SSM compared to Squeeze casting offered more complex geometries, near net-shapes produced with lower in-gate velocities, close tolerances, high productivity, improved strength and heat treatable products due to reduced porosity. In addition, as SSM feedstock possesses higher viscosity, e.g., around 50% solid and 50% liquid, compared to 100% liquid, the injected metal has a laminar flow compared to Squeeze casting's near-laminar flow. Finally, SSM can deliver thick and thin parts, while with Squeeze casting only thick parts are possible.

A further demonstrator, engine bracket Figure 6, utilizing high fraction solid feedstock produced via the SEED method, has been used as a case study to investigate the performance of SSM die-cast parts in relation to conventional HPDC parts [30]. The study demonstrated that even though the shot weight for the SSM feedstock used increased from 4.8 to 5.3 kg, because of the thicker runners involved in SSM die-casting, the resulting component conferred 33% reduction in component weight; cycle times remained comparable [30].

Figure 6. Until the end of 09/2019, 130,000 engine bracket pieces have been delivered to customers.

GISS Co. Ltd., using a gas induced methodology to produce the high fraction liquid feedstock, see Figure 7., claim significant reduction of gas and shrinkage porosity in their products, 2 to 4 time extension in die-life and 10-20% cycle time reductions [10]. Auto-parts they have produced for Hyundai show porosity reductions from 1.2% down to 0.36% and their break caliper parts produced in 7075 alloy t-6 condition have 450 MPa UTS and 7% E [32].

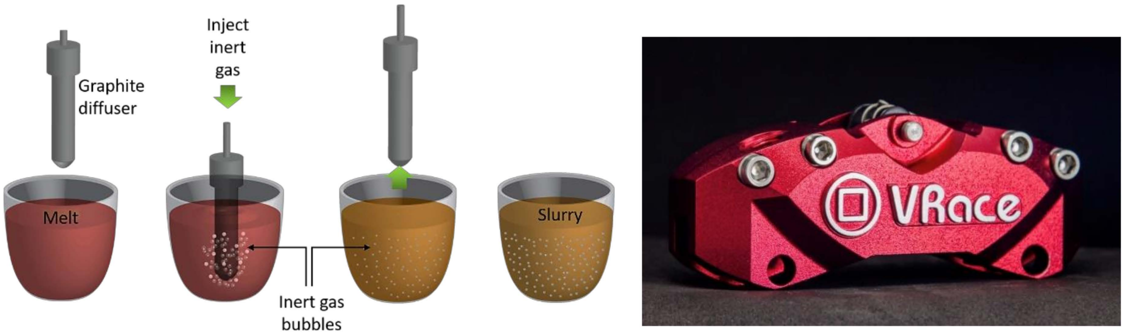


Figure 7. Schematic of the Gas Induced Semi-Solid Process and 7075-T6 anodized brake caliper produced by GISS Slurry Forging process. Courtesy of GISS-technology. http://www.gissco.com/GISS-Technology [10].

Zhu and Midson have given an update to the status of Magnesium Injection Molding in China [36] pointing out that by 2016 Thixomat reportedly had over 450 thixomolding machines installed worldwide, with around 170 of them being in China, with most producing parts for the electronics industry as well some for the automotive market [36], see automotive development examples in Figure 8. The electronic components produced by this route in magnesium range with casting thicknesses 0.5–0.6 mm with components as thin as 0.35–0.4 mm, and the largest castings around the 400 mm size. The same authors run a comparison of Thixomolding versus HCDC (Hot Chamber Die Casting), which showed favorable cost comparison results for Thixomolding. There seems to be some applications targeting components for flying drones that are in full production with up to 20,000 pieces of daily production volumes.

4. Future Prospects

"Prediction is difficult, especially about the future" is a statement commonly attributed to Niels Bohr and on occasions to Richard Feynman; either way, the essence of it is that prediction is difficult, which rings quite true. However, there is nothing stopping us to imagine future scenarios and then attempt to create them for ourselves, this way becoming masters of our future and not bystanders to it.

From the 'long' history of SSM applications [37,38], its past successes and occasional setbacks, as well as the most recent industrial applications discussed above, Net-Shape Die Casting of Semi-solid alloys (SSMDC) looks that will indeed establish itself as a conventional manufacturing process, generating improved products as compared to those from traditional HPDC and other casting technologies.

