Essential Readings in Light Metals: Cast Shop for Aluminum Production.
Edited by John F. Grandfield and Dmitry G. Eskin.

From *Light Metals 1991*, Elwin Rooy, Editor

INVESTIGATION IN THE EFFECTS OF CASTING PARAMETERS ON THE EXTENT OF CENTERLINE MACROSEGREGATION IN DC CAST SHEET INGOTS.

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Abstract

The centerline macrosegregation patterns of large as-cast sheet ingots were investigated to determine leading DC casting parameters and quantify their effects on compositional variations. The paper describes the experimental methods and the results of extensive quantitative OES* analyses in 25" and 26" thick ingots. The results show the relative extent of negative segregation of alloying elements such as Fe, Si, Cu, Mg, Mn and Ti in the AA-3xxx and AA-5xxx series. Their relation to the distribution coefficient taken from binary phase diagrams is also discussed. The direct and combined effects of various grain refiner practices, casting speeds and feeding systems were investigated in the Mg alloying range of 1% to 5%. Solidification and segregation phenomena are discussed with regards to the effects of heterogeneous nucleation and flow patterns in the sump. The paper concludes with a discussion on the phenomenon of negative centerline segregation in relation with previously published litterature on the subject.

Introduction

The Aluminum DC casting process has evolved rapidly over the past ten years. New and quite complex technologies have been industrially implemented to cast better and bigger ingots than ever. This is particularly true in the large market of sheet ingot production, however most of the emphasis was put on improving the very surface of sheet ingots while the characteristics of the bulk of an ingot were left mostly unattended.

Macrosegregation phenomena have been known and reported[1] to cause significant variations in chemical composition especially in large sheet ingots.

The main purposes of our work were to:

1- Measure the extent of macrosegregation in a variety of alloys of commercial size.

2- Define the major casting parameters affecting segregation and measure their individual or combined effects on chemical composition.

Although the effect of ingot thickness is significant, it is not introduced here in order to limit the discussion to ingot thicknesses of 635 mm and 660 mm (25" and 26"). Moreover initial testing showed that water flow and temperatures (water and metal) did not significantly affect the extent of macrosegration. Hence they were not included in the full experimentation. Somewhat similar results were reported recently by MM. Dorward and Beernsten[2].

Particular attention was given to casting speed and metal feeding system. Both parameters were reported[1,2,3,4] in previous works to have a strong effect. Finally we believed that grain refining practices should be closely studied as they directly affect the primary phase of solidification also known to be at the source of centerline macrosegregation.

Experimentation

The study of macrosegregation has already shown that maximum depletion of eutectic alloying elements occurs at the very center of an ingot. Experimental sampling consisted in taking a 50 mm by 50 mm bar across the thickness (from rolling face to rolling face) at the mid-ingot width. Bars were cut at a distance equal to at least one sump depth from both ends to avoid foot of head effects. A chemical composition profile was achieved following a series of OES analyses across the bar. A minimum of 25 to 30 optical emission spectroscopy (OES) analyses were done unevenly across thickness with maximum concentration of points in the center portion of each bar. Results are reported on the basis of the relative deviation in composition as compared to the average chemical analysis of the whole ingot. This representation was found to be more effective than absolute values in comparisons between various alloys and alloying elements. A typical plot for Mg and Fe segregation in AA-3104 is shown in figure 1.

The macrosegregation profiles of figure 1 show the spread of analytical data points and the extent of deviation from average composition. The ingot composition is characterized by an alloying element content below average and lowest at the center of the ingot. This is called the low deviation point. The depleted zone is shouldered on each side by an alloying content above average called the high deviation points. The total alloying element deviation is simply the sum of the absolute values of the low deviation and the average of the high deviation points. It is expressed in % of the average ingot composition for a specific alloying element. In that case Mg and Fe varied respectively by 14.1% and 18.9% throughout the bulk of the ingot in relation to their average content. Accordingly, the total deviation of an alloying element will be used hereafter to characterize the ingot bulk chemical variations and to make mathematical analyses of casting parameters.

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* OES: Optical Emission Spectroscopy

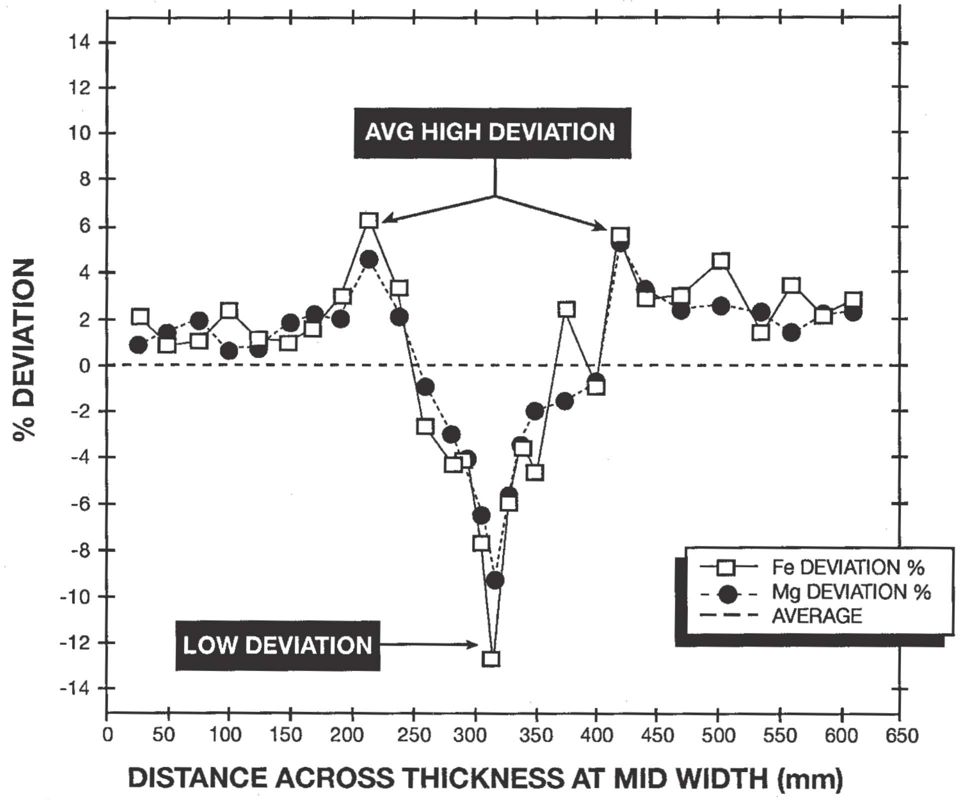

Figure 1: Sheet ingot centerline segregation typical variations in composition across thickness.

