Rheoforming of Novel Aluminium and Magnesium Alloys

By Geoff Scamans and Zhongyun Fan

There have been multiple variations of rheocasting and thixocasting technologies available for many years although very few of these have resulted in commercially successful alloy production. Recent work at BCAST (Brunel Centre for Advanced Solidification Technology) at Brunel University has resulted in the development of a new family of rheocasting technologies that are suitable for application in a wide range of aluminium and magnesium casting applications. These technologies have been called rheoforming technologies and after six years of intensive R&D, they are now ready for industrial exploitation.

The most developed form of rheoforming at BCAST is rheo-diecasting (RDC) to improve the properties of aluminium and magnesium high pressure die castings. High pressure die casting (HPDC) process is a mature technology, which has been extensively used by the metal processing industry due to its unique characteristics, such as high efficiency, high production volume and low production cost. Currently, the majority of the aluminium and magnesium castings used by the automotive and mass transport industry are produced by the HPDC process. However, the quality of components manufactured by the HPDC process is limited by the presence of a substantial amount of porosity, which not only excludes the application of HPDC components in high-safety and airtight systems, but also denies the opportunity for further property enhancement by heat treatment. Further increase in aluminium and magnesium applications in the transport industry requires a major advance in processing technologies like RDC to provide castings without these inherent defects.

The BCAST RDC process is an innovative one-step semisolid metal (SSM) processing technique to manufacture near-net shape components of high integrity directly from liquid alloys. The process innovatively adapts the well-established high shear dispersive mixing action of the twin-screw extruder to the task of in situ creation of a SSM slurry with fine and spherical solid particles followed by direct shaping of the SSM slurry into a near-net shape component using the existing cold chamber diecasting process. The RDC equipment (Figure 1) consists of three basic functional units, a twin-screw slurry maker, a standard cold chamber HPDC machine and a central control unit. The twin-screw slurry maker has a pair of co-rotating, fully intermeshing and self-wiping screws rotating inside a barrel. The screws have specially designed profiles to achieve high shear rate and high intensity of turbulence. During the rheo-diecasting process, a predetermined dose of liquid alloy from the melting furnace is fed into the slurry maker. The liquid alloy is rapidly cooled to the SSM processing temperature while being mechanically sheared by a pair of closely intermeshing screws converting the liquid into semisolid slurry with fine and spherical particles of a given volume fraction dictated by the barrel temperature. The semisolid slurry is then transferred to the shot chamber of the HPDC machine for component shaping.

The RDC process originated from theoretical understanding of the rheology of semisolid metals and solidification behaviour under intensive forced convection. The most important objective of semisolid metal processing is to achieve laminar mould filling to avoid gas entrapment by increasing the viscosity of the feed material while maintaining adequate fluidity for a complete mould filling. It is important to have a good understanding of the rheological behaviour of semisolid slurries. Theoretical modelling has defined the ideal semisolid slurry for semisolid processing, (a suitable volume fraction of solid particles with fine particle size and spherical morphology dispersed uniformly throughout a liquid matrix). The ideal semisolid slurry is achieved by controlling the nucleation and growth processes during solidification. In conventional casting processes, overheated liquid metal is poured into a relatively cold mould and heterogeneous nucleation takes place in the undercooled liquid close to the mould wall. The majority of the nuclei are transferred to the overheated liquid region and re-melted and only a small proportion (as low as 0.3%) of the nuclei survive and contribute to the final microstructure, giving rise to a coarse and non-uniform microstructure. The most important step towards microstructural refinement is to make sure that every single nucleus formed during nucleation can survive. This is achieved if the solidifying liquid metal has uniform temperature, uniform chemical composition and well-dispersed nucleation agents throughout the entire volume of the liquid alloy. Under such conditions, nucleation will occur throughout the entire volume of liquid and every nucleus will survive and contribute to the final solidified microstructure, creating a fine and uniform microstructure (Figure 2). The next step is to ensure that the survived nuclei grow into spherical particles, rather than dendrites or rosettes. Analysis on the morphological evolution during solidification has revealed that with increasing shear rate and intensity of turbulence, the growth morphology changes from dendrites to spheres due to the change in the diffusion geometry in the liquid around the growing solid phase. Theoretical prediction has been verified by experimental results and the conditions to achieve spherical crystal growth are high shear rate and high intensity of turbulence. Once the conditions to achieve ideal semisolid slurry were understood, we needed to identify a physical mechanism to realise such conditions. After intensive search and comparison of available mechanisms, we adapted the well-established high shear dispersive mixing action of the twin-screw device to the task of in situ creation of SSM slurry with fine and spherical particles. A combination of the twin-screw slurry maker and a conventional HPDC machine forms the basis of the rheo-diecasting (RDC) process.

The main advantages of the rheo-diecasting process over the conventional HPDC process can be summarised as follows:

- Fine and uniform microstructure throughout the entire component (Figure 3)
- Close-to-zero porosity (well below 0.5 vol.%) thus fully heat treatable
- Well-dispersed oxide particles with fine size and spherical morphology
- Increased tolerance of impurities allowing more scrap to be used
- Significantly improved mechanical properties, >100% increase in elongation and >15% increase in strength (Figure 4)
- Capability of processing wrought alloys, immiscible alloys and other alloys that are difficult to cast
- Longer die life, lower scrap rate, shorter cycle time and higher materials yield
- Lower overall component production cost (up to 25% cost saving)

Technologically, the RDC process brings a step change to the metals processing industry. It provides near-net shape components with high integrity, substantially improved performance and considerably lower cost. More importantly, the RDC process is an enabling technology, which provides cast components with wrought quality. It, therefore, eliminates the conventional boundaries between cast and wrought products and the division between cast and wrought alloys. Scientifically, it pushes the boundary of conventional solidification under static condition into solidification under intensive forced convection. In conventional casting, solidification starts from the mould wall and pushes into the centre of the cast, resulting in the typical 3-zone structure. In contrast, nucleation and growth in the RDC process take place throughout the entire volume of the liquid alloy due to the extremely uniform temperature and composition fields, giving rise to a fine and uniform microstructure and therefore improved mechanical performance. Environmentally, the RDC process, as an enabling technology, can promote wider applications of light-weight components in the automotive industry. The weight savings achieved will result in reduced fuel consumption and CO_2 emission.

