FLUIDITY OF ALUMINIUM FOUNDRY ALLOYS

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Thesis submitted to the
Norwegian University of Science and Technology (NTNU)
in partial fulfilment of the requirements for the degree of
Philosofiae Doctor

Trondheim, September 2005

IMT-Report 2005:76

To my parents and
grandparents with love

The beauty of our achievements is in the people
we can share our success with …
M. Di Sabatino, "Le mie Poesie", 2004, Unpublished

PREFACE

This doctoral thesis is the result of three years full-time studies, including compulsory courses and research at the Norwegian University of Science and Technology (NTNU) from September 2002 to August 2005. The experimental work was carried out at the Department of Materials Science and Engineering at NTNU, at SINTEF Materials and Chemistry, Trondheim, and at the Metal Processing Institute (MPI) at Worcester Polytechnic Institute (WPI), USA, during a six months visit from January to July 2004.

The work was funded by the NorLight Shaped Castings project. The partners were: Alcoa Automotive Castings, Scandinavian Casting Center; Elkem Aluminium; Fundo Wheels; Hydro Aluminium Metal Products; Hydro Magnesium; the Netherlands Institute for Metals Research; NTNU; and SINTEF. Additional financial support was given by the Norwegian Research Council, the Dr. Ing. Håkon Styri fellowship administered by Polyteknisk Forening and the Advanced Casting Research Center (ACRC) at WPI.

Professor Lars Arnberg, Head of the Department of Materials Science and Engineering, was the principal supervisor. Adjunct Prof. Morten Langøy was the assistant supervisor; Dr. Øyvind Nielsen and Prof. Diran Apelian also made an important contribution to this work.

The results were reported and published throughout the three years period and the articles included in the thesis are presented in the form they were submitted for publication or printed. The thesis consists of two parts:

PART 1 is intended to give the reader sufficient background on fluidity, physical fundamentals and literature review as well as industrial challenges, motivations and goals.

PART 2 is a collection of six articles dealing with different aspects of fluidity of aluminium foundry alloys. The manuscripts included in this section are:

Article 1

An improved method for fluidity measurement by gravity casting of spirals in sand moulds

M. Di Sabatino, F. Syvertsen, L. Arnberg, and A. Nordmark, International Journal of Cast Metals Research, vol.18, 59-62, 2005.

Article 2

Effect of grain refinement and dissolved hydrogen on the fluidity of A356 alloy

M. Di Sabatino and L. Arnberg, International Journal of Cast Metals Research, vol. 18, 181-186, 2005.

Article 3

Influence of temperature and alloying elements on fluidity of Al-Si alloys

M. Di Sabatino, S. Shankar, D. Apelian, and L. Arnberg, TMS 2005, Shape Casting: The John Campbell Symposium, Ed. by M. Tiryakioglu and P.N. Crepeau, 193-202, 2005.

Article 4

The influence of oxide inclusions on the fluidity of Al-7wt.%Si alloy

M. Di Sabatino, L. Arnberg, S. Rørvik, and A. Prestmo, Presented at the International Conference on Advances in Solidification Processes, Stockholm, Sweden, June 7-10, 2005. Also accepted for publication in Materials Science and Engineering A, June 2005.

Article 5

Fluidity evaluation methods for Al-Mg-Si alloys

M. Di Sabatino, L. Arnberg, S. Brusethaug, and D. Apelian, Accepted for publication in International Journal of Cast Metals Research, August 2005.

Article 6

Simulation of fluidity in Al-Si alloys

M. Di Sabatino, L. Arnberg, and F. Bonollo, Accepted for publication in Metallurgical Science and Technology, Ed. by Teksid Aluminum, July 2005.

In addition to the articles included in the thesis, parts were presented in the following publications:

1. **Fluidity of aluminium foundry alloys**, M. Di Sabatino and L. Arnberg, NTNU Report, June 2003.

2. **Fluidity of Al alloys: the effect of temperature and alloy chemistry**, M. Di Sabatino, S. Shankar, D. Apelian, and L. Arnberg, NTNU Report, March 2005.

3. **New equipment for measuring fluidity by sand casting**, F. Syvertsen and M. Di Sabatino, Presented at the NorLight Shaped Castings Seminar 2003, Trondheim, Norway, October 21-22, 2003.

4. **Measurement of fluidity in Al cast alloys**, M. Di Sabatino, D. Apelian, and L. Arnberg, ACRC Spring Meeting, WPI, Worcester, MA, May 25, 2004.

5. **A review on the fluidity of Al based alloys,** M. Di Sabatino and L. Arnberg, Metallurgical Science and Technology, Ed. by Teksid Aluminum, vol. 22, 9-15, 2004.

6. **Fluidity and microstructure analysis of Al-Mg-Si alloys for High Pressure Die Casting processes**, M. Di Sabatino, L. Arnberg, S. Brusethaug, and D. Apelian, NTNU Report, June 2005.

7. **The role of temperature and alloy chemistry on the fluidity of aluminum foundry alloys**, M. Di Sabatino, S. Shankar, D. Apelian, and L. Arnberg, To be presented as "Invited Talk" at the 10^{th} International Conference on Aluminium, Kliczków Castle, Poland, October 12 -14, 2005.

ACKNOWLEDGEMENTS

First of all I would like to thank my supervisor, Prof. Lars Arnberg, for scientific advice, inspiration and guidance during the three years spent on this project. Besides, Prof. Arnberg and his family gave me a great support and encouragement for which I am grateful.

This thesis work was part of the NorLight Shaped Castings project. All the industrial partners and the Norwegian Research Council are gratefully acknowledged. It was a great pleasure for me to work in such a dynamic and stimulating project. A special thank goes to Dr. Øyvind Nielsen, project leader, for his stimulating ideas and enriching discussions.

I thank both Dr. Øyvind Nielsen and Dr. Paul Schaffer for proof reading my thesis and for helpful advice. I thank Adjunct Prof. Morten Langøy for interesting discussions.