Casting Conditions and Results

A) Effects of Alloy Composition and Distribution Coefficient

It is interesting to note that Fe varies relatively more than Mg in spite of much lower alloying content. We have found that the extent of deviation of the various alloying elements closely follows the distribution coefficients. The coefficients are defined as the slope of the liquidus over the slope of solidus lines in binary phase diagrams of the particular elements in aluminum. It is an indicator of solute concentration in the liquid as alloys solidify and therefore of the propensity towards segregation. Table 1 gives corresponding values for Fe, Si, Cu, Mg, Mn and Ti[5]. Eutectic elements have coefficients lower than 1.0 and show negative centerline segregation. On the other hand peritectic elements, notably Ti, have coefficients greater than 1.0 and therefore a positive centerline segregation (figure 2).

Table 1 also reports examples of deviations of the various elements in AA-6009, AA-3104 and AA-5182. The reader will notice the very strong positive segregation of Ti exceeding 100% in the case of AA-5182 grain refined with TIBOR 5:1 in this particular case. Results for eutectic elements are shown in graph form in figure 3. Two important observations are made:

a) The deviation in composition is inversely proportional to the distribution coefficient. Fe is subject to highest segregation tendency with a coefficient of 0.03 followed in order by Si, Cu, Mg and finally Mn at 0.90.

b) The extent of relative segregation of a particular alloying element depends more or the alloy itself than its absolute content in that alloy.

Table 1 Centerline Segregation of Various Alloying Elements In 25" Thick Sheet Ingots of Alloy Series AA-6009, AA-3104 and AA-5182

Alloying Element	Distribution Coefficient	AA-6009 Deviation %	AA-3104 Deviation %	AA-5182 Deviation %
Fe	0.03	10.00	19.80	31.50
Si	0.13	8.75	16.80	28.20
Cu	0.17	8.40	14.80	20.20
Mg	0.43	7.20	10.60	3.30
Mn	0.90	3.10	2.80	3.30
Ti	13.00			111.00

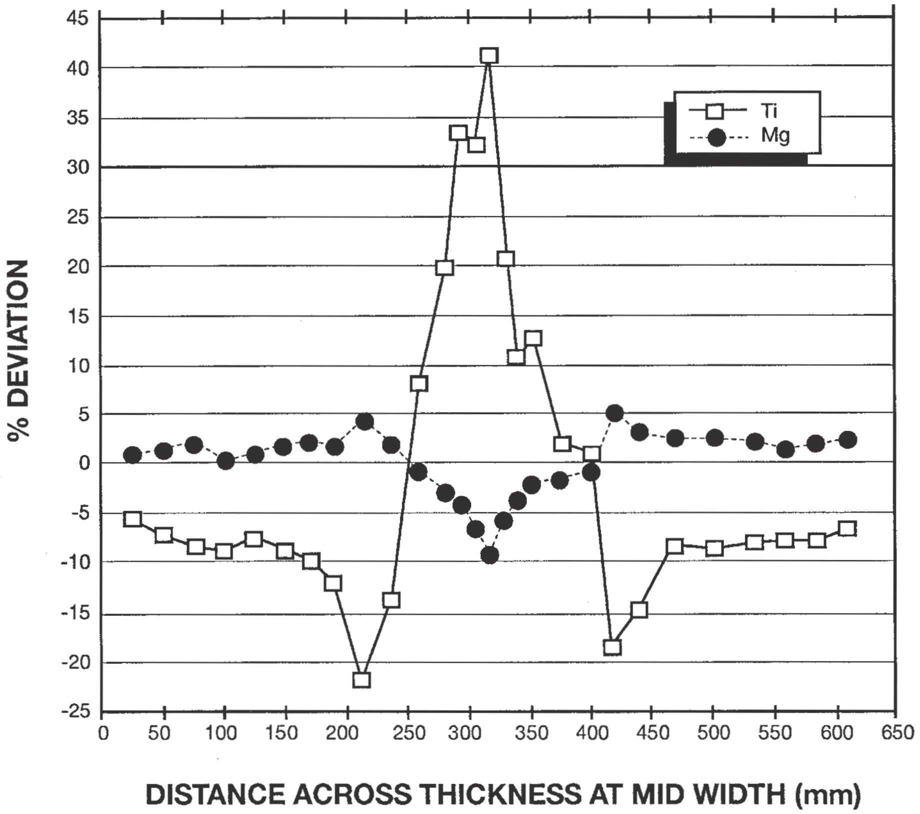

Figure 2: Positive and negative centerline segregation of peritectic (Ti) and eutectic (Mg) elements.

