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SOLIDIFICATION MECHANISMS OF MELT CONDITIONED DIRECT-CHILL (MC-DC) CASTING

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ABSTRACT

Melt conditioned direct-chill (MC-DC) casting is a novel technology which combines vertical direct-chill (DC) casting with a high shear device directly immersed in the sump for in situ microstructural control. In this paper, the solidification mechanism of DC casting under varying conditions is discussed. The temperature profiles in the sump were measured under the steady state casting conditions by using sacrificing thermocouples. Detailed comparisons of the derived thermal condition are made. The individual role of grain refiner additions, natural thermosolutal convection and forced convection in the sump and the interplay of these factors in determining the solidification structures of DC cast billets are discussed. The MC-DC casting technology can be used to control microstructural constituents and casting defects in DC cast billets/ingots by in situ manipulating of the thermal and fluid flow conditions.

KEYWORDS

Direct-chill (DC) casting, Melt conditioning, Thermal gradients, Grain structures, Secondary phases

INTRODUCTION

Direct-chill (DC) casting of aluminium, has been the essential commercial process for producing feedstock suitable for subsequent processing, such as extrusion, rolling or forging. Fine and equiaxed grain structures in the as-cast billets/ingots are required to enable a fine and uniform distribution of second phase particles and microporosity. This leads to higher productivity, more cost-effective homogenisation and more efficient downstream thermomechanical processing. The addition of chemical inoculants has been the standard industrial operation prior to casting for grain refinement of Al alloys. However, it has been established that less than 1% of the grain refiner particles added actually act as heterogeneous nuclei to refine the grain structures, showing a very low grain refining efficiency (Greer, Bunn, Tronche, Evans, & Bristow, 2000). Moreover, the remaining particles from the grain refiner addition in the final casting may cause surface defects during downstream processing. A major issue of the metallurgical quality of large sized ingots/billets is the non-uniformity of microstructures even with chemical grain refiner additions. This is due to the fact that the grain structure formed in the different zones of the billet depends on the local chemical composition and local cooling rate. The local cooling rate can vary from 0.4~1 K/s at the centre of the billet to around 10–20 K/s at its surface zone (Nadella, Eskin, Du, & Katgerman, 2008). The large thermal gradient along radial direction between billet surface and interior of the melt during conventional DC casting induces thermal stress and cold cracking even with grain refiner addition. Therefore the control of casting defects, such as macrosegregation, porosity, cold/hot cracking and distortion of the billets/slabs, etc., is still challenging in industry, causing high scrap rate of DC cast ingots/billets even with grain refiner addition.

Melt conditioned direct-chill (MC-DC) casting is a key technology for in situ microstructural manipulation and casting defects control (Fan, Zuo, & Jiang, 2011; Fan, Jiang, & Zuo, 2013; Xia, Prasada, & Fan, 2013; Patel et al, 2014; Li, Patel, Kotadia, & Fan, 2015; Li et al., 2017). The MC-DC casting process combines conventional vertical DC casting with a high shear device directly immersed in the sump for in situ microstructural control (Figure 1). This paper presents an overview of the solidification mechanisms during MC-DC casting.

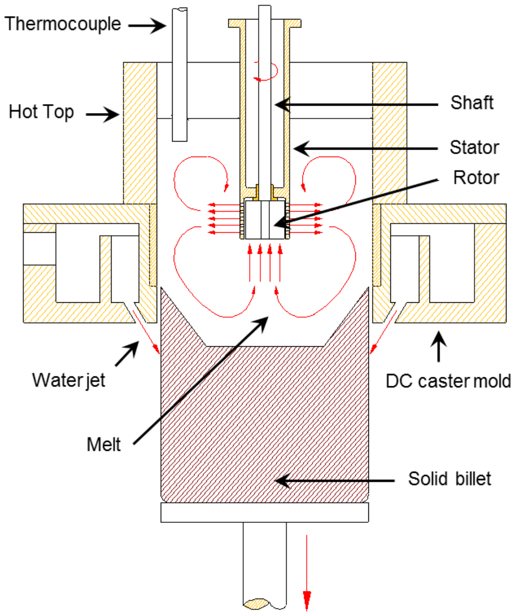

Figure 1. Schematic illustration of the MC-DC process, combining conventional vertical direct-chill (DC) casting with a rotor-stator high shear device directly positioned in the sump of a DC caster.

