Development of Axial Continuous Metal Expeller for melt conditioning of alloys

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Abstract. ACME (Axial, centrifugal metal expeller) is a novel processing technology developed independently for conditioning liquid metal prior to solidification processing. The ACME process is based on an axial compressor and uses a rotor stator mechanism to impose a high shear rate and a high intensity of turbulence to the liquid metal, so that the conditioned liquid metal has uniform temperature and uniform chemical composition as it is expelled. The microstructural refinement is achieved through the process of dendrite fragmentation while taking advantage of the thixotropic property of semisolid metal slurry so that it can be conveyed for further downstream operations. This paper introduces the concept and its advantages over current technologies.

1. Axial Continuous Metal Expeller (ACME) –Theory and evolution of design

The hall petch relationship tells us that the yield strength is inversely proportional to the grain size. Research shows that applying shear to a semisolid melt results in the formation of fine equiaxed grains rather than dendritic structures with much larger grain size [1,8]. This is because the shear force effectively breaks the forming dendrites and distributes them evenly through the melt. Further to this due to the turbulent nature of the uncooled liquid phase formed dendritic arms are also smoothened and melt the dendritic arms until the resultant structure is near spheroidal. There two overall mechanisms that occur in this phenomenon. These are detailed schematically below in Figure 1 and 2.

1. Increase in shear rate and intensity of turbulence

Fig. 1(a) undeformed dendrite; (b) after bending (c) formation of high angle grain boundary; (d) fragmentation [1]

Fig. 2 Schematic of morphological transition from dendritic to spherical via rosette with increase in the shear rate and intensity of turbulence [1]
Currently there are two prevailing technologies being developed to achieve this and a third that combines the two to produce continuous profiles. However these methods are inherently not suitable to the application of this sort of metal processing.

2.1 MCAST

In 2002 the BCAST institute at Brunel University discovered that turbulence and high shear can effectively spheroidise the grain shape and accordingly created the MCAST machine to process light metals (aluminium and magnesium) [2,3]. However since it is a co-rotating twin screw design, the MCAST machine has limited transport capability as the machine is inherently a mixer. Furthermore due to the number of wearing parts the machinery cannot be built out of ceramics and metal is used instead. This gives it limited applicability when considering aluminium alloys due to the corrosive nature of molten aluminium. Molybdenum is used for this particular application and even this has been found to be ineffective against the chemical attack of aluminium leading to contamination of the melt. There is another overlooked flaw in the design that makes porosity is inherent, this is schematically described below. Currently the machine is operated with a tilt to overcome the transportation limits of the co rotating screw design. This creates an air pocket that creates porosity. Furthermore Pascal’s principle means that liquid will want to find its own level and travel backwards causing leakage and jamming screws in the bush. [6]. This is highlighted in Figure 3.

Fig.3 Schematic illustration of MCAST machine [4]

2.2 HSM

To overcome some of these shortcomings the second concept being tried is the High shear mixer (HSM) shown in Figure 4. This is a compact device that uses rotor stator technology to deliver shear to a melt. Currently the HSM is being developed at Brunel University [4] and represents a step change in the technology available to process material. The machinery can be built using ceramics however the concept is lacking in process controllability and transport/pressure build up capability limiting its applicability to continuous casting and melt delivery operations.

Fig.4 Schematic illustration of High Shear Mixer (HSM) [4]
2.3 Rheo-Extrusion

To overcome this BCAST developed the Twin screw rheo-extrusion (TSRE) technology that incorporates a counter rotating twin screw extruder in conjunction with the HSM to produce continuous bars of metal [5]. Although known for transport/ positive displacement capability counter rotating screw extruders are known to produce less shear compared to their co rotating counterparts and the technology is used in combination with the HSM to overcome the limitations of each technique.[6]

![Fig.5 Schematic illustration of Twin-Screw Rheo-Extrusion [5]](image)