A key factor for this will be the ability to produce consistent quality SSM feedstock suitable for mass production applications. The indications are that there will continue to be two main routes to feedstock production as defined by the fraction liquid content in the feedstock. Low fraction liquid or high solid fraction billets (typically around 50% F_s and 50% F_l) such as in the MHD, SEED, SIMA (Strain Induced Melt Activation) and RAP (Recrystallization and Partial Melting) processes and high liquid fraction content, as with the GISS, SSR, Rheometal, routes [5,39,40]. Other more exotic feedstock production routes might prove appropriate for niche applications, such as Spray formed or powder metallurgy routes [26,41–43].

The second important aspect of large-scale commercialization of SSMDC will be an expanding portfolio of alloys of consistent quality and appropriate microstructures without any premium production costs attached to them. This is commercially feasible, as applications in other than the currently perceived limited range of 'standard' SSM alloys are already proving to be commercial successes [14,23,24,29–34].

The final piece in the DDMDC commercial success puzzle will be the correct choice and clear understanding of future markets. SSMDC has provided plenty of evidence of its ability to deliver large-scale mass-produced, high performance, complex near net-shape parts. These are offered at competitive costs as a number of case studies prove [14,23,24,29–34,40]. Already, manufacturers with an eye to a sustainable future are looking to exciting opportunities in traditional and non-traditional markets [44–47], as illustrated by the various parts shown in Figures 9–13.

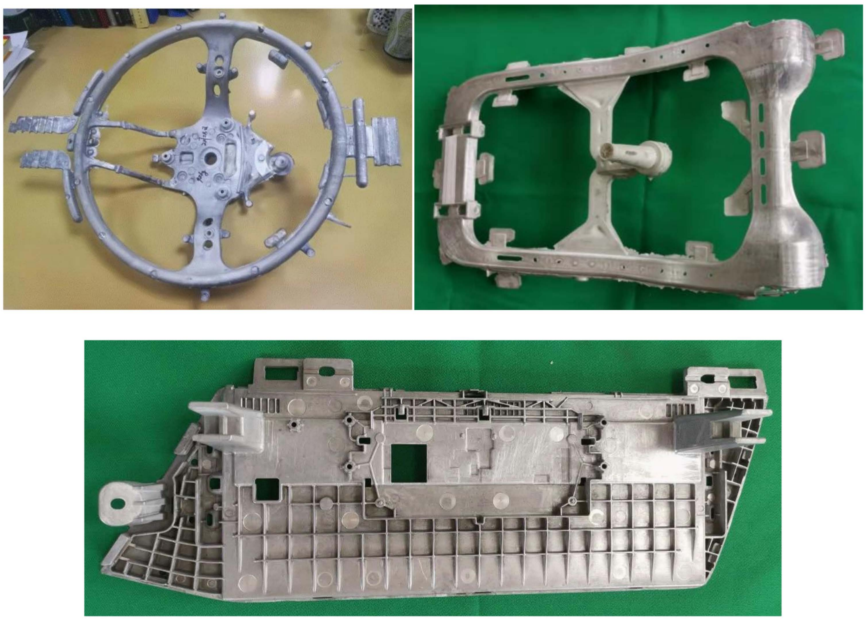


Figure 8. Automotive parts, semi-solid magnesium alloy, seat frame, steeling wheel and dashboard bracket (Courtesy of Alan Yang, Sales, Zhu Yibing's company www.ssd-magnesium.com) [36,40].