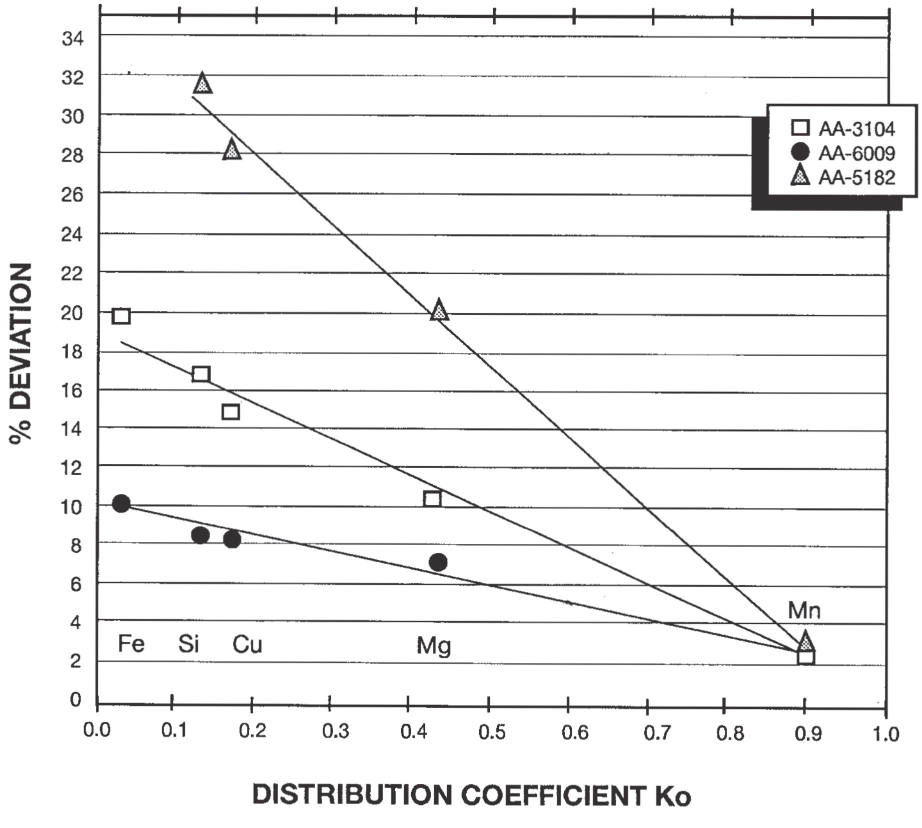

Figure 3: Centerline segregation of alloying elements vs distribution coefficient.

We have subsequently established the following analysis of the effect of casting parameters on the basis of Mg segregation in the major alloy series of AA-3104 and AA-5182. Extrapolations to other alloying elements can be made using relationships above.

B) Effect of Metal Feeding System Into Moulds

The purpose of this segment of our investigation was to isolate the effect of feeding arrangements used in bi-level metal transfer systems. In particular we wished to study the effect of the direction of the metal flow as it enters the ingot sump. The possible influence of feeding was supported by mathematical modelling carried at our Banbury labs and earlier published at the AIME[6].

A series of four metal flow distributors were designed with varying degrees of metal entry direction from horizontal to vertical feeding as shown in figure 4. The distributors were made of solid refractory boards to ensure the desired flow direction and equal flow distribution on each side. The exit cross section area was also kept as close as possible to maintain similar flow velocities. Nominally exit areas were 35 mm high by 90 mm wide for an exit velocity of about 0.13 m/sec. Finally each distributor was simulated in a water model to visualize flow patterns.

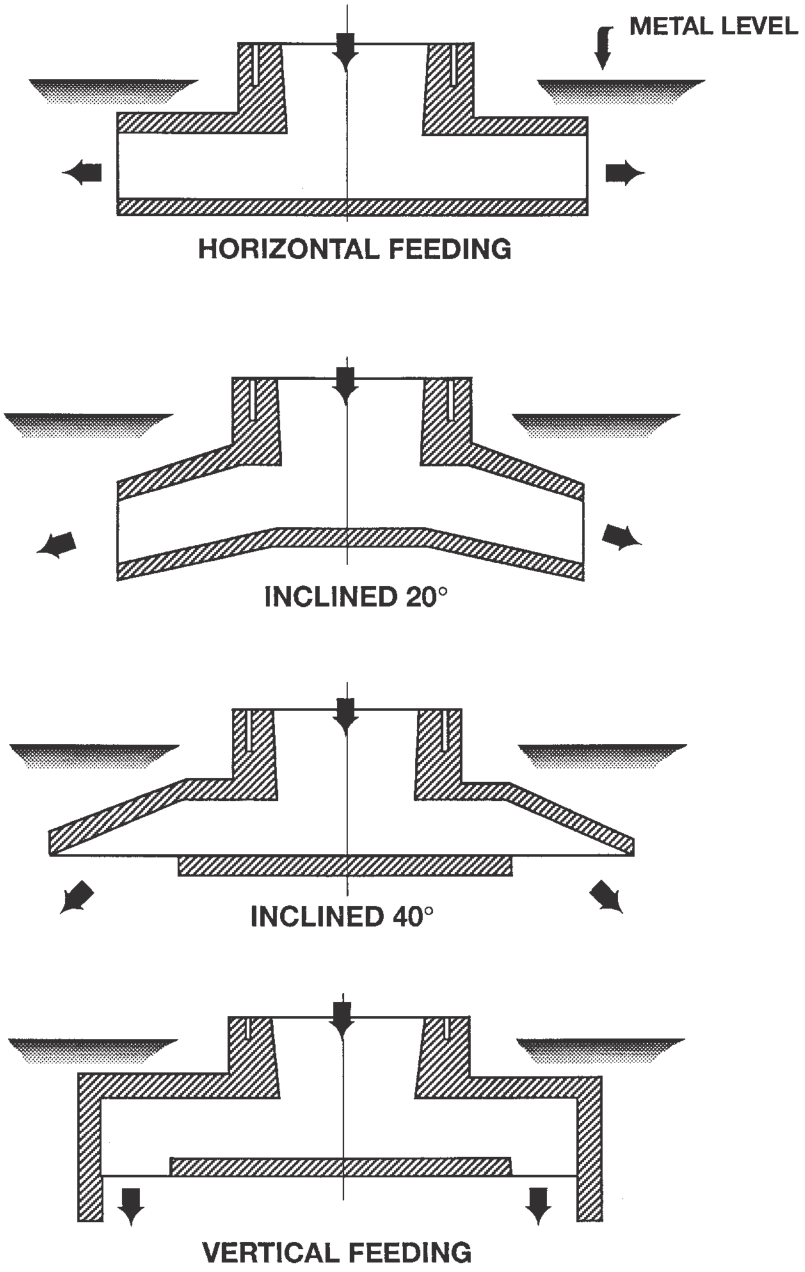

Figure 4: Design of metal flow distributors used in bi-level transfer systems.