THERMAL CONDITIONS DURING DC CASTING

Sump Profile and Thermal Gradient

The sump profile during DC casting provides critical information for the understanding of the solidification mechanism, in particular the thermal conditions. Sacrificial thermocouples were used to obtain temperature data at different positions within the sump during DC casting to estimate local cooling rate/thermal gradient. The sump profile can be derived by using these temperature data, given the liquidus temperature (T_L) and solidus temperature (T_S) are known and the dendrite coherency temperature (T_C) can be estimated. The dendrite coherency temperature is the temperature at which a coherent dendrite network is established during solidification, which depends strongly on the grain morphology and grain size.

Figure 2 shows schematically the sump profile formed during DC casting under varying conditions. The sump profiles of conventional DC with and without grain refiner (GR) addition (Figures 2a and 2b) are consistent with those reported in the literature (Vreeman, Schloz, Krane, 2002). In all cases, the mushy zone has a high thermal gradient but the thermal gradient in the slurry zone is quite different. The thermal gradient in the slurry zone is relatively high in conventional DC casting (Figure 2a), but relatively low in conventional DC casting with GR (Figure 2b). Due to the substantial spread of the nucleating particle sizes, the nucleation occurs across a certain temperature range in the slurry zone based on free growth model (Greer et al., 2000). The latent heat released during growth of these nuclei leads to a slurry zone with low thermal gradient. When the melt is sheared at a higher speed, it is characterised by a very low thermal gradient in slurry zone (Figure 2c), whilst a high thermal gradient exists in the slurry zone when sheared at a lower speed (Figure 1d). With MC-DC, the sump becomes shallower, as shown in both Figures. 2c and 2d (Li et al., 2017).

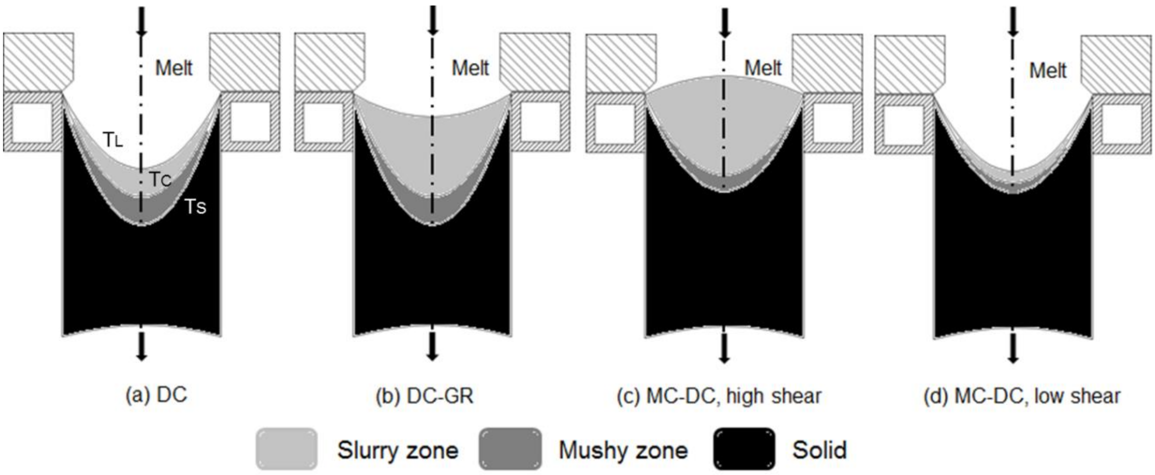

Figure 2. Schematic illustration of the sump profile derived from the temperature measurement results using sacrificial thermocouples at different positions along radial direction during DC casting under varying conditions. (a) Conventional DC casting; (b) conventional DC casting with grain refiner addition (DC-GR); (c) MC-DC casting with a relatively high shear speed; and (d) MC-DC casting with a relatively low shear speed. (T_L, liquidus; T_S, solidus; and T_C, dendrite coherency temperature.)

