Effect of different grain structures on centerline macrosegregation during direct-chill casting.

D.G. Eskin[1], R. Nadella[1], L. Katgerman[2]
[1] Netherlands Institute for Metals Research, Mekelweg 2, 2628CD Delft, The Netherlands
[2] Delft University of Technology, Dept. Materials Science and Engineering, Mekelweg 2, 2628CD Delft, The Netherlands

Abstract

Duplex grain structure consisting of coarse-cell and fine-cell dendritic grains is frequently found in the central portion of direct-chill cast billets and ingots. Coarse-cell grains are usually considered as free-floating grains settled to the bottom of the billet sump. These grains are assumed to be solute-lean and contribute to the negative centerline segregation. In this paper the contribution of coarse-cell and fine-cell grains to macrosegregation is for the first time studied experimentally by direct measurements of their composition. It is shown that the coarse-cell, floating grains are depleted of solute and the areas of their accumulation contribute to the negative macrosegregation. The areas of fine-cell grains can be either enriched in solute or be close to the nominal composition. It is argued that their composition results from the interplay between thermo-solutal and shrinkage-induced flows. The roles of casting speed and grain refining are also under scrutiny in this paper.

Keywords: macrosegregation; microsegregation; aluminum alloy; direct-chill casting; floating grains

1. Introduction

Direct-chill (DC) casting of aluminum alloys is a major technological route in production large-scale castings for further deformation processing, e.g. extrusion or rolling. Despite many years of research and development of this technology, the main challenges in making defect-free and high-quality billets and ingots remain the same: hot and cold cracks, brittle inclusions, rough surface, and macrosegregation. The last problem will be in the focus of this paper. Macrosegregation is an inhomogeneous distribution of alloying elements on the scale of the casting. The fundamental reason for segregation is the partitioning of solute elements between liquid and solid phases during solidification. In the case of hypoeutectic aluminum alloys (which is the majority of commercial aluminum alloys) the liquid phase is enriched in and the solid phase is depleted of the solute elements such as Cu, Mg, Zn, Fe, Si, etc. These elements have the so-called partition coefficient K less than unity, meaning that the concentration of the element in the solid phase is less than in the liquid. In the case of elements with $K > 1$, e.g. Ti in Al, the solid phase becomes enriched during solidification. However, the partitioning of the elements during solidification and even their inhomogeneous distribution at the scale of a grain induced by incomplete diffusion (so-called microsegregation) do not cause big problems in practice. Microsegregation can be eliminated by homogenization annealing of the casting. What translates the microscopic partitioning and segregation to the macroscopic scale is the relative movement of liquid and solid phases in the two-phase zone of the casting. The mechanisms of such a relative movement are the mechanisms of macrosegregation, and they are generally known. Some of them are acting in the upper part of the two-phase zone, i.e. in the slurry region where the liquid fraction is above the coherency point. There thermo-solutal convection causes the macroscopic movement of the liquid phase, its penetration into the slurry zone and transport of solutes in the direction of convective flows. In addition to that, the convective flows pick up the free-floating, solute-lean solid grains and transport them within the slurry region until the moment when these grains become heavy enough to settle down. In the case of direct-chill casting, thermo-solutal convection facilitates the enrichment of the central part of the billet in solute elements with $K < 1$, whereas the free-floating grains promote the negative centerline segregation. In the lower part of the two-phase region, i.e. in the mushy zone where the solid phase is coherent and does not move on the macroscopic scale, other mechanisms are acting. The most important is the shrinkage-induced flow that is driven by the pressure difference between the regions with the lower and the higher fractions of solid. An alloy increases the density during solidification and low-pressure gaps are formed closer to the solidus. This pressure difference triggers the melt flow in the direction normal to the solidification front. This shrinkage-induced flow transports the solute-rich liquid away from the centre of the casting, producing negative centerline segregation. At even higher fractions of solid, thermal contraction of the coherent solid network can result in macroscopic thermal strain that may increase or decrease the pressure drop depending on the direction of the strain. Deformation-induced macrosegregation is an important mechanism of subsurface segregation.

In our previous papers we discussed the effects of convective and shrinkage-induced flows on macrosegregation during direct-chill casting of aluminum alloys [1, 2, 3]. The relevant review of literature is given in these papers.

The contribution of free-floating grains to the observed chemical inhomogeneity of the billets (ingots) is the most controversial issue in the modern theory of macrosegregation. Duplex structure consisting of coarse- and fine-cell dendritic grains frequently found in the central part of DC cast billets and ingots have given rise to a viewpoint that some of the grains are indeed floating grains that travel along long trajectories in the slurry region of the billet and then settled down [4, 5, 6, 7, 8, 9, 10, 11]. The mainstream concept assumes that if the *coarse-cell dendrites* are solute-poor, fine-cell dendrites are close by their average composition to the nominal alloy composition [5, 10]. Quite an opposite line of argument is proposed by Chu and Jacoby [11], who suggested that the *fine-cell dendrites* originated from the start of the solidification in the region of rapid cooling (i.e. dendrites detached and transported from the periphery to the centre and frozen into the solidification front without further growth) and coarse-cell grains grew *in situ*. Consequently, fine-cell grains are solute-poor and responsible for the negative centerline segregation, while coarse-cell dendrites are solute-rich. Yet another suggestion is made by Glenn et al. [6]. They found that the structure of a non-grain refined billet contains, along with normal-size dendritic grains, fine grains, which allegedly represent grain fragments brought from the mold walls to the ingot center by turbulent flows.