Following on from the RDC process the twin screw slurry maker has been considered as a means of feeding liquid metal into a direct chill caster, resulting in the development of direct chill rheocasting (DCRC Figure 5) process for slabs and billets and into a twin roll caster, resulting in the twin roll rheocasting (TRRC Figure 6) process for sheets and thick plates. The slurry can also be fed into an extrusion press as the basis of the rheo-extrusion process for a variety of extruded profiles. This family of rheoforming technologies can provide the structural materials sector with a new generation of high performance, high quality products that are cost competitive with existing products.

Basically the rheoforming technologies circumvent existing liquid metal processing and casting technology boundaries with a simpler, lower cost process. A specific innovative impact is the ability to produce alloys with compositions beyond those available from conventional melting technologies. This means that alloys with extended compositional ranges can be provided for the first time. Such alloys have only been made in the past by expensive and multi-step complex powder routes and/or by mechanical alloying. The rheoforming technologies can potentially make alloys of extreme specific strength, modulus and ductility for both aerospace and other transportation applications. The potential for new alloys and applications is enormous and the technology is particularly effective for the recycling of highly impure secondary metal (low grade scrap) due to the inherent microstructural refinement.

For wrought aluminium the range of conventionally cast alloys is really quite limited and is based on several well known alloy families that make up the alloy series from AA1xxx to AA8xxx. Structural applications are generally served by alloys of the AA2xxx (AlCuMg), AA3xxx (AlMnMg), AA5xxx (AlMg), AA6xxx (AlMgSi), AA7xxx (AlZnMg(Cu)) and AA8xxx (AlLiCuMg) families. The alloy ranges are limited mainly by solid solubility considerations as there are only a few elements that have extended solid solubility in aluminium. This results in many coarse constituent phases with conventional solidification process and a dramatic loss of alloy properties. Generally these properties are recovered by extensive thermomechanical treatment from the cast state. These treatments are mainly designed to refine and homogenise alloy microstructures.

For the past 100 years the aluminium industry has tried to develop and expand the useable alloy range and to develop alternative production routes to novel alloys. Alloys have been developed for all types of extreme applications where high temperature performance or high levels of corrosion performance are required. In many cases the only way to reach property targets has been by rapid solidification of powders followed by expensive compaction processes or by the development of complex routes to metal matrix composites.

Preliminary work has shown that both high iron and high silicon aluminium alloys can be rheo-diecast to provide refined uniform defect free microstructures. These alloy systems can form the basis of alloys for the required highly demanding applications. Bearing alloys based on immiscible systems have also been produced.

There is also considerable scope for process innovation as the rheoformed slurry can be fed into variants of the standard DC casting process for example both thin DC casting and horizontal DC casting processes have been developed. The thin DC process is particularly applicable to plate and sheet production and is used to produce a near net shape product to reduce the amount of thermomechanical processing required. This can takle advantage of the refined, uniform as cast microstructure provided by the DCRC process. Horizontal casting means that there is no need to dig casting pits and that casting can be continuous and not limited by the pit depth. This also takes advantage of the fine uniform as cast microstructure. It is also possible to rheocast one aluminium alloy on to the surface of another.

The twin-roll rheocasting (TRRC) process consists of three basic functional units: twin-screw slurry makers, a slurry accumulator and a standard twin-roll caster. The basic function of the accumulator is to bridge the gap between the batch processing of the twin-screw slurry maker and the continuous processing of the twin-roll caster. During the TRRC process, liquid alloy is sequentially fed into the slurry maker where it is transformed into high quality semisolid slurry with a designated solid fraction. The semisolid slurry is then transferred into the slurry accumulator, from which the slurry is fed continuously into the twin-roll caster for sheet production.

The advantages of the TRRC technology include:

- Cost-effectiveness. Compared with the conventional DC casting-rolling route, the TRRC process reduces the processing steps to a minimum. This reflects a significant saving on capital investment, raw materials, energy consumption, operating space and manpower.
- High quality. The TRRC process offers aluminium sheet products with a fine and uniform microstructure over the entire cross-section. The fine and uniform microstructure not only facilitates the subsequent component production process, but also ensures enhanced mechanical properties and improved component performance.
- Flexible manufacturing. The key equipment in the TRRC process is the slurry supply system, which can be attached to different twin-roll casters for the production of aluminium sheets with a variety of sheet widths and thicknesses. In addition, TRRC process has a large processing window and is capable of producing sheets from a large range of alloys.
- Eco-friendliness. The TRRC technology offers a low-cost and high-quality route to sheet products. This will greatly facilitate the penetration of such eco-friendly materials into the transportation industries for reduction of fuel consumption and CO_2 emissions. This will eventually create a better environment for sustainable development.

Technologically, the TRRC process represents a step-change in the manufacturing technology for production of lightweight automotive sheets. Together with other related technologies, such as rheo-diecasting, rheoextrusion and DC rheocasting, TRRC process provides the automotive industry with a complete technological solution to vehicle weight reduction.

Innoval Technology is working directly with BCAST to promote the development and industrial application of the rheoforming technologies. This combines Innoval's extensive knowledge of aluminium alloy technology and industrial application with BCAST's solidification expertise.