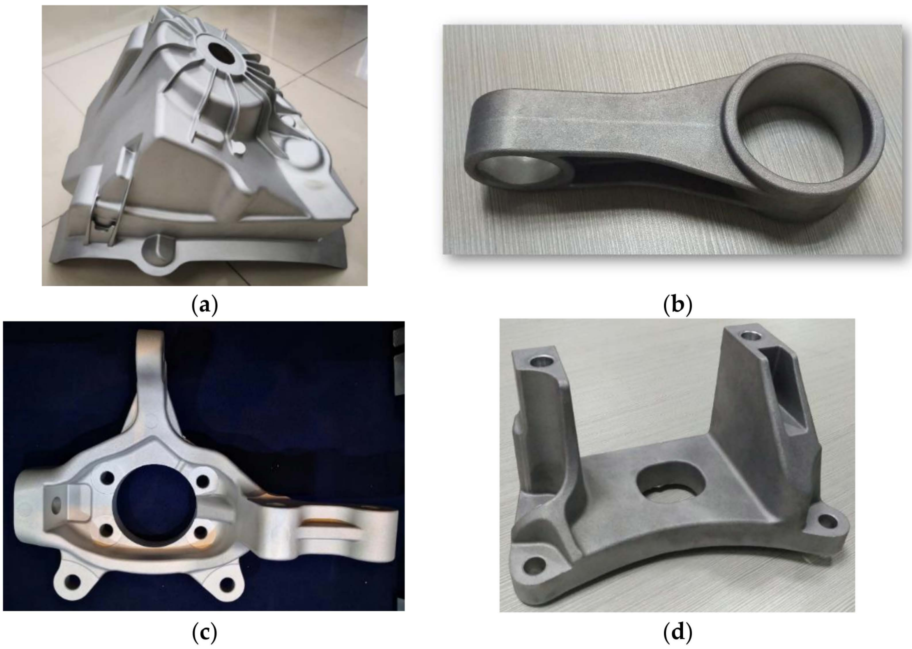
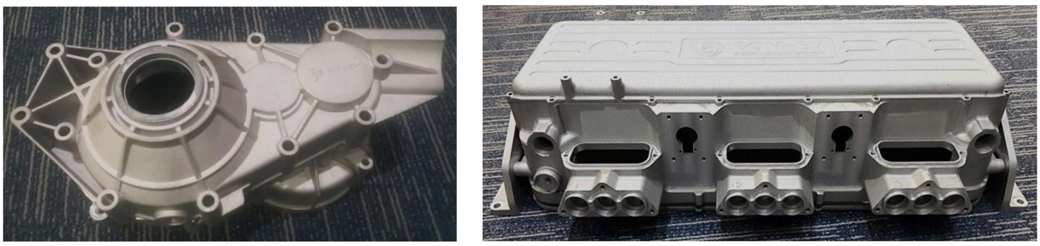


Figure 9. Automotive parts, various stages of acceptance, China. (**a**) End motor cover; (**b**) torque link; (**c**) knuckle arm; (**d**) engine support (Courtesy Qiang Zhu, GRINM) [45].

Figure 10. Large components incorporating thin parts. Left: 4G antenna case shell, size: 793 × 166 × 86 mm, addendum thickness: 1 mm. Right: communication base station cooling shell, size: 733 × 470 × 46 mm, addendum thickness: 1.1 mm [33] (Courtesy of Mingfan Qi, School of Materials Science and Engineering, University of Science and Technology Beijing).

The components shown in Figure 10 were made using Al-8%Si alloys and resulted in 58% grain size reduction, UTS, YS, E%, hardness and thermal conductivity of Rheo-HPDC parts showed increases of 21%, 24%, 158%, 10% and 11%, respectively, compared to HPDC parts [31].

Further applications by Zhuhai Runxingtai Electric have yielded favorable comparisons between Rheo-diecasting and conventional Die-casting methodologies [46]. In parallel with these activities, magnesium molding is also taking place in China with applications in components for drones [37].



(**a**) (**b**)

Figure 11. (**a**) Motor reducer housing, Size: 465 mm × 216 mm × 282 mm, the main body thickness is 3 mm; (**b**) power converter shell, Size: 648 × 302 × 128 mm, thin wall is 2 mm [33] (Courtesy Mingfan Qi University of Science and Technology Beijing).