Uniformity of Local Cooling Rate

In conventional DC casting, the cooling rate decreases as the centre is approached (Nadella et al., 2008). The non-uniform cooling rates across the cross-section of billets result in the radial variation of grain size (Nadella et al., 2008). During MC-DC casting, due to intensive forced convection, enhanced mass transfer leads to an increased heat extraction rate in the sump. Thus the cooling rate in the slurry zone in MC-DC casting is higher compared to that of conventional DC casting. The more uniform distribution of cooling rate across the cross-section enables a uniform microstructure across the whole transverse section.

NUCLEATION AND COLUMNAR TO EQUIAXED TRANSITION (CET)

Nucleation Mechanism

Based on our understanding of melt conditioning and previous investigations on MC-DC casting process (Fan, Wang, Xia, & Arumuganathar, 2009; Men, Jiang, & Fan, 2010; Fan et al., 2011, 2013; Xia et al., 2013; Patel et al, 2014; Li et al., 2015, 2017), intensive melt shearing in the sump has the following effects: (1) effective dispersion and uniform distribution of solid particles (such as naturally occurring oxides and other inclusions), which can act as nucleating sites and thus enhance heterogeneous nucleation during the solidification; (2) intensive melt convection in the sump enhances the kinetics for both mass and heat transfer; and (3) a precisely controlled thermal field in the sump can be achieved by variation of the rotation speed of the high shear device. For both Al and Mg alloys, the dominant oxides naturally formed in the molten alloys have been found to be highly effective nucleating substrates for the α-Al phase during solidification (Li, Wang, & Fan, 2012; Wang, Li, Fan, 2012).

Columnar to Equiaxed Transition (CET)

In MC-DC casting sheared at higher speed, the low thermal gradient favours the achievement of CET. In MC-DC casting sheared at lower speed, with the higher thermal gradient obtained, as suggested from Hunt's criterion (Hunt, 1984), columnar growth is favoured at the higher ratio of thermal gradient to casting speed (G/Vc); therefore a higher nuclei density is necessary in order to achieve the CET. Theoretical analysis confirmed that intensive melt shearing can increase the number density of oxide particles in the melt by three orders of magnitude to enhance heterogeneous nucleation (Men et al., 2010). Considering the high number density of oxide particles with melt shearing (Fan et al., 2009; Men et al., 2010; Li et al., 2012; Wang et al., 2012), the MC-DC casting provides a unique condition for grain refinement: (1) with low thermal gradient and high growth velocity when the melt was sheared at a relatively high speed; or (2) with a high thermal gradient when sheared at a lower speed. The word "relatively" is used here just for comparison, but both cases are characterised by a high enough shear rate to enhance nucleation and dispersion. As a consequence, grain refinement and CET can be achieved in both cases. However, the difference in shear speed resulted in different grain structure due to the different thermal conditions in the sump (Figures 2c and 2d).

SOLIDIFICATION MECHANISM OF DC AND MC-DC CASTING

In DC casting, the development of grain structure affects mushy zone permeability (affecting interdendritic feeding and thus castability) and shrinkage induced interdendritic flow. These in turn have a strong influence on the formation of casting defects, such as hot tearing, porosity and macrosegregation. Figure 3 shows the different grain structures formed under varying DC casting conditions. In conventional DC casting without GR, twinned columnar (feathery crystals) grains form with large elongated grains of twinned dendrites (Figure 3a). With GR addition, the grain structure is more likely to be granular or rosette-like (Figure 3b). In MC-DC casting sheared at a relatively high speed, rosette-like grain develops (Figure 3c), whilst fine equiaxed dendritic grains with fine dendritic arm spacing are obtained under a relatively lower shear speed (Figure 3d).

