Light Metals 2012 *Edited by: Carlos E. Suarez*
TMS (The Minerals, Metals & Materials Society), 2012

INFLUENCE OF DIRECT CHILL CASTING PROCESS VARIABLES ON SURFACE QUALITY OF ALUMINUM ALLOY SHEET INGOTS

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Keywords: Direct chill casting, Surface quality, Extruded surface segregation layer

Abstract

Surface defects formation and their effects on the surface quality of aluminum direct-chill cast sheet ingots have been investigated by metallographic examinations and mathematical modeling. The influence of process variables such as alloy composition, casting speed and lubricant on the surface defects especially extruded surface segregation layer has been determined. The metallographic study for collected samples of plant trials involved visual, micro-examinations and macrosegregation analysis. A 2-D mathematical model has been developed to characterize the thermal, solidification, interdendritic strain and macrosegregation distributions. Also, the model contained a new approach to evaluate qualitatively the macrosegregation formed during dendritic solidification. The model predications were compared to measurements from collected samples to verify the model, where a good agreement was obtained. The model predications illustrate that all the process variables tested have an observed effect on the surface quality by different levels. The mathematical analysis of strain fields as well as metallographic study has been used to explain and discuss the effects of different process variables on the surface quality.

INTRODUCTION

Surface quality of aluminum direct chill cast ingots is characterized by the degree of surface defects such as cold shuts, melt run out, interdendritic surface cracks and high positive surface segregations. One of the most important surface defects and also one of the most important causes of interdendritic crack is the presence of extruded surface segregation layers "***ESSL***". These layers form non-dendritically and randomly in the early stage of solidification in the mold zone on the surface of the direct chill ingots of aluminum alloys [1]. The extruded segregation layers have a severe influence on the surface and subsurface quality and the removal of this layer before further processing of the ingot entails high costs. Quality requirements are increasing and the process is continuously improved with respect to ingot quality as well as casting recovery. Thus, it is interest to study the extruded surface segregation layer phenomenon in the direct chill casting metallographically and develop a mathematical model to simulate it and explain its mechanism with different casting conditions as well as its effect on the surface quality.

Various mechanisms for the extruded segregation layer in aluminum DC casting have been proposed and discussed by several authors [2-4]. These investigations pointed out that the extruded segregation layer is caused by the changes in the magnitude and direction of interdendritic solute liquid flow through incoherent and coherent mushy regions and then solidifies in air gap space. However, numerous numerical models have appeared in the literature for simulating the coupled heat and fluid flow phenomena during aluminum DC casting [5-7]. These models can not cover the significant effect of interdendritic strain on the macrosegregation and on the interdendritic cracks formation [8]. Also, they ignored the fact that the convection streams are very small in the mushy zone especially close to solid front due to the low permeability which increases the resistance of interdendritic fluid flow [7,8].

The present study has been conducted as experimental and theoretical investigation on early solidification stages in the aluminum DC sheet ingot casting to clarify the mechanism of interdendritic strain with the surface defects mainly with an exudation surface segregation layer.

Experimental Work, Metallo-Graphic Study & Measurements

The industrial trials were carried out during three groups casting heats with 125×425 mm rectangular section and the length of 2350 mm sheet ingots where the simulated DC ingot caster is based on an actual industrial casting machine in use at Egyptian Copper Works, Hagar El-Nawatia, Alexandria in Egypt [9-11]. The operating conditions of industrial trials groups were designed based on a complete review of well published previous works [1-7,9-11]. These conditions are composition, casting speed and lubricant for group 1, 2 and 3, respectively as tabulated in Table I.

Middle slices for different requirements of metallurgical study were cut from the ingots broad faces. Samples were taken from these slices for micro-examinations, measurements and macrosegregation analysis. The samples locations were selected from visible *ESSL* areas of cutting slices as shown in Fig. 1(a). The details of cutting principles and samples dimensions are summarized in Ref. [11].

To inspect the ingots surfaces and subsurface structure in the vicinity of *ESSL* areas and positive segregation at interdendritic boundaries of equiaxed structure, middle slices were cut into small specimens as shown in Fig 1(b) based on the cutting principles taken from Ref. [12]. Then, these specimens taken from slices were machined flat, grinded, polished and macro/micro-etched based on the standard methods explained in Ref. [12].

