Casting of Aluminium Alloys after MCAST (Melt Conditioning Using Advanced Shear Technology) Processing

By Geoff Scamans, Chief Scientific Officer, Innoval Technology Ltd. &
Zhongyun Fan, Director, Brunel Centre for Advanced Solidification Technology

Nucleation research has centred on the practical development of effective grain refiners for as-cast microstructural refinement. Today, addition of grain refiners (inoculation) in both continuous and shape casting is a common industrial practice [1]. For instance, Al-Ti-B or Al-Ti-C master alloys are added to Al-alloys, Zr or C to Mg-alloys, ferrosilicon to cast iron, Fe, Co or Zr to Cu-alloys, P to hypereutectic Al-Si alloys, and Ti to Zn-alloys. However, there is no consensus on the precise mechanisms responsible for grain refinement. Following the historical models, such as the carbide-boride, the peritectic reaction, the adsorption and the hyper-nucleation models (as reviewed in [1]), two major theories of grain refinement have emerged: the free growth theory [2] and the constitutional undercooling theory [3]. A major contribution from the free growth theory is the recognition of the importance of particle size and size distribution in grain initiation. With appropriate experimental data as input, this approach can correctly predict the grain size of aluminium alloys as a function of processing conditions. The constitutional undercooling theory emphasises the importance of solute elements and the potency of nucleating particles on the evolution of grain size, and can also be used to predict the grain size of aluminium and magnesium alloys once critical model parameters have been determined by experiment. However, both theories fail to specify the exact nucleation mechanisms at nucleating particles, thus limiting their practical use in the development of more effective grain refiners.

The benefits of enhancing nucleation can be numerous. For continuous casting of wrought alloys, enhanced heterogeneous nucleation reduces the propensity for hot tearing and cracking allowing higher casting speeds. It also promotes the formation of fine and equiaxed grains and a more uniform microstructure with significantly reduced chemical segregation, resulting in improved down-stream processability and a reduced cost of subsequent thermo-mechanical processing. For shape casting, grain refinement promotes equiaxed solidification, which again results in better liquid feeding, a reduced tendency for hot tearing, reduced and/or better dispersed porosity and an improved surface finish, all leading to improved mechanical properties of the final cast components. Since shape cast components are usually used in their as-cast state with little (if any) further processing, grain refinement and the reduction of casting defects are more crucial than for continuously cast feedstock materials. The key challenge in solidification research is to understand nucleation and to develop techniques for nucleation control. A critical question is “can we directly produce components with fine grain size, uniform chemistry and free from casting defects by solidification processing?” Recent work on melt conditioning [4] at the Brunel Centre for Advanced Solidification Technology (BCAST) has convincingly demonstrated that this is feasible.

The major technological challenges facing the metallurgical casting and fabrication industry are:

- Development of effective solidification processing technologies that produce both high quality components directly from liquid metals and semi-fabricated forms that require minimal thermomechanical processing for microstructural optimisation.
- Development of effective technologies for reuse, remanufacture and recycling of post consumer scrap metals so that there is only a limited need for primary metal production each year.

Our long-term aim is to establish a nucleation-centred solidification technology, based on which sustainable materials, highly efficient processing methods and new products can be developed with the widest possible impact.

Control of Nucleation using Oxides

We have proposed the following criteria for the selection of effective nucleating particles [5]. They need to be (1) stable crystalline solid particles at temperatures above the alloy liquidus, (2) fully wetted by the alloy melt, (3) available in sufficient numbers, with favourable particle size and with a narrow size distribution, (4) of a small crystallographic mismatch (<10%) with the nucleated solid phase and (5) insensitive to the processing conditions. From these criteria and the crystallographic data in we have predicted that oxide particles are potentially potent for heterogeneous nucleation. Work at BCAST has confirmed that MgO particles are potent for nucleation of α-Mg and Al_8Mn_5 intermetallics in Mg-alloys [6], and that $MgAl_2O_4$ particles are potent for nucleation of α-Al , primary silicon and Al-Fe-Si-Mn intermetallics in Al-alloys [7]. An example of the use of dispersed oxides to modify the nucleation and growth of primary silicon in an Al-15%Si alloy is shown in Figure 1 where both samples were cast at a cooling rate of 3.5℃/sec in a standard mould and Figure 2 shows the reduction in as cast grain size due to melt conditioning of a sand cast LM25 alloy. In addition, other research groups have identified oxide inclusions as nucleation sites for $TiAl_3$ intermetallics [8], and have reported enhanced nucleation of δ-ferrite by Al_2O_3 particles [9].