The grain morphological evolution during solidification process depends on the growth mode defined by solid/liquid interface stability, which can be understood by Mullins-Sekerka criterion (Mullins & Sekerka, 1963). Based on Mullins-Sekerka criterion, a high nucleation rate and a low thermal gradient favour the granular growth. In conventional DC casting, solidification proceeds by an advancing columnar (or coarse dendritic) front through a relatively narrow mushy zone (Figure 3a). In conventional DC casting with GR, low thermal gradient and high nucleation rate by inoculant particles favours granular growth. But the thermosolutal convection in the slurry zone is relatively low compared with the forced convection during MC-DC casting under a high shear speed. A coarse dendritic arm spacing develops after interfacial instability occurs whilst a fine dendritic arm spacing (DAS) develops in the deep mushy zone (Figure 3b). In contrast, solidification in the MC-DC casting sheared at a high speed proceeds by sedimentation of rosettes which nucleate and predominately grow in the slurry zone with an almost isothermal temperature and severe convective melt flow (Figure 3c) (Xia et al., 2013). So the dendritic arms develop much less resulting in rosette-like morphology with coarse DAS. In the literature, the formation of granular/rosette-like grains is reported in relation to melt treatment by a range of physical fields (ultrasonic, electric current pulses, electromagnetic field treatment). Despite of different alloy chemistry, physical field treatment produces granular/rosette-like structure, which is attributed to the establishing of a slurry zone with low thermal gradient and temperatures just below the liquidus (Räbiger et al., 2014; Eskin, 1998; Zuo et al., 2012).

In MC-DC casting sheared at a lower speed, grain nucleation is also initiated in the slurry zone, however, which is characterised by high thermal gradient/high undercooling (Figure 2d), compared to conventional DC casting (Figure 2a), due to an enhanced rate of heat extraction by the intensive forced convection. This results in a very early breakdown of spherical growth and therefore, fine equiaxed dendritic grains developed (Figure 3d).