I am grateful to Prof. Diran Apelian for his enthusiastic support and advice. He gave me the wonderful opportunity of being part of his group at MPI, working at the ACRC laboratory and meeting excellent researchers and wonderful people. Mrs. Carol Garofoli and Mrs. Hailan Li helped me with all my practical needs. I thank Dr. Libo Wang and Dr. Sumanth Shankar for helping me during the experiments at ACRC and for scientific discussions. All my friends at MPI and Worcester made my stay in USA memorable.

I also would like to thank Mr. Arne Nordmark, Dr. Freddy Syvertsen and Mr. Alf Sandberg for their support during the experiments at SINTEF Materials and Chemistry, Trondheim, and for sharing their knowledge with me.

Mr. Stig Brusethaug, Mr. Petter Åsholt, Mr. Asbjørn Prestmo, Mr. Stian Rørvik, Dr. Jan Ove Løland, Mrs. Jorunn Voje and Mrs. Jorunn Snøan Mæland gave important help providing with alloys, chemical analyses and fruitful discussions.

My office mates Dr. Hans Ivar Laukli and Mr. Raimo Helenius, my *"lunch and coffee breaks*" mates Mr. Harald Görner, Miss Jorun Z. Albertsen and all

my colleagues at the Department of Materials Science and Engineering made my stay at NTNU the most pleasant.

My acknowledgements go to all my friends in Norway, the ISU people, my Italian friends in Trondheim who always made me feel *"at home"* and to my *"far"* friends in Italy and USA who supported me with their warm e-mails and telephone calls.

I also thank the Lundberg's family for their lovely support and encouragement.

My deep gratitude goes to my family: my mother Ada and my father Marino for always supporting my choices; my grandparents for their love and prayers; my sisters Silvana and Antonella, my brother in law Giuliano for being patient with me during the stressful times.

I thank my dearest Alf Wilhelm who, with love and patience, helped me along the path undergone to complete this project. I also thank him for his generosity while listening to my presentations before International Conferences. He did that with enthusiasm being always a *"good reviewer"*.

Finally, I thank Who has always been at my side and brought me here today.

SUMMARY

The fluidity of an alloy plays a key role for the foundry and transport industries as it affects the quality and soundness of the cast products. Particularly, fluidity influences the reject rates, hence casting costs and the production of thin-walled, hence light components. Fluidity is a complex technological property and depends on many parameters. However, many aspects of this subject are still not fully understood. The motivation of the research presented in this doctoral thesis was, therefore, to fill this gap in knowledge. The study has aimed at understanding the influence of various parameters on the fluidity of aluminium foundry alloys and, in particular, Al-Si foundry alloys.

A literature review of previously reported results on fluidity was carried out. It was found that a lack of a highly reproducible test method as well as some contradictory results existed in the literature. Therefore, a new fluidity test method was developed. To study the accuracy and reproducibility of this test was one of the goals of this work. The new test method allowed a constant melt superheat, which is considered as one of the major factors affecting fluidity measurements, and a constant pouring velocity. It was found that the reproducibility of the new method was higher than previous methods.

The effect of casting temperature, and hence melt superheat, was assessed through a series of tests. A linear relationship between casting temperature and fluidity length was observed.

The effect of grain refiner on the fluidity of an A356 alloy was systematically investigated. The fluidity lengths without grain refiner and with three additions of Al-5wt%Ti-1wt%B master alloy were measured. The results showed that grain refinement reduced the grain size throughout the spiral somewhat, particularly at the tip, but there were no statistically significant effects on fluidity.

The effect of dissolved hydrogen was also investigated in this study. The hydrogen content was drastically increased by plunging pieces of wood beneath the surface of the molten metal. The fluidity of this melt was measured and compared to a melt with low hydrogen content. It was concluded that the

difference in fluidity between the melts with different hydrogen levels was not significant.

The effect of minor alloying elements (Sr, Ti, Fe and Mg) on the fluidity of Al-7wt%Si alloys was investigated. The Design Of Experiment (DOE) technique and the Taguchi approach were used to design the experiments. The Analysis Of Variance (ANOVA) was performed to analyse the results. It was concluded that the addition of minor alloying elements to a major alloy system, *e.g.* Al-7wt%Si, does not significantly affect its fluidity and the melt superheat had a far greater impact on fluidity than the minor alloying elements.

The effect of mould coating on fluidity was studied on a commercial strip mould which consisted of a H13 die with five channels of different cross sectional areas. The coating was sprayed to achieve a thickness of 0.2mm. Fluidity measurements were performed on the uncoated and coated mould. It was concluded that mould coating significantly increases fluidity. In addition, fluidity measurements on the uncoated and coated mould were undertaken at two different melt superheats and it was found that coating the mould plays a more significant role at low melt superheats.

The effect of oxide content on fluidity was also investigated. Three alloys, namely a standard A356 alloy, the same alloy with 20% (A356+20%) and 50% (A356+50%) re-melted turning chips, were used and their fluidities compared. Qualitative analysis on the type of oxides present in the three alloys was carried out with a PoDFA test apparatus and the oxide level was quantified with optical microscopy analysis. The results showed that the addition of turning chips significantly increased the oxide content. Among the investigated alloys, A356 without turning chip additions showed the lowest oxide content and the highest fluidity. No significant differences in either oxide content or fluidity were found between the A356+20% and A356+50% melts.

Two fluidity test methods, a commercially available one and an experimentally developed test, were used for measuring the fluidity of Al-Mg-Si alloys. Although the two methods were different, they gave consistent results.

Numerical simulations of fluidity tests were carried out on an A356 alloy and the results showed that numerical simulation software can be a useful tool for predicting fluidity in aluminium foundry alloys.

These are the major findings achieved by this thesis work which contribute to improve our understanding of the effect of several key variables on fluidity. It is believed that these results will solve some of the problems currently encountered in foundries and improve their processes.