The specimens then were examined under a microscope and micrographs were taken. The characteristics dimensions of extruded surface segregation layer as well as grain size and crystal distortion correlation factor "*CDCF*" for mushy permeability were measured by using standard methods illustrated in Refs. [13-15]. Also, segregation of elements (Mg and Si) in the surface and sub-surface areas of *ESSL* has been determined with a spectrometry as illustrated in Fig. 1(b) and based on the principles described in details in Ref. [15].

Experimental Results

The broad faces of aluminum direct chill sheets ingots shown in Figs. 2(a,b) for AA-6061 and AA-1050 alloys, respectively, exhibit equaxied structure and extruded surface segregation layers "*ESSL*". All the examined samples reveal that the characteristics of these layers are small segments distributed on the ingot

Table I. Summary of Industrial Trials Groups for Tests

Al-alloy composition, %							
IT1, IT2	Si	Fe	Cu	Mn	Mg	Zn	Ti
AA-6061:	0.4	0.7	0.15	0.15	1.2	0.05	--
AA-1050:	0.25	0.4	0.05	0.05	--	0.05	0.03

Casting speed, mm/s			
	IT3	IT4	IT5
AA-1050:	1.41	2.45	3.92

Mold lubricant		
AA-6061:		
Lubricant	IT6	IT7
	Graphite oil	No

surface or as continuous small segments form in discontinuous lines distributed randomly in the direction of casting with different densities. These densities appeared in Fig. 2(a,b) was measured where these measurements involved the density per unit area, diameter and length of segments, as well as their thickness with different casting conditions tabulated in Table I. The results from these measurements are summarized in Table II.

The measured results in Table II indicate that the *ESSL* depends primarily on the alloy composition, casting speed and mold wall lubricant. In the case of alloy composition, the difference in *ESSL* characteristics is obvious. This is due to difference in the densities of alloying elements of AA-6061 and AA1050 alloys. This agrees well the measurements and metallographic studies by El-Bealy, [10,11] and may explain the formation mechanism of *ESSL* in DC casting process. These measurements also reveal that the casting speed is inversely proportional to the severity and density of *ESSL*. This results from the different interdendritic strain hypothesizes generation due to the various solidification behaviors associated with diverse heat fluxes from ingot into copper mold wall [16]. Also, the measurements show the effect of mold lubricant on *ESSL* where the lubricant has a positive effect to reduce the characteristics dimensions of this phenomenon. This is due a reduction effect of lubricant on the heat flow process between the ingot surface and mold wall which affect directly the interdendritic strain generation in the mushy regions [17].

This paragraph presents and discusses the micrographs, measured results of the macro-segregation ratios "S_i" and *CDCF* of middle cutting slices illustrated in Figs. 3(a-g) and 4(a,b), respectively, for different industrial groups tabulated in Table I.

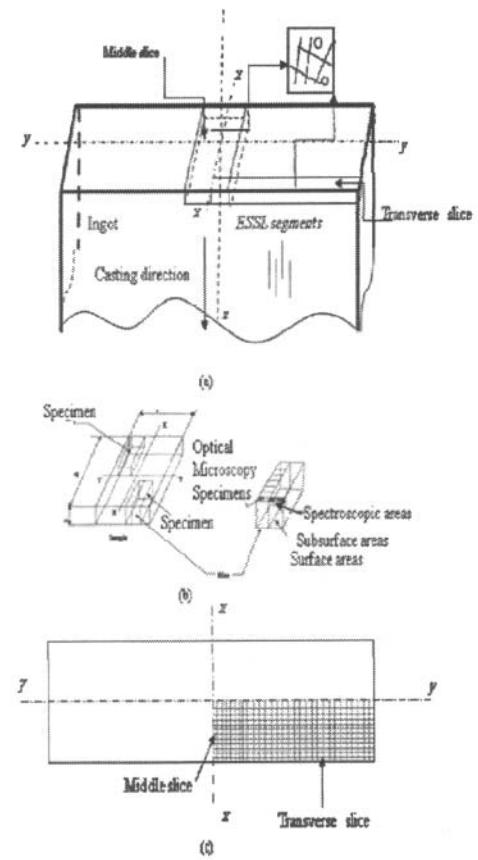

Fig. 1. Schematic representation of a) position of collected sample, b) sectioning of sample for metallurgical examinations and c) computational slices [12].