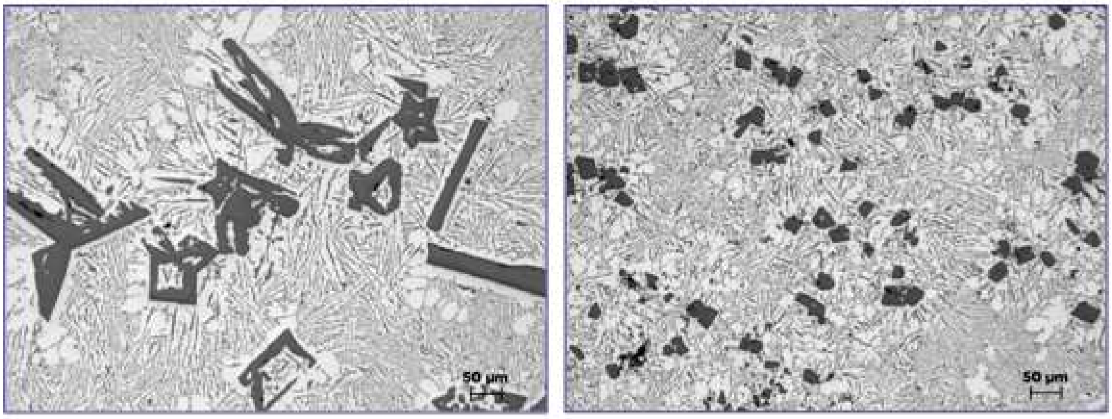
Oxide particles exist in nearly all liquid metals and alloys exposed to air, even under protective atmospheres. Oxide exists in liquid metals in the form of dross formed during melting in the furnace, oxide films formed during melt handling and oxide skins incorporated from the original solid ingots [6]. Oxide particles are often considered as harmful inclusions since they reduce castability of the alloy melt, degrade ductility and fatigue strength of castings and cause severe difficulties in downstream processing of continuously cast feedstock [10]. In current foundry practice, the norm is either to prevent oxide formation by using protective gas during melting and handling or to clean the melt by melt treatment processes, such as filtering, fluxing and manual de-drossing. However, our recent research work at has demonstrated that the oxide film contains a high volume fraction of fine solid oxide particles and more importantly, that such films can be effectively dispersed into individual particles with a fine size and a narrow size distribution by intensive melt shearing provided by the MCAST (melt conditioning by advanced shear technology) process developed at BCAST [6]. An example of the use of melt conditioning to disperse oxide films and agglomerated oxides in an aluminium casting alloy (LM24) is shown in Figure 2.

Our technical approach is to condition liquid metal prior to solidification processing using a twin screw melt conditioner with a pair of intermeshed co-rotating screws inside a barrel. The melt conditioners can be configured for batch or continuous liquid metal treatment. We have confirmed that intensive melt shearing can disperse oxide and other naturally occurring inclusion particles in liquid metals, and that such dispersed oxide particles not only reduce/eliminate the harmful effects of inclusions and impurities on both casting processes and mechanical properties, but also can be positively utilised to enhance heterogeneous nucleation of both intermetallics and the primary phases, and therefore can be used to promote equiaxed solidification, to prevent chemical segregation and to reduce casting defects [6], and can consequently provide a significant improvement in mechanical properties [11] and a substantial increase of the tolerance to inclusions and impurity elements [11,12]. For instance, melt conditioning can increase the elongation of HPDC LM24 alloy by over 100% the iron tolerance of HPDC LM24 alloy by 100%, the fatigue life of HPDC LM24 alloy by a factor of 10 and can eliminate centre line segregation of twin roll cast (TRC) AA5754 alloy strip as shown in Figure 4. Thus, melt conditioning by intensive melt shearing can be combined with various casting processes to produce as-cast materials (or components) with refined microstructure, uniform chemical composition, minimised casting defects and increased secondary metal content.