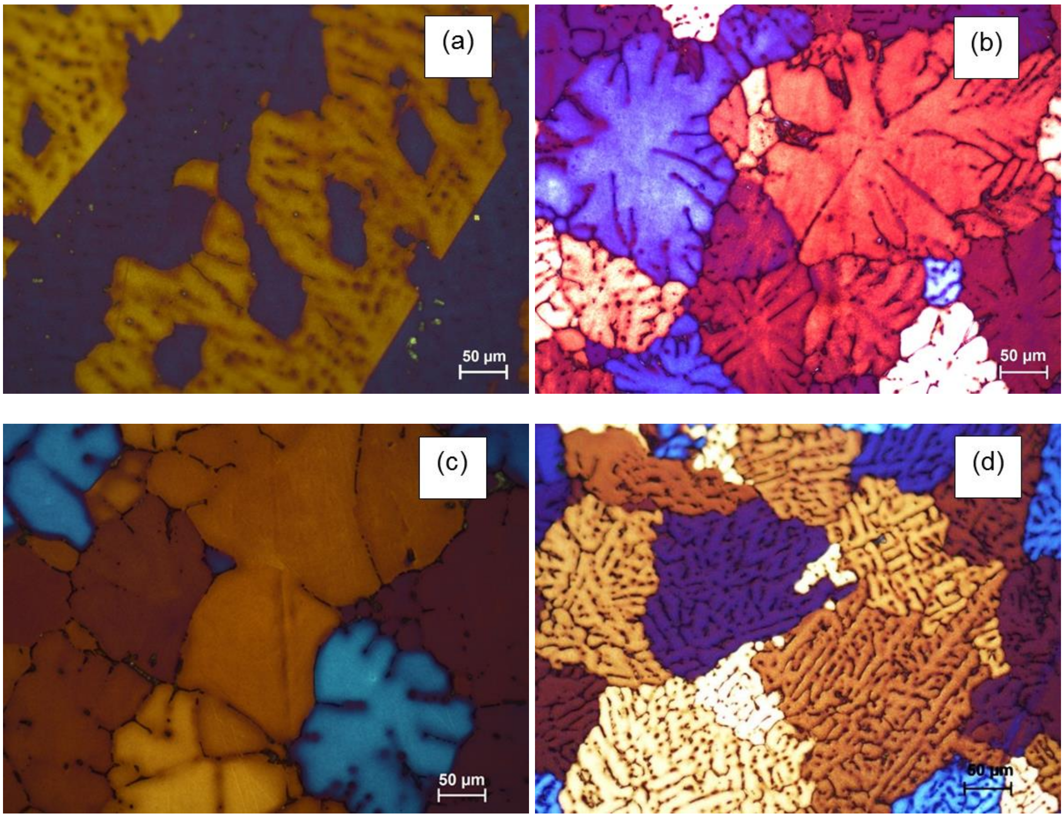

Figure 3. Development of grain structure under varying processing conditions in the 204 mm diameter DC cast billets of an A6063 alloy. (a) Coarse feathery grains in conventional DC cast billet without grain refiner additions; (b) rosettes in conventional DC cast billet with 1 ppt Al-5Ti-B grain refiner addition; (c) fine rosette in MC-DC cast billet sheared at a relatively high speed; and (d) fine equiaxed dendritic grains in MC-DC cast billet sheared at a relatively low speed. Except for (b), all the rest conditions without grain refiner additions.

In summary, the grain structure evolution during DC casting is a result of combined effects of nucleation inoculant addition, thermal gradient and convective flow related to natural thermosolutal convection and/or forced convection in the sump and their interactions under a given DC casting condition. The transition from granular/spherical grain to dendritic grain can be analysed based on the Mullins-Sekerka interfacial stability criterion for the initial growth stage at low solid fraction. Ripening happens for the dendritic arm spacing coarsening at the late stage of low solid fraction. Further development including arm coalescence of dendritic grains occurs after the dendritic coherency point in the mushy zone, affecting mainly the development of high order dendritic branches. Due to the higher cooling rate in this zone for both conventional DC-GR and MC-DC casting, its effect on grain structural development might not be as significant as that in the slurry zone.

IMPLICATION FOR METALLURGICAL QUALITY IMPROVEMENT OF DC CASTINGS

Grain structure plays a vital role in determining the behaviour in the mushy zone, such as permeability (interdendritic feeding ability), size and distribution of second phases and thus has significant influence on the formation of various casting defects like hot tearing, cold cracking, porosity, and macrosegregation, etc. As an example, Figure 4 shows the relationship between grain structure and size and distribution of the second phases (eutectic phases). Fine and uniform distribution of the second phases can be achieved by the formation of fine equiaxed dendritic grains. MC-DC casting technology offers a promising approach to manipulating microstructural constituents and casting defects in DC cast billets.

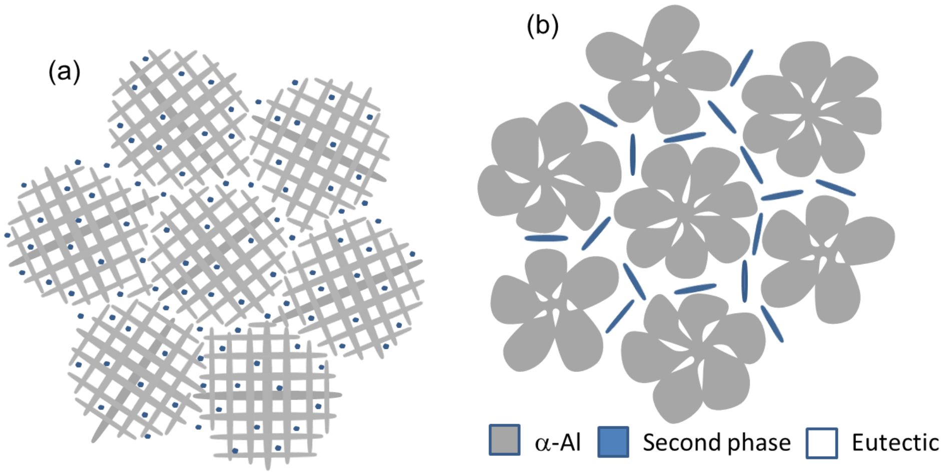

Figure 4. Schematic illustration showing the relationship between grain structure and the size, morphology and distribution of the second phase particles. (a) Fine equiaxed dendritic grains with fine dendritic arm spacing favour the fine and uniform distribution of second phase particles; (b) rosette-like grains result in coarse second phase particles concentrated in the inter-dendritic regions.

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