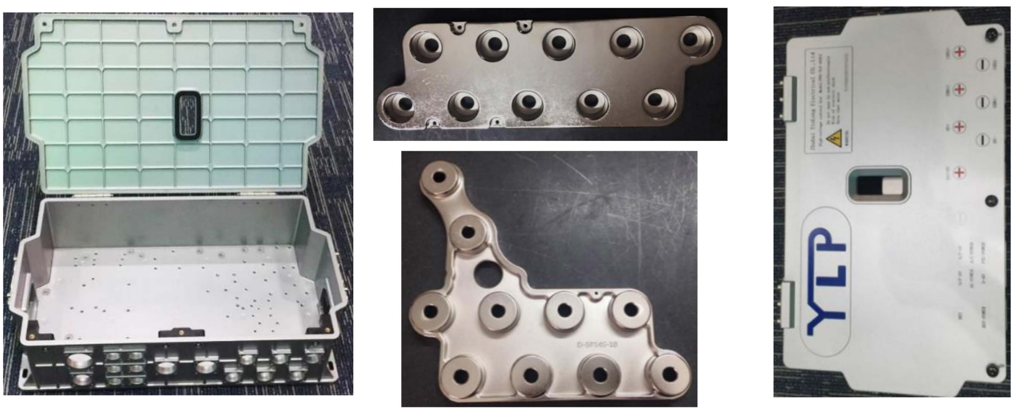


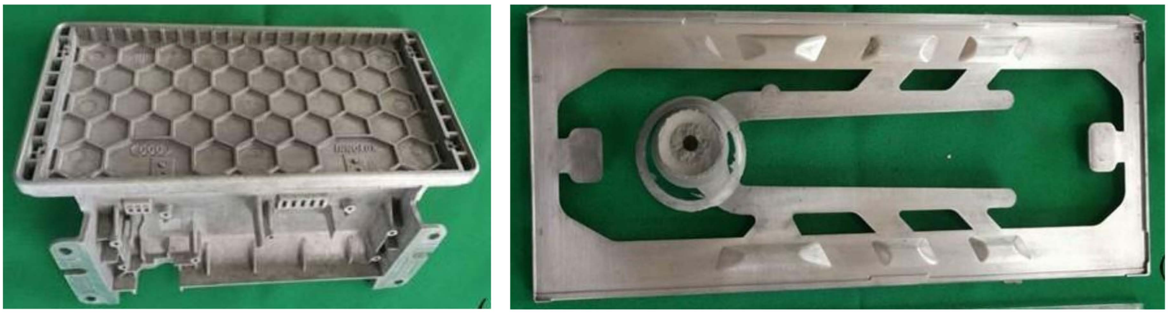
Figure 12. Application Case of Semi-solid Die Casting Technology New Energy Vehicle Power Battery Structure Parts [33] (Courtesy Mingfan Qi University of Science and Technology Beijing).

The case example shown in Figure 12 has generated a useful comparison between the products of Rheo-HPDC and conventional HPDC as shown in Table 1 below, with clear indications of product improvements via the former process [33].

Table 1. Product characteristics and comparison.

Attributes	SSM Product	Traditional HPDC Products
Process	Rheo-HPDC	HPDC
Flatness	0.4 mm	0.6 mm
Minimum wall thickness	3.5 mm	4.5 mm
Condition	No pores or shrinkage holes	Porosity and shrinkage
Weight reduction	300 g	Not achieved

Figure 13 shows examples of AZ91D magnesium high volume automotive products using semisolid injection molding currently in production by Kunshan Shengshida Machinery Co., Ltd. www.ssd-magnesium.com [46].



(**a**) (**b**)

Figure 13. SSM magnesium parts. (**a**) Car navigator member AZ91D, 280 g and (**b**) car dashboard member AZ91D, 138 g [40] (Courtesy of Frank Czerwinski—Canmet Materials).

A further interesting piece of work comparing Semisolid HPDC Al-25% Si with HPDC A383 aluminum alloy (Figure 14) demonstrated that the higher fluidity of the Al-25% Si alloy allowed the forming of thin parts, 60 mm fin height and slight increase in emissivity [47].