Experimental observations show that the presence of floating grains in DC cast billets does not necessarily mean enhancement of negative centerline macrosegregation. Glenn et al. [6] observed duplex structures in a non-grain refined ingot with less severe negative macrosegregation than in the grain refined counterpart where no floating grains were found. Finn et al. [4] found negative centerline segregation in non-grain refined ingots without floating grains, whereas the positive centerline segregation was measured in grain-refined ingots with the duplex grain structure present. We reported the increase in the amount of floating grains with melt superheating while the centerline macrosegregation remained the same [9]. Grain refinement may considerably increase the amount of floating grains with no apparent effect on the extent of macrosegregation [12]. Which leads us to another controversial issue in the modern macrosegregation theory – the effect of grain refining. Addition of transition metals or their compounds to aluminum alloys with the aim to refine the grain structure is the common casting practice. Yet there are contradicting accounts in the literature. Some researchers observed more severe centerline segregation in grain-refined billets and ingots [6, 13, 14]. Others – reversal to the positive centerline segregation with grain refinement [4].

It is worth to note that most of the conclusions on the role of coarse-cell or floating grains in macrosegregation were not substantiated by compositional measurements.

This paper is a summary of experimental research in the contribution of coarse-cell grains to the centerline macrosegregation of DC cast billets from non-grain refined and grain-refined aluminum alloys.

2. Experimental

A round billet was cast in a pilot DC casting facility at Delft University of Technology. A conventional hot-top mold 200 mm in diameter was used to produce billets up to 1500 mm in length. The detailed description of the installation can be found elsewhere [7, 9]. A 2024 alloy with the nominal composition (wt%): 3.5 Cu, 1.41 Mg, 0.37 Mn, 0.14 Fe, 0.01 Si was cast at a melt temperature of 720 °C, water flow rate 170 l/min and casting speeds 80 and 120 mm/min. The casting started with the alloy of the nominal composition at a speed of 80 mm/min. After sufficient length of the billet was produced (appr. 250 mm) and the steady state was reached, grain refiner was added in a form of Al–3%Ti–1% B rod and the casting continued at the same speed. When another 250 mm of the billet was cast, the speed was increased to 120 mm/min and again a 250-mm long section was produced. After that more grain refiner was added. The summary of the alloy compositions and casting regimes is given in Table 1.

All structural observations and macrosegregation measurements were made in the central plane of the billet. The ingots were longitudinally sectioned in the centre and rectangular bars approximately 20 mm wide and 20 mm high were cut in the horizontal cross-section of the billet, along the diameter. The samples were cut from the sections of the billet cast at least 200 mm after the start-up or the change of the casting speed to ensure steady-state conditions. Composition measurements were carried out by a spark spectrum analyzer Spectromax on all 4 sides of each bar at regular intervals of approx. 10 mm, and the average values are reported. In addition, the chemical composition at the billet surface was analyzed. The absolute error in these measurements is 0.05 wt% for Cu and 0.02 wt% for Mg. For structural observations, smaller samples were cut at different locations along the billet radius. Grain size and morphology were studied under cross-polarized light after anodizing the samples in a 3% HBF_4 water solution. Other structure features such as dendrite arm spacing (DAS) and ‘floating grains’ were revealed after etching the samples with 0.5% HF water solution. Line scan measurements with electron probe microanalysis (EPMA) were carried out on selected samples cut from the central portion of the billet to measure the variation of local composition across the dendritic microstructures with different cell sizes. In addition, area-scan analysis was performed on some samples.

3. Results and discussion

The structure of all alloys was equiaxed and dendritic. A detailed analysis of the structure is reported elsewhere [15], here only some relevant data are given. Addition of a grain refiner resulted in significant decrease in the grain size as illustrated in Fig. 1. The grain size in the central portion of the billet decreased from approximately 275 μm in non-grain refined alloy (NGR80) to 50–80 μm in grain-refined alloys (GR80, GR120L, H).

