Twin Roll Rheocasting of Aluminium Alloys

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Introduction

The advantages and disadvantages of twin roll casting of aluminium alloy strip are well known and have been extensively discussed for many years. The hot band cost for the castable range of alloys is lower by $30 to $100/tonne compared to strip made by conventional DC casting and subsequent hot and cold rolling. However, this is offset by major concerns related to surface quality for bare or laquered products and by the limited range of castable alloys which has restricted the use of twin roll casters to painted architectural sheet and packaging products. Major developments are required to extend the castable alloy range and to improve surface quality, productivity and consistency. Specific goals are to be able to make automotive sheet, both for structural and for closure panels, and aerospace sheet by a twin roll casting route. This means that twin roll casting technology must be extended to make alloys such as AA5754, AA5182, AA2024 and AA7075, or their siblings and descendants, castable.

Semisolid metal (SSM) processing has been a promising technique for the rheocasting or thixocasting of aluminium alloys for more than 30 years although its commercial exploitation has had very limited success1-3. Recent work at Brunel University has shown that 'ideal' semi solid slurry can be developed from melts of aluminium and magnesium alloys by high shear melt processing and that such slurries can be fed into a wide range of conventional casting processes, including twin roll casting. This technology is the basis of a family of rheoforming technologies shown in Figure 1. Feeding a continuous caster with SSM opens up the range of aluminium alloys that can be considered to be twin roll castable and also increases the potential to make alloys from secondary metal and to produce strip that is essentially free of defects. Rheoformed aluminium alloys are produced with fine uniform microstructures from the cast state and subsequent thermomechanical processing can be minimised to provide cost effective high performance sheet products.

The combination of a conventional roll caster fed with a high shear processed semi-sold metal has been termed twin roll rheocasting (TRRC). The purpose of this article is to present an overview of high shear rheocasting of aluminium alloys and to introduce and discuss the potential of the TRRC process, particularly for automotive applications.

Twin Roll Rheocasting

Twin-roll rheocasting (TRRC) requires three basic units: a twin-screw slurry maker or makers; a slurry accumulator; and a standard twin-roll caster. The 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 strip production. This process is shown schematically in Figure 2. The critical component of the system is the slurry maker that provides the conditioned semi-solid melt to be fed to the caster via the accumulator. The appropriately conditioned slurry is produced by high shear melt processing using the twin screw mechanism to apply forced convection to the solidifying liquid.

High Shear Melt Processing

Subjecting a melt to high shear processing means that, unlike conventional solidification under static conditions, nucleation and crystal growth occurs in a controlled dynamic environment. Research on nucleation and growth under forced convection has been very limited4 and there is only a basic understanding of the effects on nucleation rate and growth morphology. The conventional belief is that under forced convection dendrites fragment and detached dendrite arms then undergo a coarsening process to provide the observed globular particles. However, more recently it has been shown that under intensive forced convection the globular structure is more likely to be the result of spherical growth under forced convection, rather than as a consequence of dendrite arm detachment2. The globular structure is a direct result of spherical growth under intensive forced convection and the growth morphology changes from dendritic to spherical through rosette with increasing shear rate and degree of turbulence, as is shown in Figure 3. Practically, appropriate forced convection conditions of high shear rate and high intensity of turbulence are achieved within a twin screw slurry maker and typical times to produce conditioned semi-solid slurry are of the order of 10 to 20 seconds. The output from the slurry maker can be tuned to the casting volume requirement by either increasing the size of the twin screw slurry maker or by having multiple units.

The Twin Screw Slurry Maker

The twin-screw slurry maker has a pair of screws rotating inside a barrel. The fully intermeshing screws have specially designed profiles to achieve co-rotation and self-wiping. During the slurry making process, there is an extreme, ever-changing interfacial area between the solidifying alloy and the slurry maker, providing enhanced heat transfer.