CONTENTS

NOMENCLATURE

A	$[mm^2]$	mould surface area
A_i	$[mm^2]$	cross sectional area
a	[mm]	channel radius
B		constant
C	$[kJkg^{-1}K^{-1}]$	specific heat
c_p	$[kJkg^{-1}K^{-1}]$	specific heat
df_s/dt	$[s^{-1}]$	solidification rate
f_{ij}		function of the forces acting on the control volume
f_s		fraction solid
f_s^{ch}		coherency fraction solid
f_s^{cr}		critical fraction solid
g	$[ms^{-2}]$	acceleration of gravity
H	$[kJkg^{-1}]$	heat of fusion
h	$[Wm^{-2}K^{-1}]$	heat transfer coefficient
K	$[Wm^{-1}K^{-1}]$	thermal conductivity
K_{metal}	$[Wm^{-1}K^{-1}]$	thermal conductivity of metal
K_{mould}	$[Wm^{-1}K^{-1}]$	thermal conductivity of mould
k	$[Wm^{-1}K^{-1}]$	thermal conductivity
L	$[kJkg^{-1}]$	latent heat
L_i	[mm]	length of channels (fingers)
L_f	[mm]	fluidity length
L_f'	[mm]	fluidity length
m	[kg]	mass
m_l	$[Kwt\%^{-1}]$	liquidus slope
n		total number of measurements
p	[Pa]	pressure
S	[mm]	circumference of the mould channel
S_T		heat source
T	[K]	temperature of the alloy
T_c	[K]	coherency temperature
T_{liq}	[K]	liquidus temperature
T_m	[K]	melt temperature
T_r	[K]	room temperature
t	[s]	time
t_f	[s]	solidification time

t_s	[s]	solidification time
ΔT	[K]	temperature interval
u	[ms^{-1}]	velocity
V	[mm^3]	total volume
V_i	[mm^3]	total volume
v	[mms^{-1}]	velocity of metal flow
X_i		sum of i-th components of extra forces
x		Cartesian coordinate
x_i	[mm]	single measurement
$\bar{x}$	[mm]	average measurement
Δx	[mm]	proeutectic Si-free zone
Δy	[mm]	choking range
W_a	[g]	weight in air
W_w	[g]	weight in water

Greek letters

α	[m^2s^{-1}]	thermal diffusivity of mould
Δ		interval (to indicate a distance or a range)
δ		differential sign
Φ_T		dissipation term
μ	[Pa s]	viscosity
π		constant
ρ	[kgm^{-3}]	density
ρ_{max}	[kgm^{-3}]	density of the fully dense material
ρ_0	[kgm^{-3}]	density of water at room temperature
Σ		sum function
σ	[mm]	standard deviation of single measurements
σ_m	[mm]	standard deviation in the mean values
θ	[°]	apex angle
θ^*	[°]	advancing contact angle
τ_{ji}	[Pa ms^{-1}]	viscous stress tensor

Subscripts

1,2,3	three Cartesian components
i	Cartesian component

in	internal component of forces
j	Cartesian component
metal	metal
mould	mould
out	external component of forces

Abbreviations

ANOVA	Analysis Of Variance
CPU	Central Processing Unit
CV	Control Volume
DOE	Design Of Experiment
FDV	Finite Difference Volume
GDE	Governing Differential Equation
GRF	Growth Restriction Factor
HTC	Heat Transfer Coefficient
HPDC	High Pressure Die Casting
LPDC	Low Pressure Die Casting
MSD	Mean Squared Deviation
PC	Personal Computer
PoDFA	Porous Disc Filtration Apparatus
RPT	Reduced Pressure Test

PART 1

INTRODUCTION

INTRODUCTION

The objective of this thesis work is to develop new knowledge on the influence of alloy composition, melt purity and process parameters on the fluidity of Al foundry alloys and, particularly, Al-Si alloys. To accomplish this, the following scheme has been adopted:

- A literature survey of previous investigations on fluidity has been reported in order to establish a basis for the present study.
- An experimental equipment for fluidity tests has been developed[1] and its reproducibility has been assessed.
- The influence of metallurgical parameters such as chemical composition and grain refiner additions, as well as process parameters such as casting temperature, dissolved hydrogen, oxide content and mould coating have been investigated.
- A comparison of different fluidity test methods has been reported.
- A sensitivity study of the main fluidity test experiment has been carried out using computer simulations.

1 INDUSTRIAL MOTIVATION

The castability of alloys is a measure of their ability to be cast with a given shape with a given casting process. The fluidity limits the castability of alloys and their final properties, *e.g.*, surface finish and wall thickness. Poor or insufficient fluidity affects the soundness of cast products and deteriorates their final quality, *e.g.*, rejection of a shaped casting due to incomplete filling of the mould. Due to the large production volumes involved in casting processes,

[1] The equipment for fluidity tests has been constructed at SINTEF Materials and Chemistry, Trondheim. The author has closely been collaborating with Dr. Freddy Syvertsen and Mr. Arne Nordmark, who designed and developed the equipment.

small reductions in the amount of casting defects can give large economical benefits.

This work arises from a strong industrial demand for understanding the physical and process parameters governing the fluid flow of casting alloys and improving their fluidity. Moreover, there were many contradictory and uncertain results in literature on the influence of various parameters on fluidity, which have motivated the industrial partners and the author to pursue the experimental work.

The main reason for uncertain results of fluidity is that it is difficult to measure with high reproducibility. A goal was, therefore, to develop a new fluidity test method with improved reproducibility and shed light on the gaps in our understanding of fluidity.

2 THEORETICAL AND LITERATURE BACKGROUND

2.1 Introduction

Reliable fluidity data for both pure and commercial aluminium foundry alloys are not readily available. However, such data are important in the optimization of mould filling calculations during solidification [1]. The term “fluidity” in the foundry is used to indicate the distance a molten metal can flow in a mould of a constant cross-sectional area before it solidifies [2]. This definition is different from the definition presented in physics which describes fluidity as the inverse of viscosity, a fundamental temperature related property of a liquid [1, 2].

Fluidity testing can be carried out in different ways. Since the first fluidity test in 1902 [3], several equipments for fluidity testing have been developed and modified [4, 5]. Currently, the most popular fluidity tests are the spiral-shaped mould test and the vacuum fluidity test. The first method measures the length the metal flows inside a spiral-shaped mould. The second method measures the length the metal flows inside a narrow channel when sucked from a crucible by using a vacuum pump. Traditionally, the spiral test has been extensively used because it is compact and portable, and hence can be used easily in the foundry.

