Edited by J.F. Nie, A.J. Morton and B.C. Muddle

Effect of Process Parameters on Structure Formation during Direct-Chill Casting of an Al–Cu Alloy

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Keywords: direct chill casting, solidification, casting speed, water flow rate

Abstract

Billets of an Al–4.5% Cu alloy direct-chill cast under different process conditions were systematically examined. Effects of casting speed and water flow rate on structure are studied and correlated to computer simulated solidification patterns. Main parameters that influence structure formation during direct chill casting are shown to be the depths of the liquid pool and the sump (eventually, the distance between liquidus and solidus and its radial distribution) and the flow pattern in the slurry region. The solidification rate seems not to be a significant factor. The appearance of coarse grains in the central part of the billet is explained from the transport of solid phase within the slurry region.

1. Introduction

Direct chill (DC) casting is the main technology to cast wrought aluminum alloys. The major benefit of direct chill casting is that the solidification (and the formation of structure and defects) occurs in a relatively narrow layer of a billet and can be well controlled.

During the last decade, the demand for even higher quality of cast products, especially with respect to surface quality, chemical homogeneity and fine-grained structures, called for new fundamental investigations and, in particular for the creation of mathematical models of the process. Now we have arrived at the moment when various numerical and analytical descriptions of different aspects of direct chill casting are available and can be tested against the practice.

The analysis of literature sources revealed gaps in published experimental information. Only few experimental data have been reported on the effects of casting speed on porosity and grain size; effects of water flow rate on the structure; interrelation between the sump and mush dimensions on one side and the structure on the other side.

However, there are a few relationships well established and documented. The depth of the liquid pool is directly proportional to the casting speed and the squared radius of a billet [1, 2]. The solidification rate or the velocity of the solidification front depends on the casting speed and the profile of the solidification front [2, 3]. Higher cooling rates produce finer microstructure with smaller dendritic arm spacing [3, 4] and less and finer porosity [5].

The water flow rate is usually considered as a minor factor. There are reports that the increase in water flow reduces centerline macrosegregation [6] and has little effect on cooling rates during the steady-state stage of casting [7].

The distribution of solidification and structure parameters across the horizontal section of a billet is another important feature, seldom reported.

The aim of this paper is to report the results of systematic examination of billets of an Al–4.5% Cu alloy cast under different process conditions. Effects of casting speed and water flow rate on structure are examined and correlated to computer simulated solidification patterns.

2. Experimental

Round billets were cast in a pilot DC casting installation equipped with a hot-top mould 200 mm in diameter with an effective mold height of 20 mm. The process parameters such as melt temperature, water flow rate, casting speed, and melt level in the launder are controlled and recorded. The operation is semi-automatic, with a manual start-up phase and a fully automatic steady-state casting. A unique feature of the set-up is the possibility to change process parameters during a single drop. Two types of experiments were performed as shown in Table 2. In the first casting the casting speed in the steady state stage was changed step-wise, while the water flow rate was maintained constant. About 200 mm of length were cast at each casting speed. In the second experiment, the water flow rate was changed step-wise, while the casting speed was maintained constant. At the end of the casting at a water flow rate of 250 l/min, the casting speed was also increased to 180 mm/min. At least 300 mm of billet were cast at each casting condition. No grain refiner was used.

Cast billets were sawed at horizontal sections corresponding to the end of each process condition (steady-state stage, the corresponding billet length being about one billet diameter [1]). The sections were then cut to smaller samples that were ground, polished, etched or oxidized and examined in an optical microscope. Structure parameters such as dendritic arm spacing and grain size were measured on photographs using the random linear intercept technique. Porosity distribution was determined by digital image analysis using a QWin software. Statistical analysis of the results was performed.

Table 1. Experimental conditions and chemical composition of model alloys

Alloy	Casting speed, mm/min	Water flow rate, l/min	Cu, %	Si, %	Fe, %
Experiment 1	120, 160, 200	150	4.31	0.11	0.22
Experiment 2	120, 180	150, 200, 250	4.49	0.06	0.19

Computer simulations of the effects of casting conditions on the temperature distribution, sump profile and flow patterns during DC casting of an Al–4.5% Cu alloy were performed with a Flow3D software (version 8.1) using a finite volume approach. Thermophysical parameters used in these simulations are given elsewhere [8]. A solidification model and approaches towards simulation of water cooling of a billet are described in previous papers [9, 10]. In order to validate computer simulations of the process, temperature measurements were performed in various locations of the billet during casting, close to the surface and in the central part of the billet. In addition, the sump depth was probed by a steel rod connected to a digital length meter. Good agreement was found between calculated and experimentally measured temperatures and depths.