The complex fluid flow inside the slurry maker is characterised by high shear rate, high intensity of turbulence, and a cyclic variation of shear rate. The shear rate in the twin-screw slurry maker is continuously changing and an elemental volume of alloy melt will experience a cyclic variation of shear rate, with the shear rate being highest at the intermeshing region, and lowest between the screw root and the inner barrel surface. This is shown schematically in Figure 4. The degree of turbulence is even more difficult to quantify. However, both shear rate and degree of turbulence are proportional to the screw rotation speed. The higher the screw rotation speed, the higher the shear rate and the degree of turbulence although flow is turbulent even at low screw rotation speed.

In operation, a predetermined charge of liquid alloy from the melting furnace is fed into the twin screw slurry maker. The liquid alloy is continuously cooled to the SSM processing temperature whilst being mechanically sheared, converting the liquid into semisolid slurry. The solid fraction of the semisolid slurry is controlled by the barrel temperature. Both melt temperature and composition fields inside the slurry maker are extremely uniform during this primary solidification, owing to the dispersive mixing of the twin-screw mechanism. Heterogeneous nucleation occurs continuously throughout the entire volume of the melt and all nuclei can survive and contribute to the final microstructure, and this critical process is called effective continuous nucleation. The experimentally determined volume fraction of primary particles formed in the twin-screw slurry maker as a function of shearing time and screw rotation speed is shown in Figure 5. The average size of the primary particles formed in the twin-screw slurry maker as a function of shearing time and screw rotation speed is shown in Figure 6. The nuclei grow spherically with a very fast growth rate under intensive forced convection, and particle coarsening occurs through Ostwald ripening by consumption of the smaller particles. The coarsening rate is extremely slow due to the spherical particle morphology and the narrow particle size distribution. Increasing the intensity of forced convection decreases both volume fraction and particle size, but does not enhance the nucleation rate. A more detailed description of this solidification process has recently been published4.

A major challenge was to find a suitable material for the construction of the screws and the barrel that would survive exposure to highly reactive aluminium melts. Initial efforts to find non-reactive materials or to use coatings were unsuccessful until the concept was changed to source a material that would react to provide a protective layer. Having found and extensively tested this material, the twin screw slurry maker can now be readily fabricated and can survive prolonged exposure to turbulent aluminium alloy melts. The twin screw slurry maker is now in its fourth design generation.

Since slurry making is essentially a batch process the second key component in the slurry delivery system is the accumulator which acts as a reservoir to provide a sufficient volume of slurry for feeding into the casting system. A blade type stirrer is fitted in the accumulator to prevent particle agglomeration and to maintain the slurry uniformity. The semisolid slurry is then transferred to feed the twin roll caster.

It should be realised that solidification takes place in two distinct stages; primary solidification inside the twin-screw slurry maker followed by secondary solidification of the remaining liquid in the bite of the twin roll caster.

High Shear Rheo-casting of Aluminium Alloys

Preliminary studies have been carried out by casting high shear processed slurries of aluminium alloys into a high pressure diecaster. The mechanical properties of aluminium alloy A357 after rheo-diecasting are compared to those of the same alloy after thixocasting and ‘new rheocasting’ in Figure 7. The rheo-diecast A357 shows both improved strength and elongation compared to the samples produced by the other SSM casting technologies. Figure 8 shows the as rheo-diecast microstructures of AA2014 and AA7075 aerospace alloys. In both cases the microstructures show the typical 50µm diameter spherical particles formed in the slurry maker together with the refined microstructure of the alloy that solidified in the die chamber. This too has a spherical non-dendritic microstructure because the remaining liquid in the SSM slurry solidifies under high cooling rate. Shape castings have also been produced by feeding the conditioned slurry into a high pressure diecaster and Figure 9 shows a component cast using alloy LM24 (A380). The microstructure is uniform throughout the casting and shows no evidence of a chill zone or columnar crystal growth. The solid fraction and particle size are remarkably consistent in all parts of the component.