We have also included in the test series casting trials with a more conventional fiberglass headscreen for comparison purposes. The headscreen had a relatively fine mesh and covered a significant area of the ingot head. This had the effect of diverting the metal flow horizontally in all directions around the mould. On the other hand the solid distributors directed the flow preferentially towards the short faces of the ingot.

The experimental casting conditions were maintained throughout the series and were as follows:

- Alloy: AA-3104
- Mould dimensions: 635 mm x 1345/1395 mm
- Grain refiner: TIBOR 5:0.2 from 0.0015 to .002% Ti added
- Casting speed: 57 mm/min
- Casting temperature: 700°C ± 5°C

The results are reported in graph form in figure 5. They show a significant reduction in the extent of center line segregation as the metal flow is diverted downwardly into the upper part of the ingot sump. A total Mg deviation of 15.2% was measured in the case of a predominantly horizontal metal entry distribution. The introduction of a vertical flow component of 20 and 40 degrees reduced Mg deviations to 11.7% and 9.8% respectively. A predominantly vertical flow did not bring much further improvement as a deviation of 9.2% was measured.

These results are quite significant and demonstrate the strong effect of metal feeding systems into moulds. Simple modifications to the design of flow distributors in bi-level transfer systems can influence positively or negatively the chemical uniformity of even large sheet ingots. In this particular case of Mg in AA-3104, the depleted zone could be reduced by 35%. Extrapolations can be made to other alloying elements and alloys from relationships described above.

C) Effects of Grain Refining and Casting Speed

The effects of grain refining practices and casting speeds were studied in the alloys series of AA-3104 and AA-5182. In both cases the method of metal feeding was also included as a third parameter. Three types of metal distributors were used: Headscreen, channel bags and COMBO bag. Headscreen were used in conjunction with a layer of refractory paper underneath the spout area to divert the metal flow only in the horizontal direction. channel and COMBO bags are two types of small size fiberglass distributors which are commercially available in North America. Their use in a bi-level transfer system introduces a vertical component to the flow direction in a manner similar to the ones described above with solid distributors.

Macrosegregation in AA-3104

The experimental conditions and results on Mg total deviation in 25" and 26" thick ingots are reported in table 2. A total of 33 casts were made using the full range of grain refiners from none to 6%

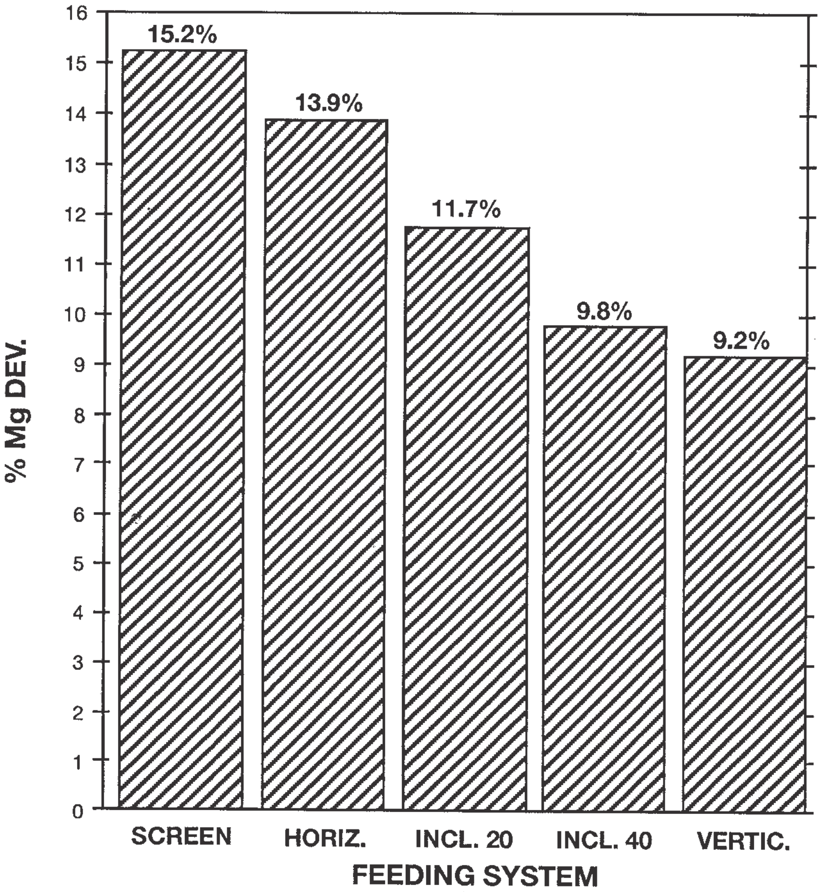

Figure 5: Mg centerline segregation in AA-3104 vs bi-level feeding system.

Ti, 5% Ti:0.2% B and 5% Ti:1.0% B. The effects of Ti addition levels was studied in conjuction with TIBOR 5:0.2 in the range of 0.0013% to 0.0055%. Casting speeds varied from 40 to 70 mm/min. Several casts were repeated at various levels of experimental parameters to measure process and analytical variations.

Figure 6 describes the effects of grain refiners and feeding system on the relative deviation of Mg in AA-3104. In both systems a reduction in grain refining additions is followed by a significant reduction in Mg segregation. The upper curve of figure 6 shows results of experiments all of which use TIBOR 5:0.2 and channel bag. Increasing Ti additions from 0.0013 to 0.0031% for example raised the level of segregation from 11.15 to 14.28 i.e a worsening of 28%. A similar effect was measured while using COMBO bags as distribution device. In that case also segregation was further reduced down to only 4.6% Mg deviation by eliminating grain refining additions. The present experimental data did not provide significant results to conclude on the relative potency of TITAL 6%, TIBOR 5:0.2 and TIBOR 5:1.0.