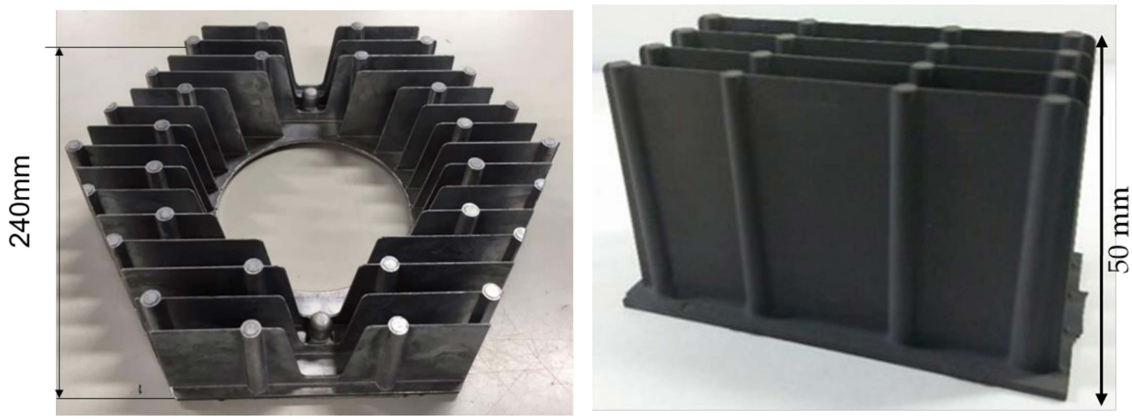


Figure 14. Semi-solid die-cast Al-25%Si heat sinks incorporating thin parts [47] (Courtesy T. Haga, Osaka Institute of Technology, Japan).

To close, some recent work on SSM of near eutectic and hypereutectic Al-Si alloys for automotive piston applications (Figure 15) showed promising properties as compared to die-casting as well as liquid forming followed by Hot Isostatic Processing (HIP) [48].

Figure 15. Piston three-dimensional (3D) model, pistons thixoformed in the AЛ25 alloy [49] (Courtesy of Prof. Boris Ivanovich Semenov).

This work is complimentary to previous work on hypereutectic Al-Si alloys for automotive applications [49].

5. Conclusions

We live in a rapidly changing world providing us with many challenges, but equally with as many opportunities. There is little doubt that humanity is affecting our environment and that in order to mitigate some of the impacts, there will have to be a concerted worldwide effort on all fronts in order to succeed in making our world sustainable. Better use of resources and a more efficient use of energy are two obvious areas that engineers and scientists can address this problem both in the short and long term. Semi-solid metal alloy die-casting (SSMDC) appears to hit a number of targets as it can provide industry with a manufacturing methodology for mass-produced, better performance near net-shape complex products, with increased energy use and efficiency. SSMDC delivers savings in all fronts as compared to conventional HPDC and other casting technologies. Because of its near net-shape capabilities, SSMDC removes extra processing steps. Through the particular microstructures associated with the process and the corresponding rheological advantages, the process delivers products with higher mechanical properties than traditional counterparts do, as metal flow into molds is uniform and porosity and shrinkage are much reduced or eliminated. This delivers the added advantage of further property enhancement through heat treatments that was not something typically associated with traditional processes. Product after product demonstrate weight savings, resulting in more efficient use of materials and associated cost savings, as well as reduced environmental impacts. There is lower energy consumption associated with the process by virtue of the fact that the metal is never fully liquid. In addition, through a combination of all the above advantages, designers can eliminate some design features associated with traditional processes that are no longer necessary, resulting in more material-efficient products. In the same spirit, certain product design features can now be combined into complex near net-shape designs that need less post-production operations before final use. In order for a manufacturing technology to be commercially viable and ultimately successful, it should deliver: better quality, better design, cost reductions, weight reductions or combinations of all of these. It is evident from the above review of the current industrial status of SSMDC that it delivers on all of these demands, and therefore, its commercial future should be assured. The mere fact that a number of producers, mainly in China, have decided to put their faith in the process gives support to the expectation that SSMDC in its current reincarnation will finally become an acceptable 'conventional' manufacturing process.

SSMDC is no longer a 'new' or 'novel' technology; it is a 'mature' technology looking for appropriate markets to impart its many demonstrable advantages.

Author Contributions: Writing—review and editing done by the author.

Funding: This research received no external funding.

Acknowledgments: The author would like to acknowledge the kind contributions of photographic and other material by so many colleagues that have made this publication possible. Thanks are due to: Qiang Zhu, founder and head of the SSM R&D team at GRINM and leader of research team at Southern University of Science and Technology (SUSTech), Xiaogang Hu (SUSTech). Frank Czerwinski—Canmet Materials. Zhu Yibing—CEO ssd-magnesium and Alan Yang—Sales ssd-magnesium. Mingfan Qi (University of Science and Technology Beijing). Zhuhai Runxingtai Electric. Kunshan Shengshida Machinery Co. Ltd. Vlastimil Bryksí—KOVOLIS HEDVIKOV a.s. (akciová společnost) (Ltd.). Pascal Côté, stas. Song Chen (GRINM). Toshio Haga (OIT).

Conflicts of Interest: The authors declare no conflict of interest.

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