Furthermore, the technology has the same limitations in applicability as the co-rotating counterpart due to wearing parts and suffers from the same contamination when processing aluminium alloys. Furthermore a high level of porosity is observed in processed material due to an ingress of air from the back of the screw barrel and from the top of the HSM.[6]

2.4 ACME [7]

The new proposed design has been engineered to overcome these weaknesses to produce the required shear while maintaining transport capabilities. The machine is auxiliary and can be easily placed in the process route of current fabrication methods. It is based on the axial compressor and consists of rotors and stators placed alternatively in a conical barrel. As it is a vertical machine the problem of melt traveling backwards to find its own level is eliminated as is the pocket of air behind the inlet i.e. the main cause for porosity in both twin screw concepts.

Heaters can be attached along the sleeve into which the barrel halves sit in stages to produce a thermal gradient and control the temperature solid fraction and shear rate and therefore the evolution of the microstructure. The rotor stator mechanism ensures shear is provided without rubbing parts allowing for the design to be made from inert ceramics. Furthermore, particles or gasses can be introduced into the melt and dispersed to produce metal matrix composites, metal foams with a refined microstructure or just aid with foundry applications such as degassing or transport of liquid metal.

2.4.1 Description

The Acme device comprises of a rotor mechanism, stator plates and a baffle plate baffle plate housed in a barrel of reducing diameter. The rotor comprises of a shaft along which are positioned several rotor blades driven by a motor. Each stator is fixed into the walls of the barrel and sits in slots. During assembly the sequence of a holding/reservoir stage followed by vertically alternating arrangements of stator and rotor stages is achieved. The assembly arrangement is as shown in Figure 6. Finally a conical sleeve is placed over the barrel to hold the assembly together.
2.4.2 Operating principles

During operation, the motor passes the power to the rotor via the rotor shaft and drives the rotors to rotate between the stators. This causes a negative pressure downwards and a swirling of the liquid. As the liquid is swirling across the stator plate, due to the small gap in between the rotor blades and the stator the melt is sheared. Furthermore the high speed of the blades causes shearing of the melt as the blade cuts through the liquid and liquid is forced across the blade. As the melt is pushed through the gaps in the stator plate it is sheared even more. As the slurry passes through stator the swirl element of the flow is reduced and this is translated into pressure energy and a subsequent rise of pressure occurs across the stator stage. Once across the stator stage the melt is subjected to an even smaller volume as the diameter of the barrel is decreased. This in turn adds to the overall pressure in the system at this stage. The purpose of the stator is to shear as well as to convert as much kinetic energy into pressure energy as this helps in the overall transport of the system. After clearing the stator the melt is again met by another set of blades and the process is repeated until enough intensive shearing has occurred and enough pressure has been built up in the fluid.

Cavitation increases the surface area exposed to air increasing the oxidation of the melt. The cavitation in the ACME machine is controlled with the use of a baffle plate. This is an extra component that is in essence a combination of a stator with protruding baffles on the top and bottom surfaces placed as the top plate on the machine assembly. The function of this plate is to nullify any surface cavitation of the spinning fluid and to dampen the inertia of the spinning liquid on the top so that a stationary pool of liquid is formed at the inlet.

The viscosity and grain size is controlled by the thermal gradient along the barrel and the rotational speed of the motor. Control of the thermal gradient along the axis of process direction is achieved by placing heaters at reducing temperatures around the outside of the barrel one on top of the other. This could provide a higher level of temperature controllability across process stages.

As the metal alloy cools down first the primary element will solidify and the material will comprise of primary particles suspended in a liquid of the alloying elements. Controlling the temperature profile allows this transition needs to take place in a specific area of choosing in
the machine. Exploiting this allows for primary particles to remain equidistant from each other in 3D space so that the sinking is minimized and segregation of the primary material and alloying elements is reduced. The functions of the apparatus and methods in a variety of forms according to this invention include, but are not limited to, the following:

The said ACME device can provide physical grain refining to metals and alloys by activating both endogenous and exogenous solid particles in the liquid metals, resulting in a significant grain refinement of the metallic materials in a continuous as well as a batch wise manner.