Occurrence of duplex grain structure in the center of the billet is typical of all studied alloy compositions. The dendrite arm spacing (DAS) differs 2–3 times, with DAS of coarse-cell grains being 60–70 μm and that of fine-cell grains – 22–25 μm. Coarse-cell and fine-cell dendritic grains can be clearly distinguished in the structure of NGR80 alloy with the volume fraction of coarse-cell grains being about 35% (Fig. 1a). The separation of coarse- and fine-cell grains in grain-refined alloys is somewhat more difficult because of the little branching of small grains and clustering of coarse-cell grains (Fig. 1 b, c). However, the structure analysis shows that the amount of coarse-cell grains increases with grain refining to appr. 65 vol.%. In the case of high-Ti alloy (GR120H) the difference become even more pronounced with coarse-cell DAS 50 μm, fine-cell DAS 17 μm, and volume fraction of coarse-cell grains 75% (Fig. 1d).

The increase in the amount of floating grains with grain refinement seems quite logical if we take into account that the solid fraction at coherency increases in fine-grained materials. The increase can be from 0.23 to 0.45–0.5 upon addition of 0.06–0.1% Ti to an Al–4% Cu alloy [16]. Hence, the coherency isotherm that marks the transition from the “loose” slurry zone with free-floating grains to the coherent mushy zone with fixed grains is positioned lower in the sump of the billet, effectively enlarging the region where floating grains may form, grow and settle. It is important to note that in grain-refined alloys, coarse-cell (floating) grains can represent the bulk of the structure. Therefore, these floating grains are no longer a defect but the factor that determines the structure of the billet.

Experimentally measured macrosegregation profiles along the billet diameter are shown in Fig. 2. Grain refinement does not change dramatically the macrosegregation profile and the extent of chemical inhomogeneity (comp. Figs. 2a and 2b). The apparent enhancement in negative centerline segregation in Fig. 2a is rather small, especially with taking into account the dramatic increase in the amount of coarse-cell grains (from 35 to 65 vol. %) and the overall structure refinement. The increase in the casting speed makes the macrosegregation much more pronounced, both in the center and at mid-radius of the billet (Fig. 2c, d). This effect is well known and is usually explained from the deepening of the sump, greater slope of the solidification front and, correspondingly, higher contribution of shrinkage-induced flow to inverse (negative centerline) segregation [1]. The amount of coarse-cell (floating) grains does not change between cases GR80 and GR120L, remaining at the level of 65 vol.%. Therefore, we can assume in the first instance that the contribution of floating grains is similar in the both cases shown in Fig. 2b and c. Further grain refinement results in more grain refinement and more coarse-cell grains in the center of the billet with no evident consequence for the macrosegregation (Fig. 2d).

In the previous discussion we assumed that coarse-cell grains represent floating grains and are depleted in solutes. This assumption is based on the review of literature (some references are given in Introduction), and our own analysis of flow patterns in the sump of a DC cast billet [7]. Let us now present the direct evidence of the composition of coarse-cell and fine-cell grains and their contribution to centerline macrosegregation. The line scans were made through the selected grains with coarse and fine dendrite branches and the examples of such scans are given elsewhere [15]. In this paper we will focus on the analysis of results that can be extracted from the compositional profiles like those shown in Fig. 3. Please note that the line scans have been performed on polished sections and do not necessarily go through the centre of the cell. The peak concentrations also do not necessarily reflect the direct intersection with cell or grain boundaries which may lie beneath the sample surface.

A long depleted plateau of almost constant solute concentration is typical of coarse cells in all the alloy compositions studied. Whereas the fine cells are characterized by a more irregular and steep change in concentration. The examination of the data immediately confirms the viewpoint that the coarse-cell grains are depleted of solute. The minimum concentration in the center of coarse dendrite cells is consistently lower than in the fine cells, throughout all the samples studied as it is shown in Table 2 and illustrated in inserts in Fig. 3c and d. This difference becomes greater at a higher casting speed and a higher concentration of grain refiner, mostly due to the increase in solute concentration in fine cells. It is possible that back diffusion is more efficient in the finer structure because of the shorter diffusion distances. It is interesting that the microsegregation of Ti becomes noticeable at a high casting speed in coarse-cell grains (Fig. 3f), while the concentration of Ti is below the detection limit in all other cases. Therefore, we can conclude that coarse-cell grains are depleted in comparison to the fine-cell dendrites, and the minimum concentrations of solute elements (Cu, Mg) in these grains do not vary much with casting conditions and grain refining.

The macrosegregation, however, would be affected by the bulk composition of the areas occupied by grains of a certain type, rather than by the minimum concentrations in the central part of these grains. These results are given in Tables 3 and 4. The integrated concentration along the line scan was normalized to the length of the line and is adopted as the average concentration of the area occupied by either coarse cells or fine cells.