The results also were observed that *ESSL* are not dendritic and solidified between the ingot surface and mold wall rapidly as seen Figs 3(a-g). Evidence of this observation, it was found in the calculated errors between the measured and simulated values performed by El-Bealy [11] where these errors are always negative on the ingot surface. Also, Fig 4(a) indicates that the segregation ratios (S_j), fluctuate between the positive ($S_j \succ 1$) and negative ($S_j \prec 1$) at different distances from ingot surface. This is due to a coupled effect of interdendritic strain associated with the sudden, continuous changes in the cooling conditions and the metallostatic head [1-11]. Another interesting result arises from the distribution of *CDCF* measurements shown in Fig. 4(b). It is observed that *CDCF* is very sensitive to macro-segregation level especially in the high positive segregation areas and close to the ingot surface as demonstrated in Figs 3(a-g). Therefore, it can be considered as an addition measurement to define the location and morphology of macrosegregation phenomenon [11].

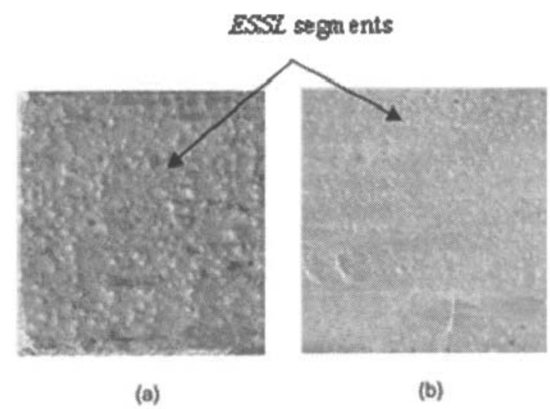

Fig. 2. Macrophotographs of typical *ESSL* areas from sheet ingot surfaces of a) AA-6061 (IT1) and b) AA-1050 (IT2), magnification 0.37 times.

Model Formulation

In this study, the mathematical model computes 2-D transient fluid flow, heat flow, solidification, interdendritic stain and macrosegregation through the mushy zone and solidifying shell. This model has been developed based upon the general frame work for governing equations as presented by Mortensen, [18] of fluid flow fields and Poirier and his co workers of thermal analysis [19]. The interdendritic thermo-metallurgical strain and macrosegregation equations used in this study have been proposed by El-Bealy [11,15]. Also, El-Bealy, [6,9,11] proposed a new approach to evaluate qualitatively the macrosegregation formed during dendritic solidification [6,9,11]. This approach is based on the interdendritic strain criterion, dendritic solidification phases and crystal distortion correlation factor "F_c". It is called elementary interdendritic area "*EIA*" [15]. In this model, only references used are provided here and the reader is referred to the original references for the details of the model,

Table II. Characteristics of *ESSL* of industrial trials

IT no	density/area, segment/mm^2	length, diameter (mm)	thickness, (mm)
IT1	0.895	26.5/0.8	0.2
IT2	0.8	11.25/0.66	0.1
IT4	0.97	10.33/0.76	0.11
IT3	0.83	10.91/0.84	0.12
IT5	0.78	12.63/0.91	0.126
IT6	0.81	21.6/0.76	0.22
IT7	0.93	24.3/0.84	0.25

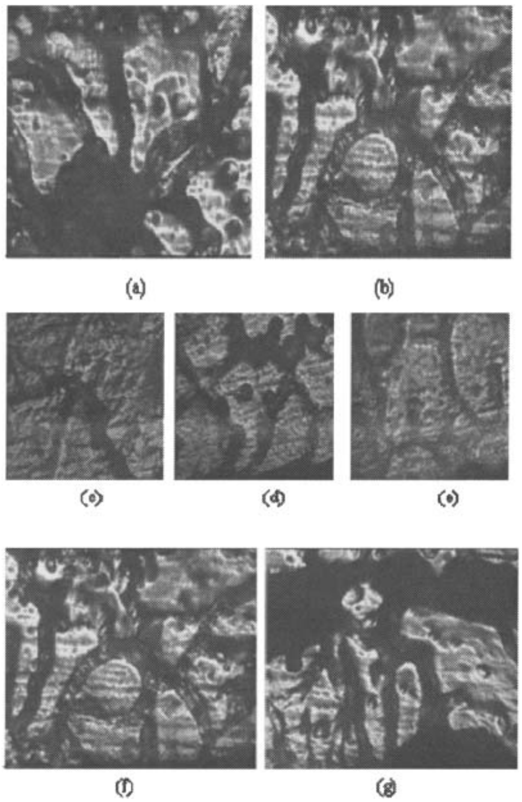

Fig. 3. Micrographs of effect of a), b) composition, c), d), e) casting speed, f) and g) mold lubricant on *ESSL* for different industrial trials groups), magnification 400 times.

the assumptions, thermo-physical properties of aluminum alloys and nomenclature made in the derivations of model governing equations [11,15,18,19].