- The said ACME device can reduce the size, disperse effectively and distribute uniformly solid particles, liquid droplets and gas bubbles in the liquid metals.
- The said ACME device can improve the homogenisation of chemical composition and temperature field in the liquid metals.
- The said ACME device can enhance the kinetic conditions for chemical reactions and phase transformations involving at least one liquid phase.

3. Comparative analysis of axial vs radial upon scaling up

This section compares the advantages of an axial design to radial designs such as the HSM to explore the commercial viability of scaling up.

3.1 Cost efficiency of design

In the axial machine, there are two dimensions in the geometry you can alter to optimise heat transfer (radius and length) versus one for the radial machine (radius). This implies a better amount of controllability to the heat transfer process. Furthermore this can also be exploited to save on floor space. This makes the machine more compact and ergonomic as one of the key applications of this machinery is to feed/compliment another process, (e.g. die casting) in an established facility to enhance their casting.

3.2 Heat Transfer

Microstructure is controlled by varying the thermal gradient along the process direction. In a radial machine increasing the critical dimension (radius) can lead to less cost efficiencies. This leads to a subsequent lack controllability of the process as the heaters across stages would have to be placed concentrically on the limited surface area of the top and bottom surfaces. Furthermore, if the height is partially increased to accommodate scaling up, the heaters along the process (radial) direction would need to permeate through more liquid metal. This is further exasperated if the machine is to sit on the floor as it would imply heat input from only one surface i.e. the top surface. This can hamper even temperature distribution leading to unfavourable properties such as a larger size distribution of particles.

In comparison, the heaters in a thinner longer machine have less fluid volume to permeate. These heaters can be placed around the barrel to provide a more effective way of transferring heat across the cross section and into the slurry as opposed to a radial machine. This implies that the heat transfer can be made more efficient allowing for the final structure to be controlled more accurately in an axial machine.
3.3 Mechanical Loading of the Blades

Finally we can also look at the centrifugal forces to demonstrate the added mechanical efficiencies of the axial design. Since the radial machine has only one alterable critical dimension (Radius), as the radial concept is scaled up the moment acting on the blade is drastically increased.

Therefore, as the radial machine is scaled up the blades would have to become thicker to handle the increase on moment. This would reduce the remaining volume in which metal can be processed. i.e. the ratio between available space and radius is maximised when the machine is smaller. This implies that there is a theoretical ceiling limit for the efficiency/viability of this concept after which increasing the critical dimension (radius) of the machine would be less commercially viable as the force/energy required would need to increase and the throughput would decrease.

In comparison, when we increase one of the critical dimensions in the axial machine (length) the volume increases as and the moment acting on the blade could theoretically remain the same.

4 Summary

Semisolid metal (SSM) forming has several advantages over solid state forming. These include reduced forming force, unlimited formability and shortened manufacturing route. Compared to conventional die casting, semisolid technology has advantages of laminar flow during mould filling, reduced solidification shrinkage and lower operating costs. SSM processing offers a noted step change in technique with opportunities to reduce cost energy and resource more than any other novel forming process. [1, 8]

The ACME machine represents an easy to manufacture technology that processes SSM to refine the cast structure. Research shows that turbulent mixing of a SSM can refine the structure of the solidified metal thereby increasing its mechanical properties leading to potential weight saving. Furthermore turbulence can disperse particles within the molten metal. These particles can be non-metallic agents used to create high performance engineering materials known as metal matrix reinforced composites (MMRC’s) and mixing can refine the structure of the metal component in MMRCs. The concept is immensely scalable, offers good control over mixing parameters and therefore the structure of the processed material. The machinery can be built out of a variety of materials to become applicable to process all metals. The core technology can be easily adapted to several other metallurgical operations.

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