The data on the composition of coarse-cell and fine-cell grain regions may help in understanding the phenomena involved in the formation of the final macrosegregation pattern in the central portion of the billet. The bulk composition of coarse-cell grains is confirmed to be less than the nominal alloy composition. Somewhat surprisingly the composition of the fine-cell grain areas appears to be higher than nominal, especially in the grain-refined alloy cast at a low speed (GR80 in Table 3). This contradicts the usual view that the fine-cell grain structure reflects the nominal composition (without macrosegregation) [10]. The real situation is far from that. It seems that the bulk composition of fine-cell regions gives us an opportunity to estimate the contribution of different mechanisms to macrosegregation. Using the data in Tables 3 and 4 we can separate the macrosegregation caused by floating grains and by other mechanisms. The results of this analysis are shown in Table 5. Indisputably the coarse-cell, floating grains are able to produce strong negative segregation, and this impact becomes more appreciable with grain refining and higher casting speeds. Actually the structure consisting entirely of floating grains would give centerline segregation about one order of magnitude greater than the observed macrosegregation (compare data in Fig. 2 and Table 5). In contrast, the structure consisting only of fine-cell grains would give positive centerline segregation at a low casting speed. We know that in the absence of floating grains the main acting mechanisms of macrosegregation are thermo-solutal convection and shrinkage-induced flow. With taking into account the shallow profile of the sump at the given, low casting speed, we can assume that the enrichment of fine-cell grain structure is mostly due to the solute brought to this structure by convective flows. (As it is shown in Ref. [1], the contribution of shrinkage-induced flow to the relative segregation of copper should be less than |–0.02| at such a casting speed).

On increasing the casting speed (GR120L), the sump becomes deeper and the contribution of shrinkage-induced flow – greater. As a result the structure consisting of only fine-cell grains contains less solutes as the enriched liquid is taken away by the shrinkage flow (see Table 4 and 5). At the same time, the contribution of coarse-cell grains becomes more significant. It is important, however, to take a notice that the data in Tables 3 and 4 were obtained on selected grains and we tried to avoid measuring large eutectic-rich areas at grain boundaries, which are the indication of solute-rich liquid. In the high-Ti alloy (GR120H) it was virtually impossible, and this resulted in very high values of average concentration in fine-cell regions (Table 4). Similarly, area scans in Table 3 also show higher concentrations of solutes. These observations indicate that the grain refined structures actually allow for a stronger penetration of thermo-solutal flow into the slurry region, and may facilitate positive centerline segregation in the absence of coarse-cell grains.

We can conclude that the effect of coarse-cell grains on the overall macrosegregation is always negative and somewhat larger in the grain-refined structure. The impact of the enriched fine-cell areas and, hence, of thermo-solutal convection is much more pronounced in the grain-refined structure where it can produce positive centerline macrosegregation, especially at a low casting speed. The contribution of shrinkage-induced flow to the centerline segregation becomes more significant at a high casting speed where, in the absence of coarse-cell grains, it competes with the thermo-solutal convection for the sign of the segregation.

Obviously the measured values given in Tables 2–5 are rather local and, therefore, the specific numbers may change. But the overall trend in the variation in macrosegregation induced by different grain structures is clear.

Based on our analysis of the mechanisms of macrosegregation and on the experimental evidence presented in Tables 3–5 as well as in the referenced literature, we can suggest the following line of logic in explaining seemingly controversial experimental results reported in literature.

A stronger penetration of the convective flows into the slurry zone of the grain-refined billet in combination with the hindered shrinkage-induced flow in the dense mushy zone* facilitates the normal segregation (positive segregation in fine-cell GR80 structure in Tables 3 and 5). On the other hand, the strongly depleted floating grains appear on the massive scale in the grain-refined slurry zone and may constitute the bulk of the macrostructure (negative segregation in coarse-cell GR80 structure in Tables 3 and 5). In dependence on the scale of the casting, casting speed and corresponding sump profile, these processes compete with each other. The resultant macrosegregation may then seem not to be affected by the grain refinement, just because the convective-induced enrichment and floating-grain-induced depletion compensate for each other, while the shrinkage-induced flow has minor impact because of the fine grains and shallow sump (Fig. 2b). However, if the grain refinement effectively hampers the shrinkage-induced flow in the mush, while opening the possibilities for more active convective flows in the slurry, then the result can be the positive centerline segregation as has been observed by Finn et al. [4]. Otherwise, when the effects of floating grains and shrinkage induced flow dominate (e.g. at a higher casting speed) grain refinement can result in more pronounced negative macrosegregation as has been reported elsewhere [6, 13, 14].

In the non-grain refined billet (with a columnar grain structure [4] or coarser equiaxed structure in our experiments) the slurry zone turns into mush at a higher temperature, preventing efficient convection, while the shrinkage flow is rather strong (less positive segregation in fine-cell NGR80 structure in Tables 3 and 5). The amount of floating grains is lower than in the grain-refined billet, though they still contribute to the negative segregation (see coarse-cell NGR80 structure in Tables 3 and 5). The experimentally observed macrosegregation will depend on the ratio between the convective and shrinkage flows as well as on the amount of coarse-cell grains. All the processes can dump each other producing negligible segregation as shown in Fig. 2a.

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* The permeability of the mushy zone will be less in the grained-refined equiaxed structure as compared with a non-grain refined grain structure according to the Kozeny-Carman relationship $K = D^2/180\ (1–f_s)^3/f_s^2$, where D is the grain size and f_s is the fraction of solid.