The influence of flow distribution devices on the extent of centerline segregation in sheet ingot is also illustrated in figure 6. The Mg deviation was on average at a level higher by 3% with channel bag than with COMBO bag. Previous work on the effect of ingot thickness showed that one third of that 3% margin can be accounted for by the one inch difference in ingot thickness between the two series.

Figure 7 shows a similar comparison in the case of flow distribution with headscreen. As previously described, headscreens are associated with a higher level of macrosegregation. It is also quite interesting to note the weaker effect of Ti additions (as TIBOR 5:0.2) when ingots are cast with headscreens. Feeding systems and grain refining thus have multiple effects on the extent of macrosegregation. This is reflected in the following predictions drawn from the various plots of Mg% deviation vs Ti% added:

Feeding	Slope	Mg % Deviation at Ti Addition of:		
		0.001%	0.003%	0.005%
headscreens	384.7	13.9%	14.7%	15.4%
channel bag	1827.2	10.6%	14.2%	17.9%
COMBO bag	1403.5	7.03%	9.84%	12.6%

The effect of casting speeds was investigated by methods of multiple regression analyses. Using the full experimental data shown in table 2, casting speed had only a slight positive effect on Mg segregation in AA-3104 i.e. increasing speed tends to increase variations in composition. Statistically this relationship is only marginally significant. It may very well be absent or reversed under specific experimental conditions. In effect we observed that variations attributable to speed changes are small compared to those of other parameters and in many cases smaller than the experimental errors in the results.

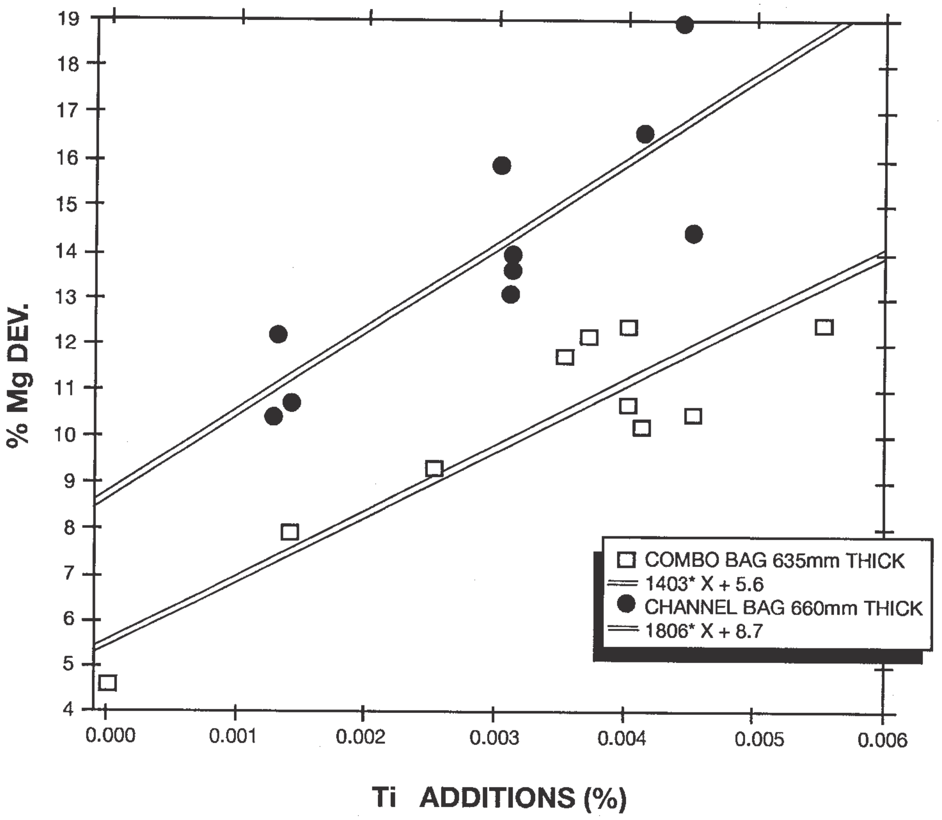

Figure 6: Mg centerline segregation in AA-3104 vs ti Addition and feeding system.

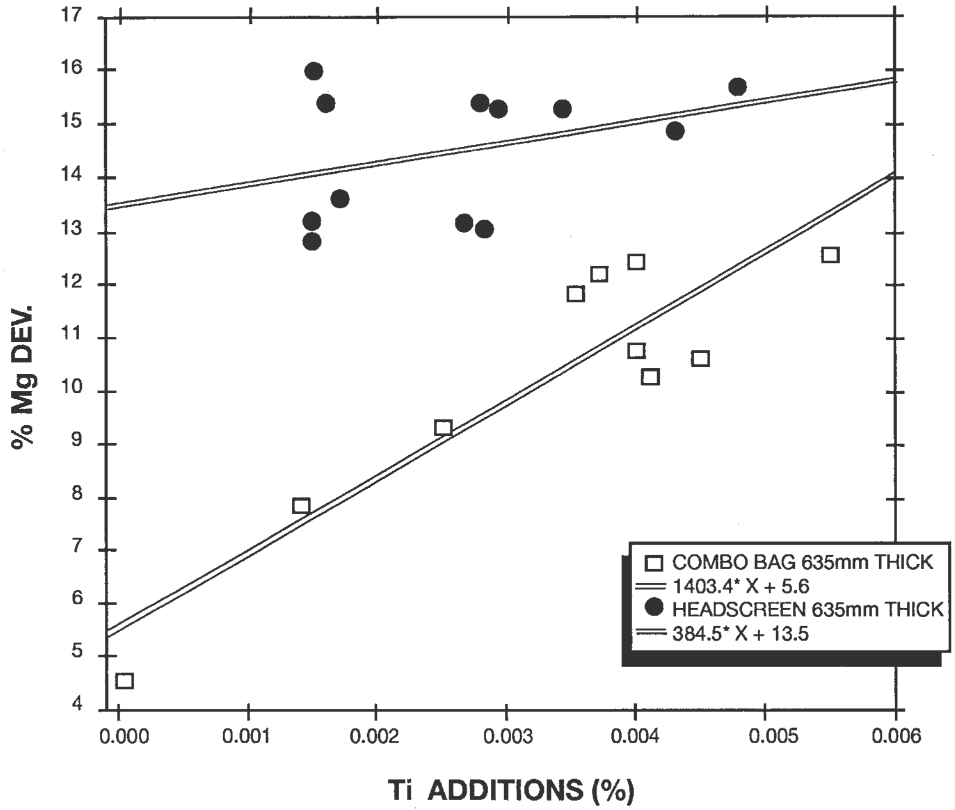

Figure 7: Mg centerline segregation in AA-3104 vs ti addition and feeding system.