Fluidity is mainly a complex technological property and it depends upon many factors [6] which can be categorized as follows:

- Metal variables:
  - Chemical composition
  - Solidification range
  - Viscosity
  - Heat of fusion

- Mould and mould/metal variables:
  - Heat transfer coefficient (coating)
  - Mould and metal thermal conductivity
  - Mould and metal mass density
  - Specific heat
  - Surface tension

- Test variables:
  - Applied metal head
  - Channel diameter
  - Casting temperature (superheat)
  - Oxide/particle content

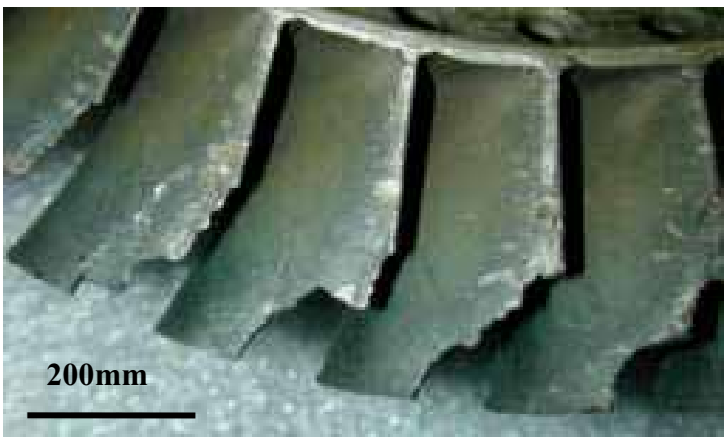


Figure 1 Misrun in a turbine blade is an example of a defect caused by insufficient fluidity [7].

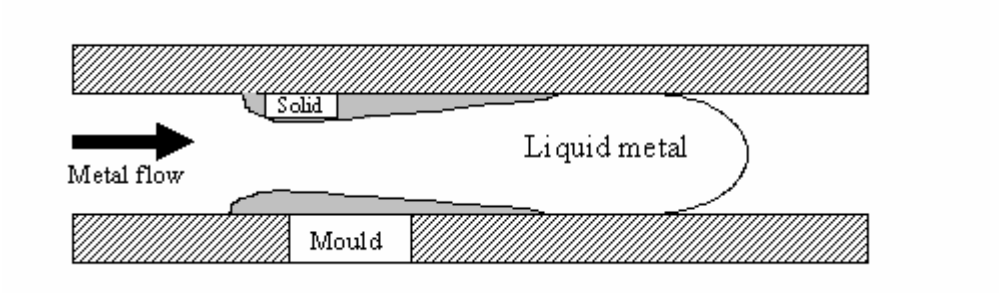
By carefully selecting the appropriate combination of these factors/variables, fluidity can be controlled. This plays a key role for thin walled castings because misruns, often encountered in these castings, are a result of insufficient fluidity of the liquid metal [8]. Figure 1 shows a misrun in a turbine blade [7]. Clearly, the metal has started solidifying before completely filling the mould.

It is not easy to control fluidity due to the large number of variables involved. However, if variations in fluidity due to uncontrolled factors can be estimated, defect problems, such as unexpected misruns and/or cold shuts, can be overcome and process costs reduced.

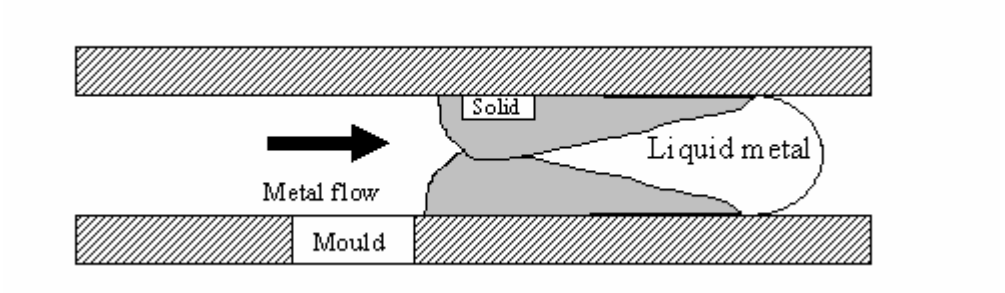
2.2 Modes of solidification

The solidification in the channel of a fluidity test mould has been shown to be quite different for pure metals and alloys [2, 9]. When a pure metal or an alloy at the eutectic composition enters the channel, solidification begins at the wall and continues by the growth of columnar grains with a planar interface as metal flows through the channel. Flow ceases when the columnar grains meet and the pinching by the grains from the channel wall stops the flow [2, 9] as shown in Figure 2.

Unlike pure metals and eutectics, the flow of alloys ceases at the leading tip of the flowing stream. As the solute concentration is increased, the mode of solidification changes from growth of columnar grains with more or less planar front (for pure metals and dilute alloys) to the formation of equiaxed dendrites or columnar dendrites where the dendrite arms fracture forming equiaxed grains (for solute rich alloys). These grains flow downstream with the liquid metal, until a critical fraction solid is reached and the flow stops by choking at the tip of the freezing metal [2, 9] as shown in Figure 3.



a)



b)

Figure 2 Schematic representation of solidification in pure metals and eutectics: a) solidification begins at the channel wall; b) pinching of the flow by grains from the channel wall. The grains impinge each other and the flow stops.

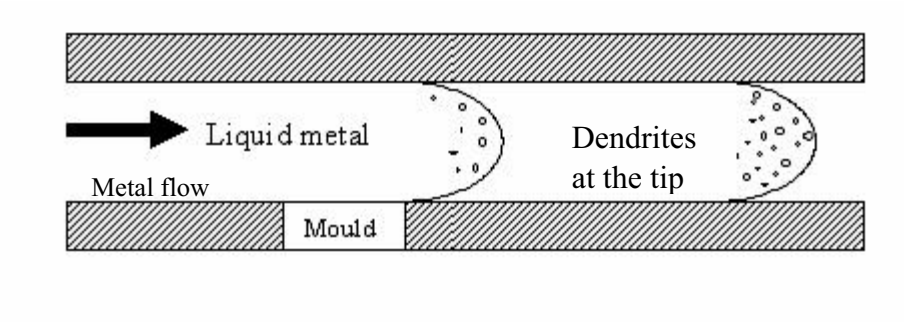


Figure 3 Schematic representation of solidification in alloys. The dendrites are carried at the tip by the flowing metal until a critical fraction solid is reached and the flow stops.