3. Results

3.1 Distribution of Structure Parameters across the Billet Section:

Examination of the macrostructure showed that the structure comprises equiaxed grains and is generally uniform across the horizontal section of a billet. No hot cracks were observed in the entire range of used process parameters. The characteristic feature of macrostructure is the appearance of “coarse” grains in the central part of a billet. These grains have thicker branches and larger dendritic arm spacing, sometimes with a rim of finer dendritic arms at the periphery of the grain. Figure 1 shows a vivid example of such a structure. The occurrence of such grains has been reported previously [2, 11].

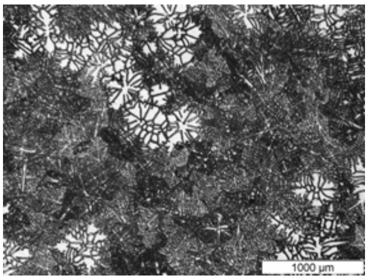

Figure 1: Macrostructure of a central part of a billet (composition 2 in Table 1) cast at 180 mm/min and 250 l/min, macroetching with NaOH.

The distributions of structure parameters observed in the horizontal section of a billet are illustrated in Figure 2. The grain size, dendritic arm spacing (not taking into account coarse grains in the central part of a billet), amount of pores tend to increase from the periphery to the center of a billet. The only peculiar feature is the zone of finer grains at approximately 2/3 of billet radius (measuring from the center). There are not so many studies where the structure was examined in the entire cross-section of DC cast billets. Håkonsen et al. [12] reported the grain size and DAS to decrease from the center to the periphery of a slab of commercially pure, grain refined aluminum, with some special effects close to the billet surface, namely a subsurface zone with a coarse structure. The occurrence of such a zone is discussed elsewhere [1, 11]. Nagaumi [5] reported similar distribution of DAS in an Al–Mg slab. He also reported that the size and number of pores increased from the surface to the center, although with a sudden drop in the central part of the billet. We did not observe any special subsurface behavior of structure parameters because first structure measurements were performed on samples cut at approximately 10 mm from the surface.

3.2 Effect of casting speed on structure:

The increase of casting speed generally results in structure refinement as illustrated in Figure 2. However, in the case of grain size and amount of porosity the effect is more pronounced towards the central part of a billet. For dendritic arm spacing, the refinement is uniform across the entire billet section.

3.3 Effect of water flow rate on structure:

The effects of water flow rate on structure are usually considered to be negligible because of very small effects of water flow rate on the heat flux density and heat transfer coefficient during steady-state casting [7]. Our results show that changing of water flow rate does not affect the general distribution of structure features across the billet. Although the effect of casting speed is much stronger than that of water flow rate, the increase in cooling water rate within the given range refines somewhat the dendritic arm spacing and decreases the amount of porosity.