In a billet with a deeper sump because of the larger size [4] or the higher casting speed (Fig. 2c, d) the shrinkage-induced flow may prevail shifting the pattern towards the negative centerline segregation. This is true for both grain-refined and not grain-refined billets. The results given in Tables 3–5 (compare GR80 and GR120L) confirm that the fine-cell regions become less enriched in the solutes with increasing the casting speed. This indicates that the shrinkage-induced flow is more active in taking away the enriched liquid that was brought to the center by thermo-solutal convection. The amount of floating grains does not change between cases GR80 and GR120L. So their contribution to the negative centerline segregation can be associated only with their somewhat larger depletion of solute at a higher casting speed (compare GR80 in Table 3 and GR120L in Table 4).

It is important to realize that the shrinkage-induced flow is a physical phenomenon that is always present in the transition, two-phase region of a solidifying billet, whereas the appearance of floating, solute-lean grains and their accumulation in a certain part of a casting is a conditional incident, the occurrence of which depends on a number of factors such as the structure evolution, temperature regime, and the direction of strong flows in the sump. Proper casting technology and recipe can minimize or prevent the accumulation of floating grains, and thus lower their impact on macrosegregation.

4. Conclusion

The experimental data presented in this paper demonstrate unambiguously that the phenomenon of macrosegregation upon direct-chill casting of aluminum alloys is very complex and cannot be explained by a single mechanism. The seemingly controversial and diverse results reported in literature are the consequences of the intricate interaction between different mechanisms of macrosegregation that can eventually produce any result, from enrichment to depletion. The analysis of macrosegregation should be always performed with taking into account all the possible mechanisms that can reveal themselves to a different extent, depending of the experimental conditions.

The analysis of chemical composition of coarse-cell and fine-cell grains in billets cast with and without grain refinement allowed us to separate the contributions of different mechanisms to the centerline macrosegregation. The minimum concentrations of solute elements in coarse dendrite cells do not depend on the casting conditions and grain refining, whereas in fine cells the minimum composition tend to increase with casting speed and structure refinement. It is unambiguously confirmed that the coarse-cell grains are depleted of the solutes with partition coefficient $K < 1$ and the bulk composition of these grains lowers with grain refinement and casting speed, while their amount increases with grain refinement. It is demonstrated for the first time that the fine-cell regions can be enriched in solutes, especially at low casting speeds and in grain-refined structures. This fact indicates the interplay between the contributions of thermo-solutal convection and shrinkage-induced flow to the overall macrosegregation.

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References

[1] Eskin DG, Du Q, Katgerman L. Scr Mater 2006; 55:715–18.

[2] Du Q, Eskin DG, Katgerman L. Metall Mater Trans A 2007; 28A:180–9.

[3] Eskin DG, Du Q, Nadella R, Turchin AN, Katgerman L. 5th Decennial Int. Conf. on Solidification Processing, Padstow: TJ Intern; 2007. pp. 437–41.

[4] Finn TL, Chu MG, Bennon WD. Micro/Macro Scale Phenomena in Solidification, New York: ASME; 1993. pp. 17–26.

[5] Dorward RC, Beernsten DJ. Light Metals 1990, Warrendale: TMS; 1990. pp. 919–24.

[6] Glenn AM. Russo SP, Paterson PJK. Metall Mater Trans A 2003; 34A:1513–23.

[7] Eskin DG, Zuidema J, Savran VI, Katgerman L. Mater Sci Eng A 2004; 384:232–44.

[8] Suyitno, Eskin DG, Savran VI, Katgerman L. Metall Mater Trans A 2004; 35A:3551–61.

[9] Eskin DG, Savran VI, Katgerman L. Metall Mater Trans A 2005; 36A: 1965–76.

[10] Yu H, Granger DA. Int. Conf. Aluminium Alloys – Their Physical and Mechanical Properties, Warley: EMAS; 1986. pp. 17–29.

[11] Chu MG, Jacoby JE. Light Metals 1990, Warrendale: TMS; 1990. pp. 925–30.

[12] Nadella R, Eskin D, Katgerman L. Mater Sci Forum 2006; 519–521:1841–46.

[13] Gariepy B, Caron Y. Light Metals 1991, Warrendale: TMS; 1991. pp. 961–71.

[14] Joly A, Grün G.-U., Daloz D, Combeau H, Lesoult G. Mater Sci Forum 2000; 329–330:111–120.

[15] Nadella R, Eskin DG, Katgerman L. Metall Mater Trans A (submitted).

[16] Arnberg L, Bäckerud L, Chai G. Solidification Characteristics of Aluminum Alloys. Vol. 3: Dendrite Coherency, Des Plaines: AFS; 1996. pp. 227–232.