2.3 Solidification models for fluidity

2.3.1 Flemings' model

Flemings developed simplified mathematical models for the fluid length, L_f, of metals that are poured into a cylindrical channel in a mould [2, 10]:

- For the fluidity of pure metals:

$$L_f = \frac{\rho a v (H + C\Delta T)}{2h(T_m - T_r)} \tag{1}$$

- For the fluidity of alloys:

$$L_f = vt_f = \frac{A\rho v(f_s^{cr} H + C\Delta T)}{Sh(T - T_r)}\left(1 + \frac{B}{2}\right) \tag{2}$$

where

$$B = \frac{h\sqrt{\pi\alpha\Delta y}}{K\sqrt{v}} \tag{3}$$

(See Nomenclature section for the definition of symbols)

Flemings' model is based on the assumptions [10] that (i) the solid particles form during the flow in the fluidity channel and travel downstream with the liquid; (ii) the flow stops when the fraction solid near the flow tip reaches a certain value (critical fraction solid, f_s^{cr}); and (iii) the flow velocity is constant until the flow stops. The method greatly simplifies the fluid-flow problem by neglecting friction and acceleration effects [2]. The results obtained with the mathematical model were consistent with the experimental results of the fluidity tests on Al-4.5wt%Cu alloy [10]. However, for other types of alloys the deviation between experimental and modeling results is significant and for many alloys some parameters in the Equations (1)-(3) are unknown.

2.3.2 McParland's model

McParland [11] also developed a solidification model. Three distinct zones were observed during the microstructural examination of sectioned Al-30wt%Si fluidity test castings. For hypereutectic Al-Si alloys, he defined three zones (see Figure 4). Zone I occurs at the casting tip, has a length of Δx (so-called "proeutectic Si-free zone") and is free of primary silicon. Zone II contains densely packed fine silicon particles and Zone III contains large silicon particles. It was suggested that flow ceased as a result of repeated bridging (densely packed fine silicon particles bridged across the channel) along the length of Zone II. Although most of the primary silicon particles are captured in Zone II, the eutectic liquid continues to flow forming Zone I. Once the flow through Zone II is sufficiently impeded, the remaining liquid solidifies as Zone III. The suggested solidification model, however, did not take into account the most important commercial hypoeutectic and hypereutectic Al-Si alloys. Further study is necessary to develop a general solidification model for Al-Si based alloys.

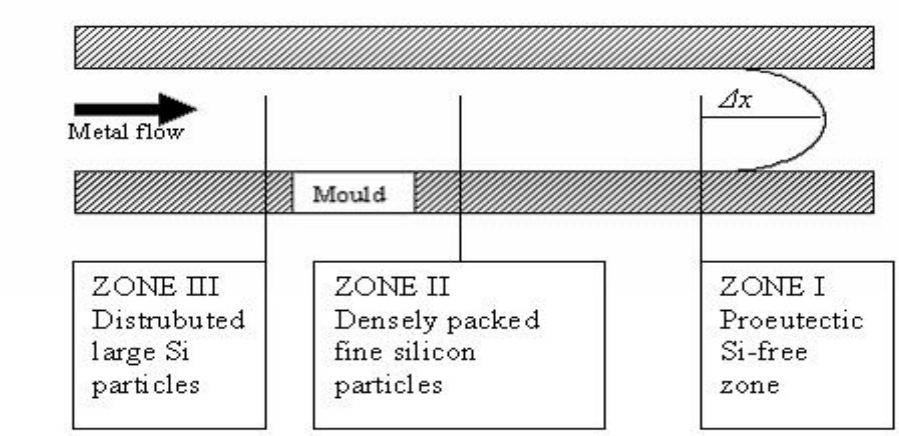


Figure 4 Three distinguished zones according to McParland' s solidification model for hypereutectic Al-Si alloys.

2.4 Numerical modeling of fluidity

Numerical modeling is used to predict mould filling and heat flow during solidification. It also aims at predicting the formation and size of casting defects, and hence being a useful tool for the modern foundries to improve their product quality and reduce their costs. Due to increased power of computers, modeling and simulation of foundry processes started in late seventies and early eighties. The process of developing mathematical models that are able to simulate the casting process throughout the production, thus improving mould design, gating practice, alloy selection, *etc*., has received increasing attention in the last decade. MAGMAsoft, PROCAST and FLOW-3D are only a few examples of commercially available software for casting simulation. Their capabilities are basically to simulate the solidification, mould-filling and thermal history. They also aim at simulating the final microstructure, thereby determining the mechanical properties. Figure 5 shows the flow chart of a "real" and "virtual" foundry process. The two processes are strictly linked and interact. Materials, equipment and thermophysical parameters are input to the simulation process which will give, in the "virtual" process, a prediction of the final properties of the "real" product.

For a deeper theoretical basis of the mathematical description of the fluid and heat flow phenomena, the reader is referred to fluid mechanics and heat transfer textbooks [12-14]. In this introduction, the governing equations and general approach to numerical simulation will be presented. The author will not go through the details of the mathematical formulation. However, the complexity of the equations is remarkable and explains the need for powerful computers, large CPU and computation time.

On a macroscopic scale, fluids can be treated like a continuum and, in the numerical simulation software currently available, the mould filling and solidification processes are described by continuum models. General conservation laws of mass, momentum and energy are used to formulate the mathematical model. Methodologically, it is useful to apply conservation principles to an infinitesimal element (control volume, CV) and derive in this way the governing differential equations (GDE) [14].