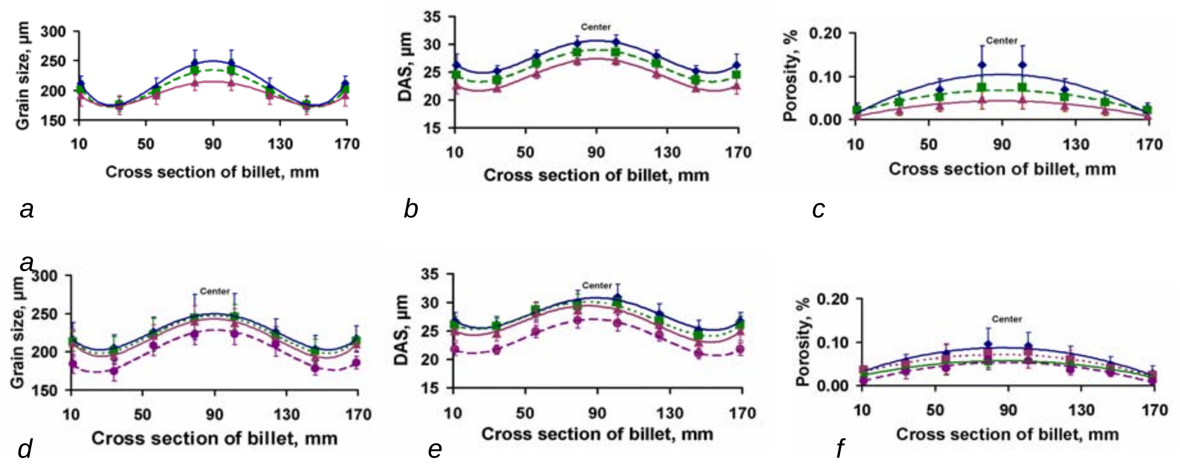

Figure 2: Distributions of structure parameters in the horizontal section of a billet at different casting speeds (a, b, c ◆120 mm/min, ■ 160 mm/min, ▲ 200 mm/min) and at different water flow rates (d, e, f, ◆150 l/min, ■ 200 l/min, ▲ 250 l/min) and casting speeds (d, e, f, ◆, ■, ▲, 120 mm/min and ●, 180 mm/min): a, d, grain size; b, e, dendritic arm spacing (DAS); c, f, volume fraction of porosity.

3.4 Computer simulations:

Geometry of the liquid pool and the liquid–solid transition zone is influenced mainly by the casting speed, Figure 3. The effect of water flow rate is noticeable only in the range below 200 l/min and at a casting speed as low as 120 mm/min. The process parameters mostly affect the depth of the liquid pool and the distance between liquidus and solidus isotherms. Computer simulations also show complex flow patterns in the liquid and slurry regions that result in dragging solid phase from the upper and peripheral part of the transition zone to the central part of a billet as shown in Figure 3a.

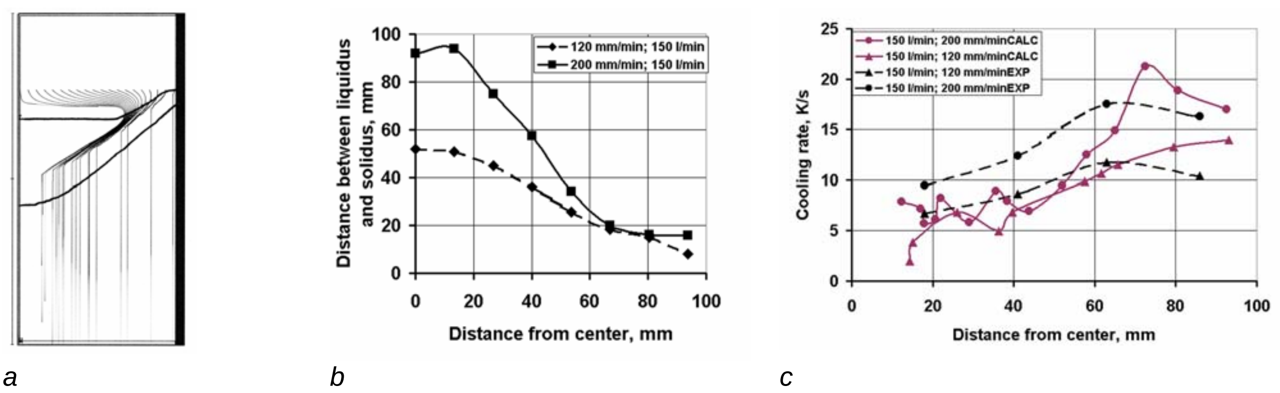

Figure 3: (a) Streamlines showing the path of tracers during DC casting (200 mm/min, 150 l/min); (b) effect of casting speed on the radial distribution of the distance between liquidus and solidus isotherms; and (c) effect of casting speed on cooling rates recalculated from dendritic arm spacing as DAS = AV_{cool}^{-n} with constants A = 57.2 and n = 0.33 (EXP) and from streamlines (CALC).

4. Discussion of Results

Analysis of experimental results and data produced by computer simulations shows direct correlation between structure parameters (Figure 2) and the parameters of the sump, e.g. the depth of the sump (eventually, the distance between liquidus and solidus isotherms and its radial distribution, Figure 3b) and the flow pattern in the slurry region, Figure 3a. Together these parameters affect the time spent by an alloy in the solidification range and the transport of solid and liquid phases within the corresponding semi-solid region of a billet.