References

[1] B.S. Murty, et al: Inter. Mater. Rev. 47 (2002) 3.
[2] A. L. Greer et al: Acta Mater., 48 (2000), 2823.
[3] M. Easton and D. StJohn: Metall. Mater. Trans. A, 30(1999) 1613.
[4] Z. Fan et al: Intl J. Cast Metal Res., 22 (2009), 103.
[5] Y. Wang, M. Xia, Z. Fan, X. Zhou, G. Thompson: J. Alloys Compounds, 2009, in press.
[6] Z. Fan, et al: Acta Mater, 57 (2009), in press.
[7] Y. Wang, and Z. Fan: to be published, Brunel University, 2009.
[8] S. Srimanosaowapak: DPhil Thesis, Oxford University 2006.
[9] T. Suzuki, J. Inoue and T. Koseki: ISIJ Intl, 47 (2007), 847.
[10] J. Campbell: in ASM Handbook, Volume 15, Casting, 3rd edition, 2008, ASM, p362.
[11] X. Fang, et al: Mater. Sci. Eng., 445-446 (2007), 65.
[12] G. Liu, Y. Wang and Z Fan: Mater. Sci. Eng. A, 472 (2008), 251.

Al-15Si

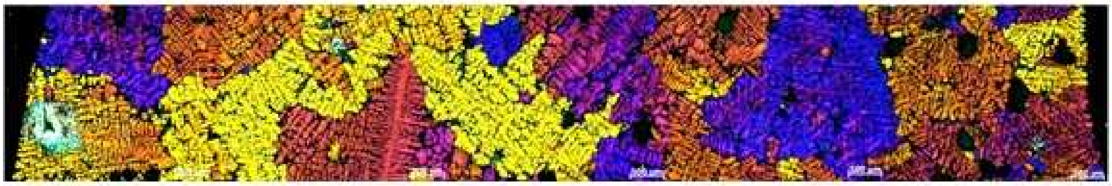


No Shear | Sheared

Figure 1: Refinement of primary silicon in a hypereutectic Al-15%Si alloy due to melt conditioning to disperse oxides

LM25

Conventional sand cast



Melt conditioned sand cast

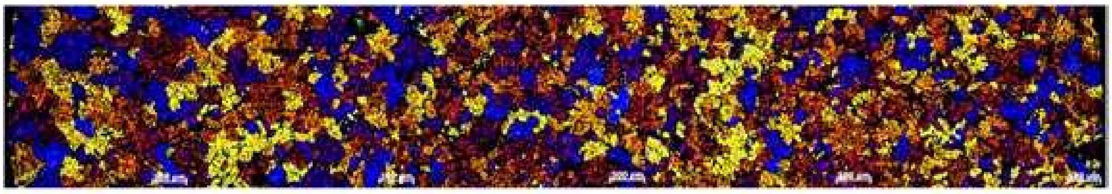


Figure 2: Microstructural refinement of a sand cast LM25 alloy after MCAST processing