Table 2: Experimental Conditions and Results: AA-3104

Cast I.D.	Ingot Thickness (mm)	Cast Speed (mm/min.)	Grain Refiner Type	Refiner Addition (% Ti)	Feeding System	Mg Deviation
1	635	51	5:1.0	0.0037	COMBO bag	12.27
2	635	45	5:0.2	0.0045	COMBO bag	10.63
3	635	64	5:0.2	0.0035	COMBO bag	11.89
4	635	50	6:0.0	0.0014	COMBO bag	7.91
5	635	40	None	0.0000	COMBO bag	4.60
6	635	40	5:0.2	0.0055	COMBO bag	12.60
7	635	55	5:0.2	0.0040	COMBO bag	12.49
8	635	55	5:0.2	0.0025	COMBO bag	9.33
9	635	55	5:0.2	0.0041	COMBO bag	10.33
10	635	55	5:0.2	0.0040	COMBO bag	10.82
11	635	51	5:0.2	0.0020	channel bag	11.80
12	660	55	5:0.2	0.0041	channel bag	16.56
13	660	59	5:0.2	0.0031	channel bag	13.21
14	660	59	5:0.2	0.0031	channel bag	13.83
15	660	61	5:0.2	0.0030	channel bag	15.99
16	660	59	5:0.2	0.0031	channel bag	14.07
17	660	65	5:0.2	0.0045	channel bag	14.57
18	660	68	5:0.2	0.0044	channel bag	19.00
19	660	65	5:0.2	0.0014	channel bag	10.77
20	660	70	5:0.2	0.0013	channel bag	10.47
21	660	70	5:0.2	0.0013	channel bag	12.22
22	635	68	5:0.2	0.0015	headscreen	16.01
23	635	70	5:0.2	0.0016	headscreen	15.43
24	635	49	5:0.2	0.0043	headscreen	14.96
25	635	70	5:0.2	0.0015	headscreen	12.93
26	635	52	5:0.2	0.0015	headscreen	13.25
27	635	62	5:0.2	0.0017	headscreen	13.66
28	635	58	5:0.2	0.0029	headscreen	15.32
29	635	61	5:0.2	0.0028	headscreen	13.09
30	635	60	5:0.2	0.0028	headscreen	15.42
31	635	50	5:0.2	0.0048	headscreen	15.70
32	635	70	5:0.2	0.0034	headscreen	15.35
33	635	63	5:0.2	0.0027	headscreen	13.20

Macrosegregation in AA-5182

Experimental conditions and results of the macrosegregation study in AA-5182 are reported in table 3. Here again the results are expressed in % of the total relative deviation of Mg. A total of 18 casts were done using various types of commercial grain refiners. Casting speed was varied within each group to study its influence.

Figure 8 shows the effect of grain refining practices. Mg deviations less than 10% were measured in the absence of grain refining additions. On the opposite side, casts made with TIBOR 5:1 and headscreen averaged 21.8% deviation in Mg content. Figure 8 also rates on a relative basis the increasing potency of TITAL 6% and TIBOR 5:0.2 in comparison to an ingot cast without grain refining addition. At the same casting speed, segregation increased on average from 11.3% to 13.9% and to 18.8% following the expected order of refiner potency. Experimental data did not allow any conclusions as to the marginal effect of using TIBOR 5:1. The higher level of segregation could also be attributed to a higher level of Ti addition as well as to the use of headscreens as flow distributor.

Table 3: Experimental Conditions and Results: AA-5182

Cast I.D.	Ingot Thickness (mm)	Cast Speed (mm/min.)	Grain Refiner Type	Refiner Addition (% Ti)	Feeding System	Mg Deviation
1	635	60	5:1.0	0.0037	headscreen	23.87
2	635	45	5:1.0	0.0039	headscreen	20.80
3	635	54	5:1.0	0.0041	headscreen	26.15
4	635	46	5:1.0	0.0038	headscreen	20.89
5	635	55	5:1.0	0.0032	headscreen	21.05
6	635	47	5:1.0	0.0036	headscreen	17.76
7	660	70	5:0.2	0.0022	channel bag	18.78
8	660	65	5:0.2	0.0024	channel bag	19.71
9	660	70	5:0.2	0.0022	channel bag	18.31
10	660	72	5:0.2	0.0021	channel bag	18.42
11	635	55	None	0	channel bag	9.10
12	635	40	None	0	channel bag	6.50
13	635	55	TITAL 6%	0.0022	channel bag	13.40
14	635	40	TITAL 6%	0.0022	channel bag	11.50
15	660	75	None	0	channel bag	11.50
16	660	65	None	0	channel bag	11.00
17	660	75	TITAL 6%	0.0023	channel bag	13.60
18	660	65	TITAL 6%	0.0026	channel bag	14.70