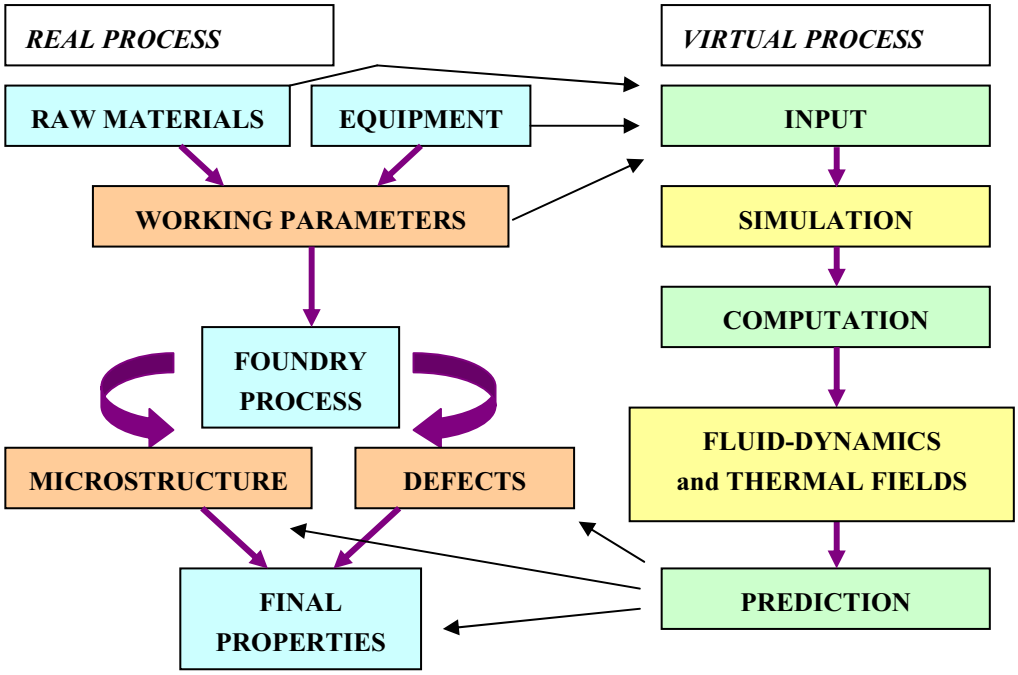


Figure 5 Flow chart of a "real" and "virtual" foundry process [14].

If one assumes that the fluid is incompressible (ρ=constant), then the mass conservation equation or continuity equation can be formulated such as:

$$\frac{\partial u_1}{\partial x_1}+\frac{\partial u_2}{\partial x_2}+\frac{\partial u_3}{\partial x_3}=0 \qquad (4)$$

Conservation of momentum is expressed by applying the Newton's Second Law of Motion to the control volume:

$$\frac{\partial\left(mu_i\right)}{\partial t}=\sum_j f_{ij}+\sum_{in}\left(\dot{m}u_i\right)-\sum_{out}\left(\dot{m}u_i\right) \qquad (5)$$

f_{ij} denotes i-th direction components of the surface and volume forces acting on the control volume. These forces acting on the control volume can be categorized as:

- Surface forces: pressure, friction and surface forces
- Volume forces: gravity and electromagnetic forces

Equation 5 can be expressed as follows:

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_1}(\rho u_1 u_i)+\frac{\partial}{\partial x_2}(\rho u_2 u_i)+\frac{\partial}{\partial x_3}(\rho u_3 u_i)= -\frac{\partial p}{\partial x_i}+(\rho g_i)+\frac{\partial \tau_{1i}}{\partial x_1}+\frac{\partial \tau_{2i}}{\partial x_2}+\frac{\partial \tau_{3i}}{\partial x_3}+X_i \quad (6)$$

The thermal energy conservation equation can be expressed as follows:

$$\left(\rho c_p\right)\frac{\partial T}{\partial t}+\frac{\partial}{\partial x_1}\left(u_1 \rho c_p T\right)+\frac{\partial}{\partial x_2}\left(u_2 \rho c_p T\right)+\frac{\partial}{\partial x_3}\left(u_3 \rho c_p T\right)= \left[\frac{\partial}{\partial x_1}\left(k\frac{\partial T}{\partial x_1}\right)+\frac{\partial}{\partial x_2}\left(k\frac{\partial T}{\partial x_2}\right)+\frac{\partial}{\partial x_3}\left(k\frac{\partial T}{\partial x_3}\right)\right]+\mu\Phi_T+L\frac{\partial f_s}{\partial t}+S_T \quad (7)$$

(See Nomenclature section for the definition of symbols)

The solution of the differential equations requires the definition of the starting conditions as well as the boundary conditions (heat transfer coefficient between interfaces, slip/no slip at the mould wall, *etc.*) which are the most critical and difficult parts of the numerical modeling.

Once the equations governing the filling and solidification processes are formulated and the boundary conditions are defined, the thermophysical data for the selected material need to be available for their solutions. MAGMAsoft [15] commercial software package has a wide data base which contains thermophysical properties for the most common steel, aluminium and magnesium alloys. However, there is a lack of data for the heat transfer coefficient between different casting interfaces, *i.e.* mould/metal, metal/pouring

basin, *etc*. Moreover, the development of an air gap and the corresponding decrease in heat transfer is difficult to simulate and limits the accuracy of computer simulations. Interfacial heat transfer, which can vary markedly with air gap formation, is of particular importance in metal- or high thermal conductivity moulds and in the use of chills in sand castings. Many researchers have been studying these phenomena [16, 17].

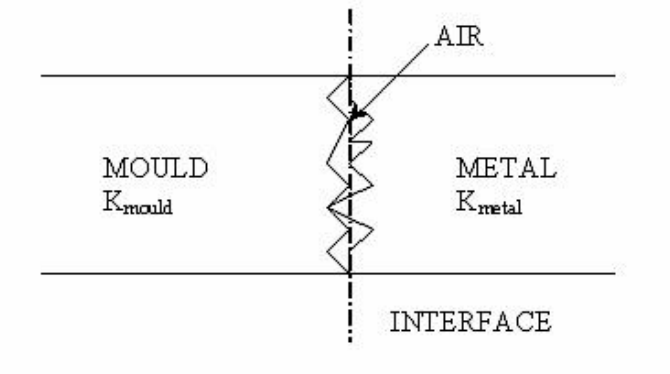


Figure 6 Schematic representation of the interface between mould and metal in a casting. The mould and metal typically have different thermal conductivities (K_{mould} and K_{metal}, respectively). An air gap formation will strongly influence the HTC.

Figure 6 shows a schematic representation of the interface between mould and metal in a casting. Due to the mould roughness, an air gap forms and strongly influences the heat transfer coefficient values. Fundamental studies and experimental measurements of thermal properties and in particular heat transfer coefficient values are needed for foundry materials.