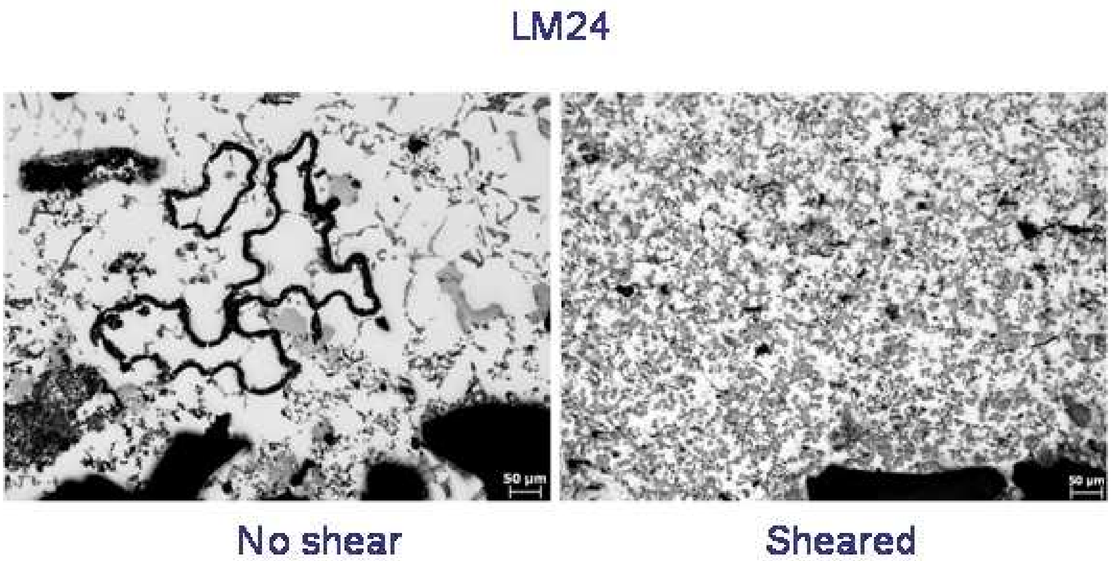


Figure 3: Comparison of filtrate from melts of LM24 alloy with and without melt conditioning. Melt conditioning has dispersed oxide films and agglomerates and has refined the particle size of the iron-rich intermetallic phases

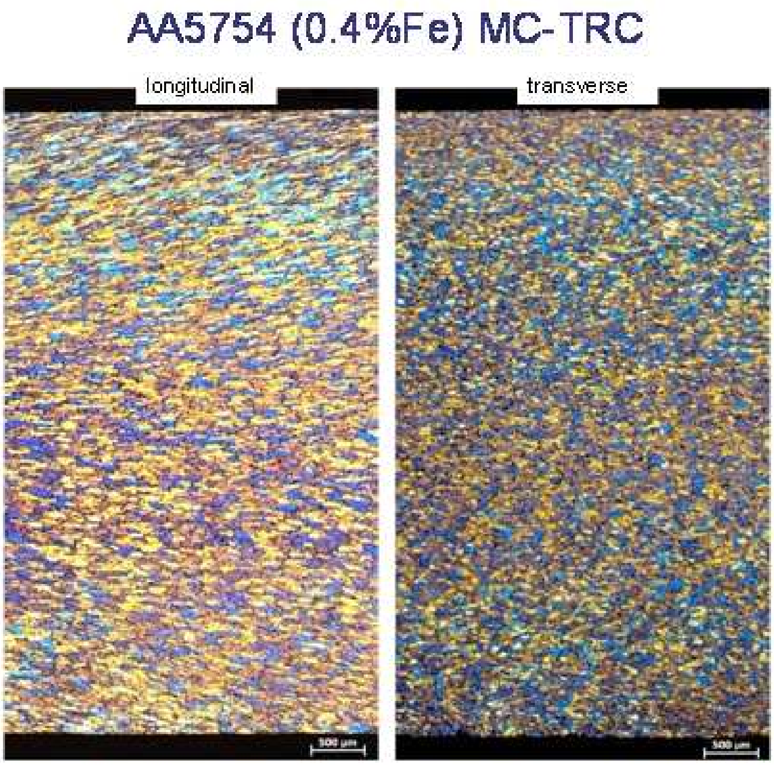


Figure 4: As cast melt conditioned twin roll cast (TRC) AA5754 strip showing a uniform fine grain microstructure the absence of centre line segregation