However, the initial and boundary conditions of 2-D domain schematically shown in Fig. 1(c) are described and summarized in Ref. [12]. Subsequently, the conditions of different cooling regions used in this study are fluctuated cooling conditions technique proposed by El-Bealy and Fredriksson [20]. This technique was modified by El-Bealy, [9,11] and it was used the fluctuated macrosegregation distribution as verification of details of cooling conditions history in the mold.

Results and Discussion

To check the validity of the model, the simulated and measured results of the segregation ratios of Mg and Si distributions of middle slices are compared and are shown in Fig. 4(c) for different industrial trials. These comparisons represent as relative average errors for macrosegregation of alloy element *j*

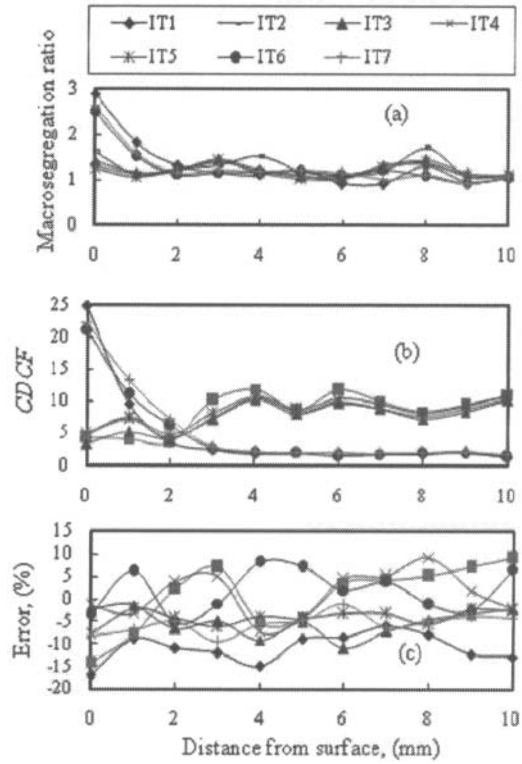

Fig. 4. Variations of a) S_j b) *CDCF* and c) Errors for different industrial trials groups.

and the equation used in this study is described in Ref. [11]. The inaccuracy is severe at surface areas of AA-6061 alloy whereas in the case of AA-1050 alloy is small. This is because *ESSL* appeared on the ingots surfaces does not solidify dendritically between the partly solidified shell and the mold wall [1-11,15]. Therefore, the macrosegregation formation does not follow the roles governed the dendritic solidification. Also, the fluctuation inaccuracy shown in Figs. 4(c) is due to a lag in the thermo-physical properties of aluminum alloys and also inaccurate information of mushy permeability of alloys.

A- Interdendritic strain analysis

The interdendritic strain distributions are often used as criterion related to the macro-segregation formation during dendritic solidification processes [8,9,11]. In order to check the validity of this criterion, the interdendritic strain distributions along the middle slice mentioned above has been simulated in the different mushy regions and are shown in Figs 5(a,b), for AA-6061 and AA-1050 alloys, respectively.

Fig. 5(a) shows the same trend of strain distributions in the solid shell and mushy zone of AA-6061 alloy under conditions of IT1, IT6

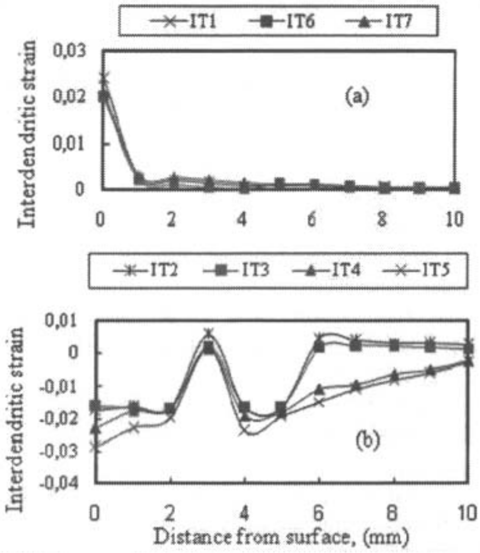

Fig. 5. Variations of Interdendritic stain at z = 180 mm from mold inlet of a) IT1, IT6, IT7 and b) IT2, IT3, IT4, IT5.