The modeling of solidification processes in aluminium alloys is difficult due to a lack of reliable data. The heat transfer coefficient value, for example, plays a key role on simulation results; however, this is a complex material property which is difficult to measure.

In this thesis work, a part of the study has been focusing on the simulation of fluidity tests. The heat transfer coefficient values between the pouring cup and the metal, and between the sand mould and the metal were approximated such that the simulation calculations and experimental measurements were in good agreement. For the stoppage criteria of the simulation studies, a fraction solid of 30% was considered as coherency fraction. The corresponding temperature was assumed as the temperature at which the metal flow stops (coherency temperature at the coherency point). Figure 7 shows a schematic representation of liquid metal flowing in a fluidity channel. The fraction solid increases with the time and for the investigated alloys, the solidified dendrites accumulate at the tip of the flowing metal. It was assumed, based on the works by Bäckerud and Arnberg [18, 19], that the dendrites start impinging and form a network that prevents further flow at a fraction solid of approximately 30%.

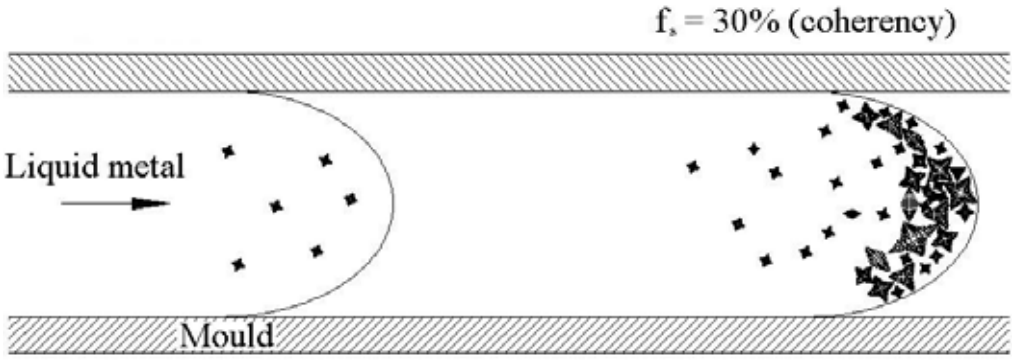


Figure 7 Schematic representation of liquid metal flowing in a fluidity channel. The fraction solid increases with the time and, for the investigated alloys, the solidified dendrites accumulate at the tip of the flowing metal. It is assumed that the dendrites start impinging at a fraction solid of approximately 30%.

2.5 Effect of different parameters on fluidity of Al alloys

The fluidity of alloys depends upon many factors and this section will summarise some of the most important results presented in the literature on fluidity. The intention here is to offer a presentation on the influence of key

metal, mould and test parameters (Section 2.1), and thus provide a useful data-base for the modern foundries and cast houses.

2.5.1 Effect of composition

Composition is one of the main factors influencing fluidity. It was found that small alloying additions to pure metals reduce fluidity [2, 20], and the fluidity of unalloyed aluminium is reduced with decreasing purity [21]. Figure 8 shows the influence of aluminium purity on fluidity measured by a fluidity spiral test [1]. Fluidity was reduced about 25% with 0.4% impurity (Al purity from 100% to 99.6%), and about 37% and 40% with 0.8% and 1.2% impurity (*i.e.* Al purity of 99.2% and 98.8), respectively [1].

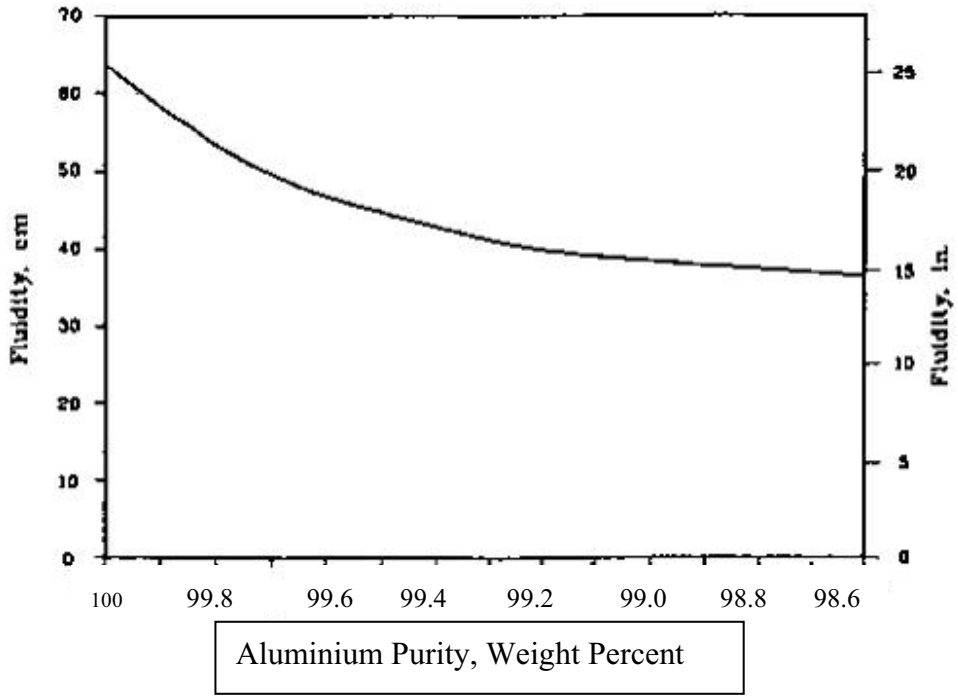


Figure 8 Influence of aluminium purity on fluidity measured by a fluidity spiral test method [1].

Pure metals and eutectic alloys have the highest fluidity. The fluidity of pure aluminium is significantly reduced by the presence of impurities, while for alloys the fluidity is increased as the fraction eutectic increases, with a marked local maximum in fluidity at the eutectic composition. This relationship between fluidity and chemical composition has been studied for a wide range of alloy systems which have shown similar relationships [1]. Two commercial alloy systems, however, exhibit exceptions from this composition-fluidity relationship: flake graphite cast iron and Al-Si foundry alloys. This introduction will focus on the Al-Si alloy system.