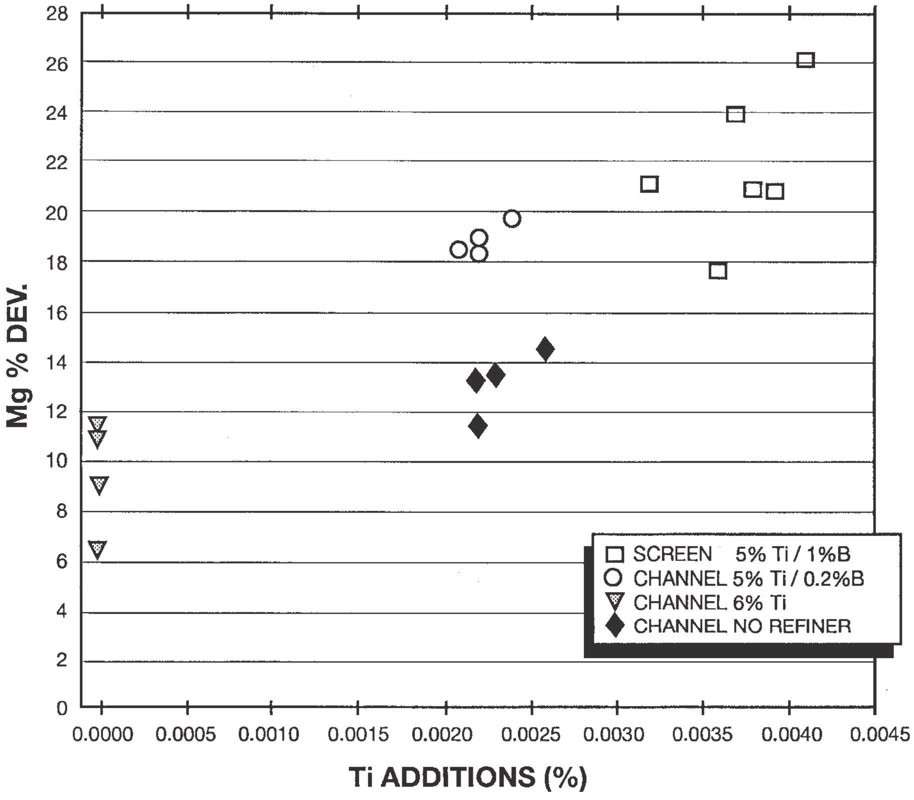

Figure 8: Mg centerline segregation in AA-5182 vs grain refiner type and addition.

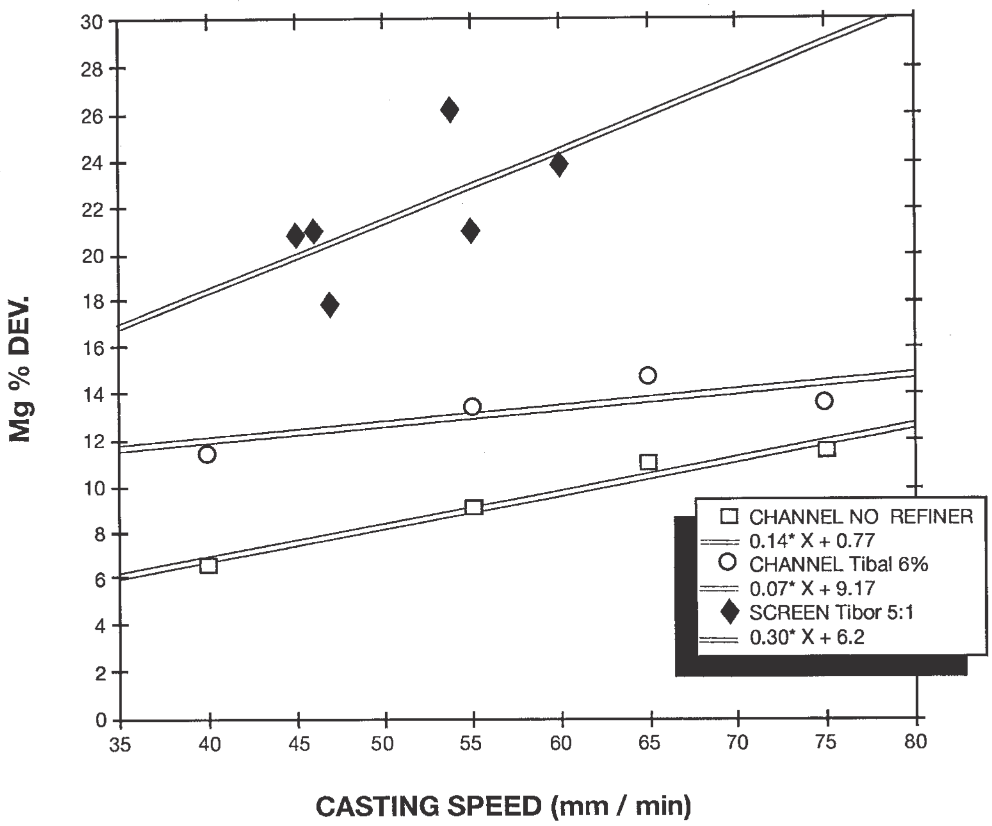

Figure 9: Mg centerline segregation in AA-5182 vs casting speed and refiner type.

The effect of casting speed is shown in figure 9. Considering the overall array of casting parameters, casting speeds had a relatively little positive effect on segregation. Their influence appeared to be stronger with more potent refiners. However it was statistically more significant when grain refiner additions were small or nil.

Discussion

The results of this investigation demonstrated the strong effect of grain refining practices on the extent of bulk segregation in large sheet ingots in AA-3104 and AA-5182 alloys. Metal distribution devices in bi-level transfer system was also seen to improve or deteriorate uniformity of chemical composition depending of flow direction into the sumps. These findings are in agreement with the centerline macrosegregation model first proposed by Yu and Granger[1]. The mechanisms of action would require the following sequence of events for segregation patterns to appear:

1. Nucleation of Alpha Aluminum crystals in advance of the coherent solidification front.
2. Mass transport of particles away from the solidification zone due to natural and forced convection currents.
3. Settling of particles at the bottom of the sump where they accumulate. Hence the ingot centerline is depleted of eutectic alloying element content.

The combined effects of grain refiners and flow distribution system becomes evident when one examines the conditions of aluminum nucleation and growth as proposed by Backerud[7] and schematically presented in figure 10. The more one favors nucleation of free dendrites at the solidification front by use of grain refiners, the more they can be swept away by flow currents in that region. The primary objective of this investigation was to measure quantitatively the effect of such parameters. The extent of negative centerline segregation has been shown to more than double by the addition of potent grain refiners. Chemical uniformity deteriorates significantly as soon as refiners are added. It continues to worsen almost linearly with the actual amount of rod fed to the metal. Results thus show the need to control the refiner additions to a strict minimum demanded by other ingot characteristics or casting requirements.