and IT7. This figure illustrate that the ingot surface reveals a high tensile strain and changes rapidly into small tensile strain within 1 mm from surface. This is due to a rapid cooling on the surface. This imposes an interdendritic tensile strain on the mushy zone and solid shell which generates from shrinkage/contraction and other sources associated with early stages of dendritic solidification in mushy regions [11,15]. This situation continues where the strain takes small values and decreases gradually within the solid shell and mushy zone until x=10 mm. Subsequently, it is concluded that the ingot cross section deformation is small in case of AA-6061 alloy [16].

In the cases of AA-1050 alloy, the ingot surface exhibits the same trend under different operating conditions of IT2, IT3, IT4 and IT5 as shown in Fig. 5(b). The predications show a high surface compressive strain followed by a rapid fluctuation between compressive and tensile strains through solid shell and mushy zone. The surface compressive strain is due to early formation of air gap close to the mold inlet. This results in a steep drop in surface heat flux through a very thin and weak coherent solid shell. Consequently, the dynamic of air gap with light metallostatic head of aluminum alloys results in non-uniform surface cooling conditions, [3,7] which generates complex inter-dendritic strain hypothesizes in solid shell and different mushy regions [11,16]. This results in a rapid fluctuation in strain generation and in its distribution as shown in Fig. 5(b). Also, it is concluded that the ingot cross section deformation is high in case of AA-1050 alloy [16].

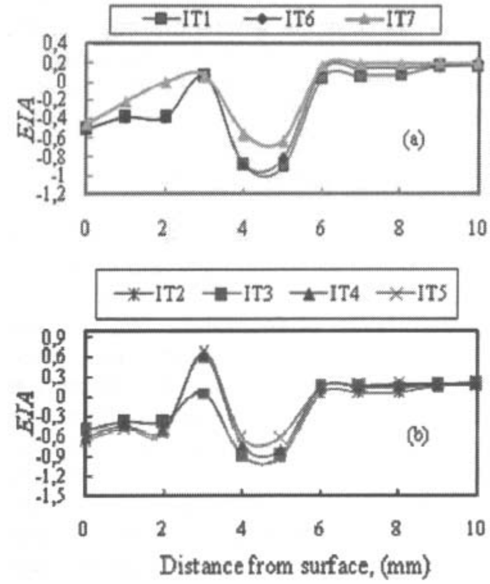

Fig. 6. Variations of *EIA* at z = 180 mm from mold inlet of a) IT1, IT6, IT7 and b) IT2, IT3, IT4, IT5.

B- Elementary interdendritic area "*EIA*"

It has also been suggested that the macro-segregation formation can be determined qualitatively by using a critical solidifying/straining criterion of the material when it is still in the mushy zone proposed by El-Bealy [8,9,11]. This concept is called elementary interdendritic area "*EIA*". It measures qualitatively the macrosegregation formation during the incoherent and coherent mushy regions as shown in Figs. 6(a,b) for AA-6061 and AA-1050 alloys, respectively [11].

The results shown in Figs. 6(a,b) demonstrate *EIA* distributions at location Z= 180 mm from mold inlet for AA-6061 and AA-1050 alloys, respectively, with the crystal distortion correlation factor "*CDCF*" shown in Fig. 4(b). These figures show the same trend of *EIA* distributions of two aluminum alloys and the difference between them is small. This is due the different operating conditions of industrial trials. Although, the strain distribution in Fig. 5(a) reveals small tensile strain but it is interesting to note the observed negative *EIA* of AA-6061 within x= 5 and 6 mm. This is due to nature of *EIA* equation which depends only on the accumulative strain especially the effect of mechanical stress distribution and interdendritic liquid phase fraction. This agrees well with mechanism of *ESSL* which the compressive stresses in the hotter regions of mushy zone squeeze the rich solute liquid into the gap between ingot surface and mold wall to solidify rapidly. Also, the measurements by El-Bealy,

[16] of ingot cross section deformations support these *EIA* distributions where the ingot shape takes concave and convex shapes based on the ingot geometry, surface cooling and operating conditions [16].