Figure captions

Figure 1. Duplex grain structure in the center of a 2024-alloy billet: a, without grain refinement, 80 mm/min (NGR80 in Table 1); b, grain refined, 80 mm/min (GR80); c, grain refined, 120 mm/min (GR120L); and d, grain refined, 120 mm/min (GR120H). Coarse-cell grains are shown by arrows.

Figure 2. Experimental macrosegregation profiles in DC cast 2024-alloy billets: a, without grain refinement, 80 mm/min (NGR80 in Table 1); b, grain refined, 80 mm/min (GR80); c, grain refined, 120 mm/min (GR120L); and d, grain refined, 120 mm/min (GR120H). Macrosegregation ΔC is shown as the deviation of the running concentration C_i from the nominal composition C_0: $\Delta C = (C_i - C_0)/C_0$.

Figure 3. Extracts from line-scan EPMA profiles representative of different grains structures found in the central portion of DC cast 2024-alloy billets: a, NGR80, fine cells; b, NGR80, coarse cells; c, GR80, fine cells; d, GR80, coarse cells; e, GR120L, fine cells; and d, GR120L, coarse cells. Alloy notations are given in Table 1. Inserts in (c) and (d) show the enlarged central portion of the cells.

Table 1. Alloy compositions and casting regimes

Alloy Id	Casting speed, mm/min	Ti, wt %	Composition, wt %
NGR80	80	<0.001	3.5Cu; 1.41Mg; 0.37Mn; 0.14Fe; 0.01Fe
GR80	80	0.006	
GR120L	120	0.008	
GR120H	120	0.04	

Table 2. Minimum concentration of solute elements in the center of dendrite cells.

Alloy Id (see Table 1)	Type of cell	Cu, wt%	Mg, wt%	Ti, wt%
NGR80	**Coarse**	**0.71**	**0.47**	**–**
	Fine	1.1	0.70	–
GR80	**Coarse**	**0.73**	**0.46**	**–**
	Fine	1.1	0.70	–
GR120L	**Coarse**	**0.68**	**0.49**	**0.04–0.045**
	Fine	1.35±0.16*	0.97±0.13*	–
GR120H	**Coarse**	**0.73**	**0.5**	**0.09–0.10**
	Fine	1.62±0.33*	1.2±0.13*	–

* The estimation of measurement error is possible on these samples as the line scan has been performed on separate dendrite cells.

Table 3. Average concentration of areas occupied by coarse and fine cells in the central portion of the 2024-alloy billet cast at 80 mm/min.

Sample Id (see Table 1)	Type of cells	Line scan		Area scan	
		Cu, wt%	Mg, wt%	Cu, wt%	Mg, wt%
NGR80	**Coarse**	**2.55**	**0.96**	**2.92**	**1.08**
	Fine	3.9	1.48	3.95	1.13
GR80	**Coarse**	**2.19**	**0.94**	**3.32**	**1.13**
	Fine	4.01	1.56	4.38	1.43

Table 4. Average concentration of areas occupied by coarse and fine cells in the central portion of the 2024-alloy billet cast at 120 mm/min (line scan data).

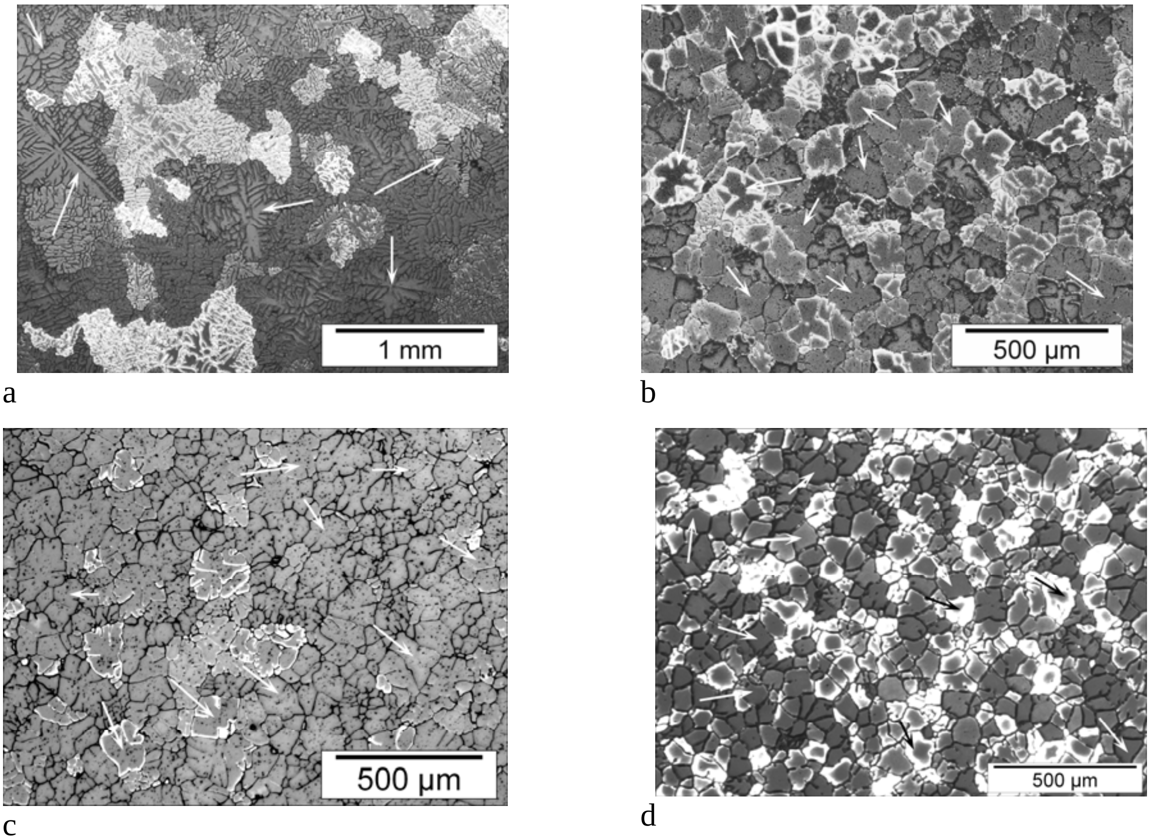
Sample Id	Type of cells	Cu, wt%	Mg, wt%	Ti, wt%
GR120L	**Coarse**	**1.58**	**0.8**	**0.012**
	Fine	3.49±0.29[*]	1.51±0.1[*]	–
GR120H	**Coarse**	**2.37**	**1.07**	**0.014**
	Fine[**]	7.0±3.1[*]	2.4±0.7[*]	–