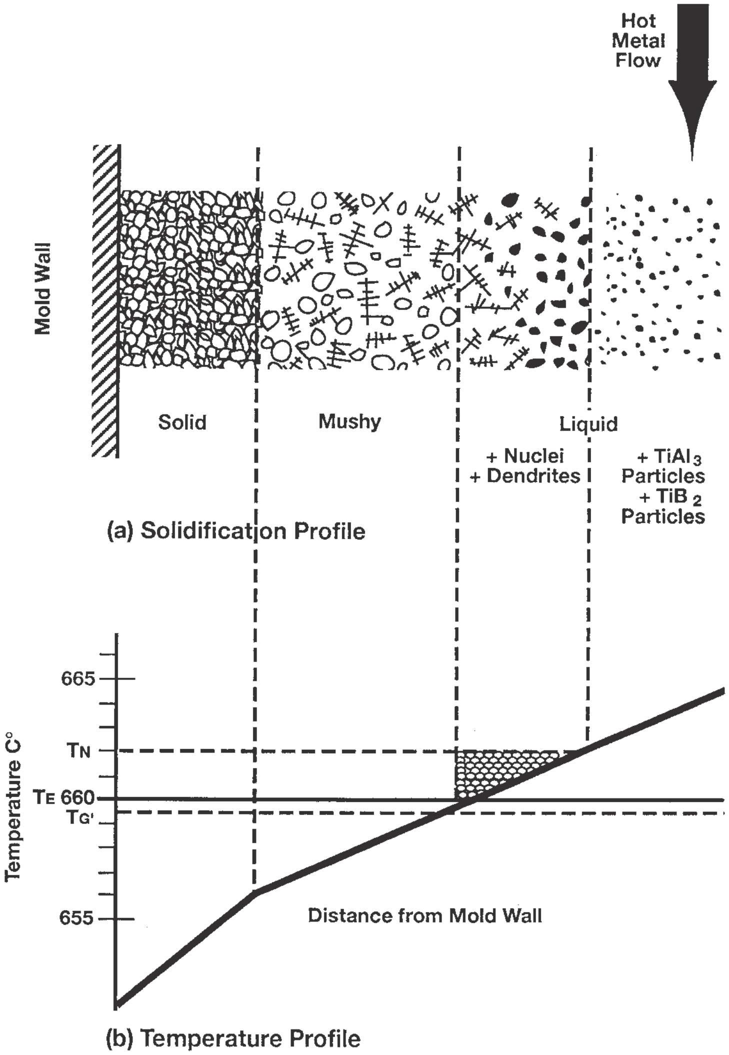

Figure 10: Representation of solidification of aluminum in a DC casting with addition of $TiAl_3$ and TiB_2 in a master alloy prior to casting.

Centerline macrosegregation was seen to vary substantially depending on the total alloying composition. Chemical uniformity decreased from AA-6009 to AA-3104 and to AA-5182. Pure alloys such as AA-1050 are also known to exhibit negligible centerline segregation. This sequence seems to follow an empirical classification which rates the various alloys as per their "grain refinability". It is quite interesting to note that the above macrosegregation rating also follows a similar classification of refinability by electromagnetic stirring (CREM process[8]). One can therefore assume that whatever the means to achieve a fine grain structure, heterogeneous or autogeneous nucleation will provide the necessary conditions for the occurence of centerline segregation. This was demonstrated in an earlier publication[9] showing CREM slab segregation patterns, albeit reduced from those of more conventional practices, but still quite substantial in AA-5052.

Metal feeding methods in bi-level transfer systems have been shown to have one of the strongest effects on the extent of centerline segregation. Forced convective currents generated in the sump by metal entry do influence segregation patterns. This is in agreement with conclusions in previously published works by Yu and Granger[1] and Chu and Jacoby[3]. However, and this is somewhat contrary to earlier findings[3], convective currents in the sump forced by bi-level entry system could be used to reduce the extent of sheet ingot segregation. Simple modifications to the design of metal distribution into moulds resulted in 30% to 40% improvements in chemical uniformity. The mechanisms by which metal entry would, in certain conditions, inhibit some of the parameters leading to segregation are still unknown. Such an investigation would have to be supported by extensive microstructure examinations which were beyond the scope of our work. However two hypotheses could be formulated:

1. By providing a vertical component to metal entry, the isotherms in general and the liquidus isotherm in particular could be pushed further down into the sump. This would have the effect of limiting the presence and growth of so-called isothermal dendrites[1].

2. Forced convection currents may favor the transport of detached dendrites towards the upper part of the sump above the liquidus line where remelting could occur.

The practical conclusion of this work is simply that bi-level transfer system can be improved with regard to segregation patterns and indeed might in some conditions be superior to level pour systems.

Conclusions

1. The extent of macrosegregation in large sheet ingot depends primarily on the alloy total composition. Mg content in 25" and 26" thick ingot can vary by 5% to 18% in AA-3104 and by 10% to 26% in AA-5182. A rating of alloy segregation tendendy was proposed which closely follows grain refinability of the various alloy systems.

2. Segregation of eutectic alloying elements in a given alloy is inversely proportional to the element distribution coefficient. Peritectic elements show a positive centerline segregation pattern. It is quite severe in the case of Ti with a distribution coefficient of 13.

3. Grain refining practices and metal feeding system showed the strongest influence on the extent of centerline segregation.

4. Grain refiner additions should be strictly limited to the amount required by desired ingot characteristics and casting conditions in order to optimize chemical content uniformity.

5. Metal feeding and distribution in bi-level transfer systems can be developed to minimize the extent of bulk segregation in sheet ingots.

6. Casting speed had only a minor effect on segregation within the tested range of experimental parameters. In many cases the variations due to speed were equal or smaller than the experimental errors in the results.

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