Observed zone of finer structures (both grain size and dendritic arm spacing) at about 2/3 of radius correlates well to the region where the liquidus line shows deflection and the slurry region starts to widen towards the center of a billet (Figure 3a). Movement of solid and liquid phases is also most intense in this region. As a result, the conditions for solid phase fragmentation (multiplication of solidification sites) and rapid growth are created, and smaller grains with finer internal constitution are formed.

The amount of porosity is larger in the center of the billet and changes mostly in the center with changing the casting speed. This behavior correlates well with the effect of casting speed on the distance between liquidus and solidus isotherms. This observation is logical if one takes into account that pores originate through solidification shrinkage (that opens gaps in a semi-solid structure) and precipitation of hydrogen (that fills those gaps and which precipitation is facilitated by slower cooling and presence of solid/liquid interfaces). The finer the internal structure of grains, the finer the pores. The coarser the structure and the slower the cooling, the greater the amount of pores.

The cooling rate (inverse time required to pass the solidification range) is usually determined experimentally by measuring temperatures by thermocouples traveling with a billet at a casting speed [2, 13]. Therefore, the cooling rate is expected to be inversely proportional to the distance between liquidus and solidus and, therefore to decrease from the periphery to the center, especially starting from the point when the liquidus line flattens (Figure 3a). However, the calculations performed using the distance between liquidus and solidus showed that the cooling rates determined in such a way fail to reproduce the observed difference in cooling rates in the central part of a billet (Figure 3c, dashed lines), the larger distance between liquidus and solidus isotherms being fully compensated by the increased casting speed. The structure found in the central part of a solidified billet has characteristics reflecting its solidification history. In particular, the average dendritic arm spacing reflects the total solidification time required for a particular grain to form. Therefore, attributing the cooling rates experimentally measured by a thermocouple moving with a billet to the structure found in the position of this thermocouple in the solid billet is incorrect. Flow patterns and transport of the solid phase within the slurry region should be taken into account.

Experimental cooling rates (Figure 3c, dashed lines) were recalculated from dendritic arm spacing without taking into account “coarse” grains (Figure 1). Computer simulation shows that a flow pattern that exists in the semi-solid region results in dragging solid phase crystals nucleated at the periphery of the billet to its center (Figure 3a). As a result, at least part of grains found in the central part of the billet were solidified during a longer time than it could be presumed based only on their final position in the billet. Cooling rates calculated using these streamlines (quantified in time) are given in Figure 3c (solid lines).

Obviously, the flow patterns existing in the slurry zone cause scatter in the solidification times and, as a result, scatter in structure parameters related to the cooling rate. Figure 3c shows that, without taking into account slower cooling rates reflecting “coarse” grains, an agreement between experimental and calculated cooling rates is very much satisfactory.

We believe that “coarse” grains that tend to appear in the central part of the billet (Figure 1) are also a result of the solid transport within the slurry zone.

The origins of these grains may be argued. In the literature several hypothesis are suggested, including (1) the formation of these grains on the open surface of the melt or on a distribution bag, or on a hot top with subsequent separation and transporting by melt flow or due to gravity and (2) the fragmentation of dendrites at the solidification front as a result of local remelting or mechanical forces with detachment of fragments and transporting of them by melt flow. Both mechanisms are possible. In addition to that, the streamlines shown in Figure 3a and corresponding cooling rates (Figure 3c) demonstrate that at least some grains found in the central part of the billet were nucleated at the periphery and then transported to the center, growing as they travel. As a result, the structure of the central part of the billet shows a scatter in cooling rates and, hence in dendritic arm spacing. Therefore, the third mechanism of coarse grains formation is a longer growth due to their trajectory within the slurry zone.

The experimental results reported in this paper are obtained under known and controlled process parameters and can be readily used for validation of computer models.

5. Conclusions

Effect of casting speed and water flow rate on structure parameters and parameters of semi-solid region during direct chill casting of an Al–Cu alloy were studied experimentally and by computer simulations.

Analysis of experimental results and data produced by computer simulations shows that main parameters that influence structure formation during direct chill casting are the depth of the sump (eventually, the distance between liquidus and solidus isotherms and its radial distribution) and the flow pattern in the slurry region. Together these parameters affect the time spent by an alloy in the solidification range and the transport of solid and liquid phases within the corresponding semi-solid region of a billet.

Acknowledgements

This work is done within the framework of the research program of the Netherlands Institute for Metals Research (www.nimr.nl), Project MC 97014.

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