Concluding Remarks

Surface quality of aluminum DC sheet ingots has been studied experimentally and theoretical to elucidate a mechanism of extruded surface segregation layer phenomenon "*ESSL*" with compositions, casting speeds and mold lubricant effects. Metallurgical exanimations has revealed that *ESSL* is not interdendritic and its characteristics are affected by different operating parameters examined. Computer predications of the interdendritic strain and elementary interdendritic area "*EIA*" distributions of the ingot coupled with knowledge of experimental results indicate that the key findings of this study are as follows;

1) direct chill casting process variables such as composition, casting speed and mold lubricant have significant direct effects on *ESSL* and therefore, on the surface quality of aluminum DC sheet ingots.
2) interdendritic strain distribution plays a minor role to determine the location, size and morphology of interdendritic area or macro-segregation between the equaxied crystals.
3) elementary interdendritic area "*EIA*" simulates quantitatively the history of macro-segregation formation and works as indicator for its level.

Although the predications of the model are generally supported by the present experimental results, it is necessary to create more investigations by both experimental and numerical modeling to refine the model, solve the remaining problems and to use this work with more plant trials and operating conditions.

Acknowledgement

The author wishes to express his sincere gratitude to Prof. Merton Flemings, Massachusetts Institute of Technology (MIT), former Head of Department of Materials Science and Engineering, Massachusetts, USA for his considerable supervision, guidance, helpful discussions throughout the work and valuable assistance. The author is indebted to Companies' Chair for Materials Processing and Technology of Swedish Iron Masters Association, Stockholm, Sweden, for financial support of this investigation

References

1. I. H. Hove, B. Andersson and D. Voss; In Proceed. of 3rd Conf. on Aluminium Alloys-Their Physical and Mechanical Properties, vol. 2, pp. 264-69.
2. R. Ellerbrok and S. Engler; Metall, 1983, vol. 37(8), pp. 784-88.
3. L. Ohm and S. Engler; Metall, 1989, vol. 43(6), pp. 520-24.
4. B. R. Henriksand and E. K. Jensen; Light Metals, TMS-AIME, Warrendale, PA, USA, 1993, pp. 969-77.
5. C. Devadas and J. F. Grandfield; Light Metals, TMS-AIME, Warrendale, PA, USA 1991, pp. 883-92.
6. G. U. Grun, I. W. Eick and D. Vogelsang, Light Metals, TMS-AIME, Warrendale, PA, USA 1994, pp. 863-69.
7. A. V. Reddy and C. Beckermann; Metall. Trans. B., 1997, vol. 28B, pp. 479-89.
8. M. O. El-Bealy; Light Metals, TMS-AIME, Warrendale, PA, USA, 2008, pp. 721-27.
9. M. O. El-Bealy; Light Metals,TMS-AIME, Warrendale, PA, USA, 2010, pp. 683-88.
10. M. O. El-Bealy; Can. Metall. Q., 2010, vol. 49, pp. 47-62.
11. M. O. El-Bealy; "Interdendritic strain and Macrosegregation Coupled Phenomena for Interdendritic Crack Formation during Solidification in Direct Chill Cast Sheet Ingots", and Homogeneity Degree of Spray Cooling Zones for Improving Quality Continuous Casting of Steel", accepted to publish in Metall. Trans. B.
12. M. El-Bealy; Scand. J. of Metall, 1995, vol. 24, Part I & II, pp. 63-80 & pp. 106-20.
13. Metals Handbook, ASM INTERNATIONAL, Materials Park, OH, 1990, vol. 2, pp. 152-77.
14. ASTM Grain size; Metallography, 1987, vol. 35, pp.18-19.
15. M. O. El-Bealy; Metall. Trans. B., 2011, vol. 43B, pp. 1-17.
16. M. O. El-Bealy; in Proceed. of Aluminum Two Thousand 7th International Congress 2011 Conference, 17-21 May 2011, Bologna, Italia.
17. C. A. Muojekwu, .V. Samarasekera and J. K. Brimacombe; Metall. Trans. B, 1995, vol. 26B, pp. 361-382.
18. D. Mortensen; Metall. Trans. B, 1999, vol. 30B, pp. 119-33.
19. D. R. Poirier, P.J. Nandapurkar and S. Ganesan; 1991, Metall. Trans. B., vol. 22B, pp. 889-900.
20. M. El-Bealy and H. Fredriksson; Scand. J. of Metall., 1994, vol. 23, pp.140-50.