[*] The estimation of measurement error is possible on these samples as the line scan has been performed on separate dendrite cells.

[**] High values result from relatively thick eutectic areas at dendrite boundaries. More selective analysis will give 3.9% Cu and 1.6% Mg which agrees well with the data on other samples.

Table 5. Hypothetical relative centerline macrosegregation in billets containing only one type of grain structure

Assumption	NGR80		GR80		GR120L	
	ΔCu	ΔMg	ΔCu	ΔMg	ΔCu	ΔMg
100% fine cells	+0.11	+0.05	+0.15	+0.11	–0.003	+0.07
100% coarse cells	–0.27	–0.32	–0.37	–0.33	–0.55	–0.43



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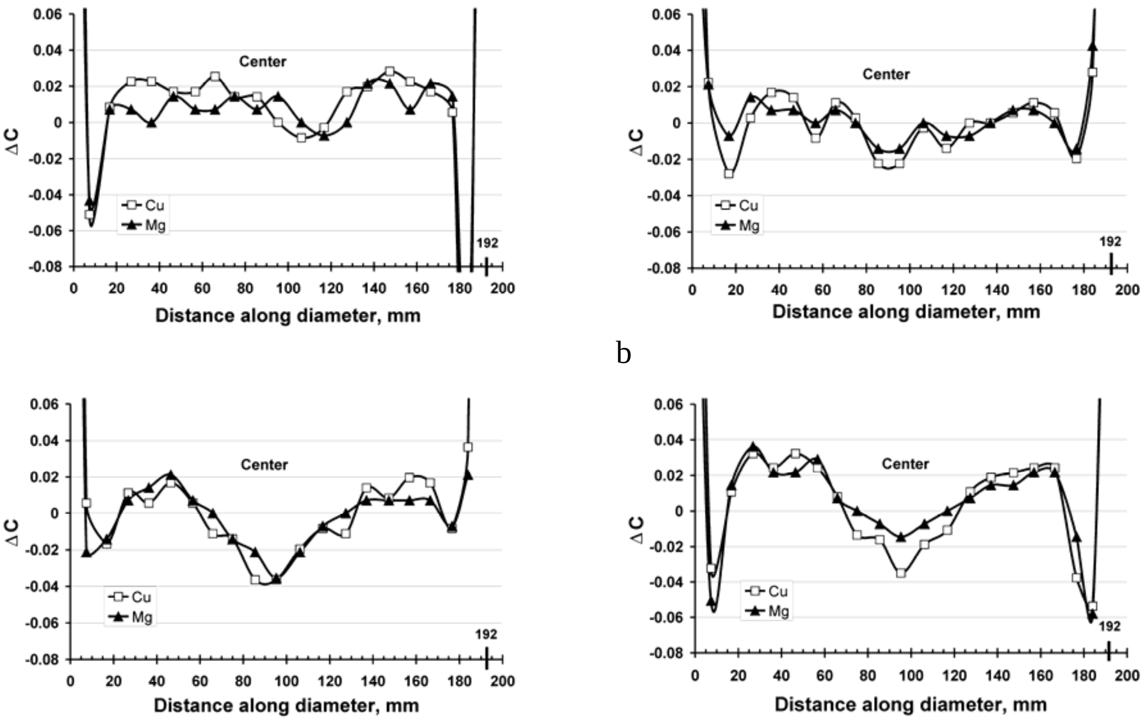