The rheocasting process can also successfully cast alloys that are essentially immiscible and/or have an exceptionally wide freezing range. Preliminary work has shown that aluminium alloys with up to 2wt% iron are readily castable with fine uniform microstructures, as is shown for the aluminium casting alloy LM24 rheo-diecast with three different iron levels in Figure 10. Tolerance of increased or higher levels of iron in aluminium alloys is of considerable importance for the future incorporation of higher levels of recycled scrap into aluminium products. In addition to the low porosity levels and dispersed oxides these rheocast alloys have advantages in that primary intermetallic particles are uniformly distributed, are refined in size and are equiaxed in morphology. The needles or plates found in conventional as-cast microstructures are completely eliminated.

Potential Automotive Applications

The initial application for TRRC aluminium sheet has been identified as structural sheet suitable for the mass production of sheet intensive body-in-white (BIW) structures. Jaguar Land Rover (JLR) has provided target properties (essentially to match the performance of conventionally produced AA5754) and a price target to match the cost of automotive steel for the same application5. Since the aluminium BIW has half the weight of a steel structure, as demonstrated by Ford with their P2000 concept vehicle6, this means providing aluminium sheet at a price close to $1000/tonne to be competitive. The aluminium price trend over the past thirty years is shown in Figure 11. Clearly, even with recent increase in the price of automotive steel sheet, this can't be achieved using primary aluminium metal so one option is to use recycled aluminium as the metal source. It should be noted that of the more than 700 million tonnes of aluminium that have been produced since 1888, more than 500 million tonnes are still in use and potentially form a global metal pool of secondary metal. The energy to convert aluminium hydrate to liquid aluminium is 8.5kWh/kg compared to 0.32kWh/kg to go from solid aluminium scrap to liquid metal, meaning that the energy consumed in recycling is less than 5% of the energy used to make the primary metal7. The most obvious source of secondary metal to use for TRRC is used beverage cans (UBCs), particularly those that are presently lost to landfill (in the UK this is 3 billion cans or 45,000 tonnes of aluminium). In the US the number of cans wasted has been estimated to be 51 billion by the Container Recycling Institute and this is 9 billion more cans than in 2000. This represents a loss of the order of 690,000 tonnes or $1 billion in value of aluminium each year. To put this in context the largest smelters in the world have an annual capacity of the order of 400,000 tonnes.

The relevant compositions of AA5754 and recycled beverage can scrap are shown in Figure 12. The magnesium level in AA5754 makes it essentially non-castable by conventional twin roll casting technology although the alloy can be successfully cast using twin belt casting technology. In addition the iron content of recycled can scrap is higher than that of the AA5754 used for automotive BIW applications. The challenge for the TRRC process is both castability and iron tolerance.

As an illustration, the 45,000 tonnes of aluminium, if recovered in the UK, could be used to make more than 200,000 lightweight aluminium BIWs per year. This could have a major impact on carbon emissions since each of these BIWs could potentially be the basis of a light weight, highly fuel efficient vehicle. The Ford P2000 with a 200kg BIW had an estimated curb weight that was 40% less than the Contour/Mondeo on which it was based6 (see Figure 13).

The production of AA5754 or equivalent, structural automotive sheet, from recycled metal via the TRRC route could be the breakthrough that allows the large potential environmental benefits of mass produced aluminium intensive vehicles to be realised. This is just one example of the potential application of the TRRC process for aluminium sheet manufacture

Summary

The advantages of the TRRC technology include:

- Cost-effectiveness. Compared with the conventional DC casting-rolling route, the TRRC process reduces 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 produces aluminium strip products with a fine and uniform microstructure over the entire cross-section. This fine and uniform microstructure not only facilitates the subsequent component production process, but also ensures enhanced mechanical properties and improved performance in the final component.
- 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, the 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 route to high-quality sheet products. This could greatly facilitate the penetration of such eco-friendly materials into the transportation industries both for reduced fuel consumption and CO2 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.

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