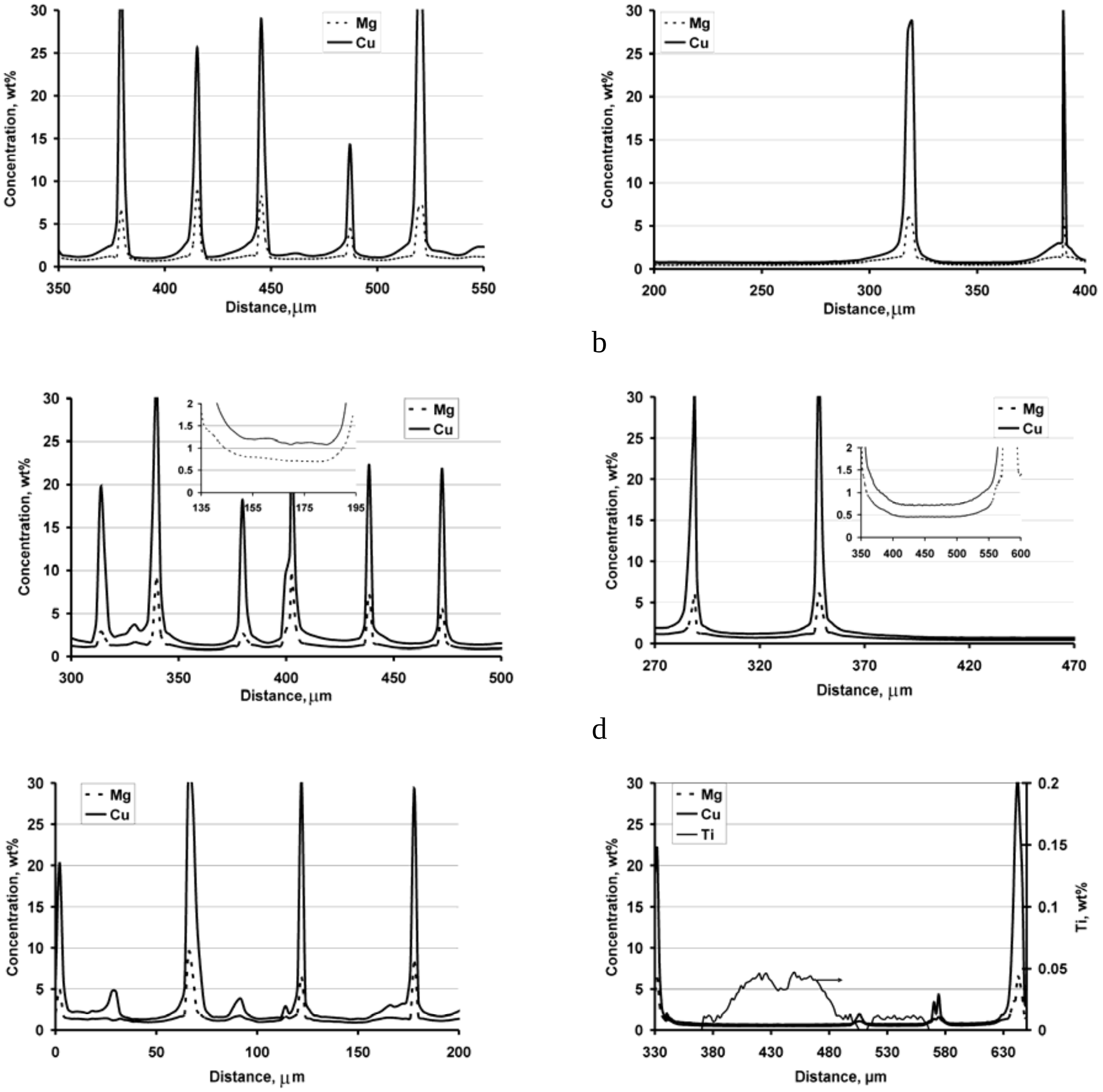
a

b

c

d

Figure 2. Experimental macrosegregation profiles in DC cast 2024-alloy billets: a, without grain refinement, 80 mm/min (NGR80 in Table 1); b, grain refined, 80 mm/min (GR80); c, grain refined, 120 mm/min (GR120L); and d, grain refined, 120 mm/min (GR120H). Macrosegregation ΔC is shown as the deviation of the running concentration C_i from the nominal composition C_0: $\Delta C = (C_i - C_0)/C_0$.



a

b

c

d

e

f

Figure 3. Extracts from line-scan EPMA profiles representative of different grains structures found in the central portion of DC cast 2024-alloy billets: a, NGR80, fine cells; b, NGR80, coarse cells; c, GR80, fine cells; d, GR80, coarse cells; e, GR120L, fine cells; and d, GR120L, coarse cells. Alloy notations are given in Table 1. Inserts in (c) and (d) show the enlarged central portion of the cells.