The fluidity of Al-Si alloys increases with increasing Si content reaching a maximum at 17-18wt% Si, as shown by Lang [22], well above the eutectic composition of these alloys (12wt% Si). The role of silicon on fluidity is shown in Figure 9 and the fluidity was measured at a constant pouring temperature (800ºC) [22]. In these experiments, the increase of Si content has changed the liquidus temperature of the alloys, and hence changed the superheat, which must be taken into account when interpreting the diagram. However, the effect of silicon has been studied by several authors [1, 6, 9] who have confirmed that the fluidity of hypereutectic Al-Si alloys is better than that of hypoeutectic and even eutectic compositions. This is due to the high heat of fusion of primary silicon which is 4.5 times higher than the heat of fusion of pure aluminium [23]. Moreover, in the Al-Si alloys, even at eutectic composition, aluminium dendrites are present due to a skewed coupled zone [24] which means that the dendrites disappear at a higher Si content than eutectic. The fluidity of Al-Si alloys has a maximum at a silicon content well above the eutectic composition. After this maximum in fluidity, further additions of Si will reduce the fluidity due to the increase in number of proeutectic silicon particles interfering with the metal flow. Hence, maximum fluidity will be achieved at a Si content where the increased interference of proeutectic silicon compensates for the increased heat of fusion from the formation of silicon [9].

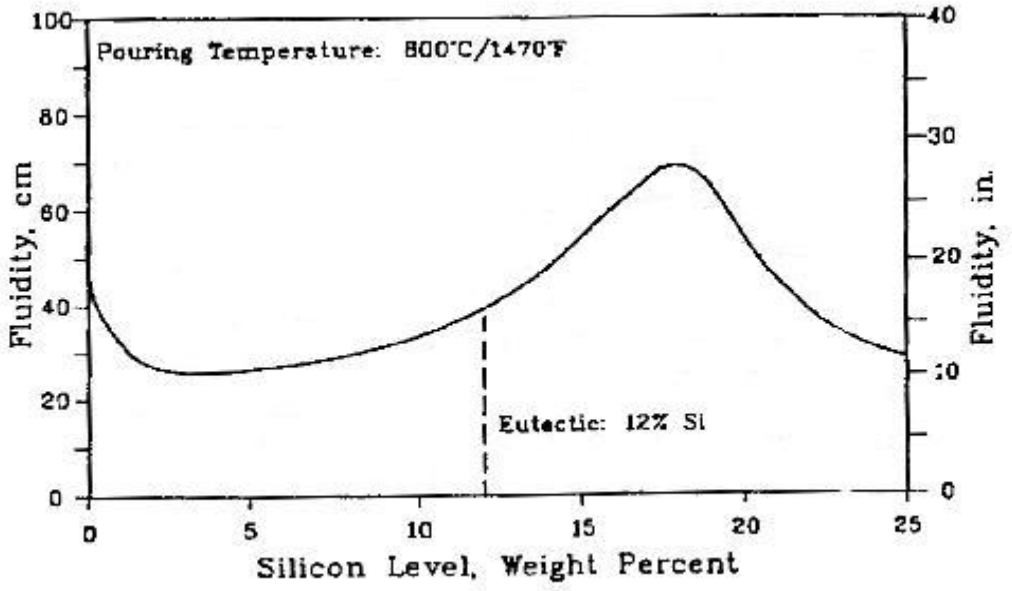


Figure 9 Effect of silicon level on the fluidity of binary Al-Si alloy [1].

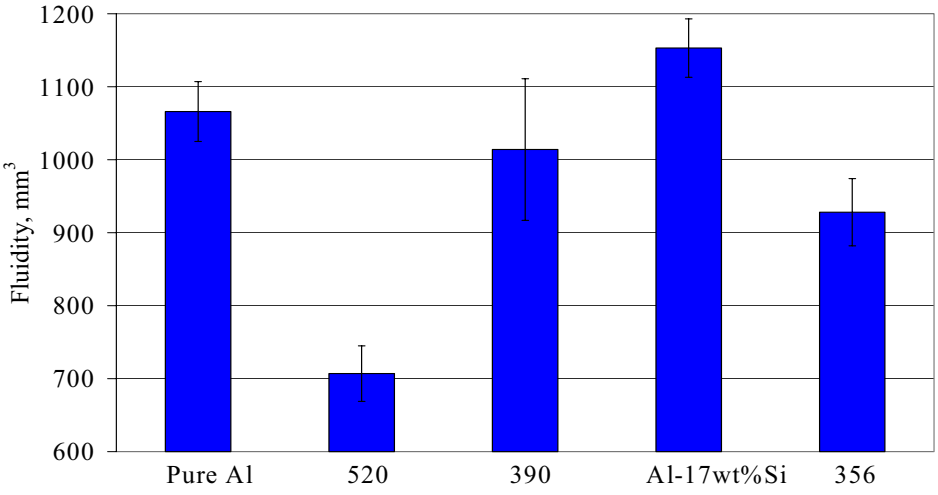


Figure 10 Graphical representation of the fluidity measurements for five alloy systems: pure Al (99.999%), 520, 390, Al-17wt%Si and 356. The fluidity was measured with a commercial strip mould test at a constant melt superheat (70K) [25].

In a recent study [25], the fluidity of five alloy systems, namely pure Al (99.999%), 520, 390, Al-17wt%Si and 356, were compared. The alloys were cast at a constant melt superheat (70K) and the fluidity was measured with a commercial strip mould. The measurements were given as the volume of metal filled in the channel [25]. Figure 10 shows the results of this investigation. Pure Al and Al-17wt%Si alloy showed the best fluidity while 520 alloy showed the lowest fluidity. The investigation also confirmed that the hypereutectic Al-Si alloys have a maximum fluidity at about 17wt%Si.

The effect of Cu in Al-Cu alloys and of Mg in Al-Mg alloys is shown in Figures 11 and 12, respectively. Fluidity was measured at a constant pouring temperature for all investigated alloys (800ºC) [22], which again gives a variable superheat and a low accuracy of the measured values for fluidity peaks. For these alloys, however, the change of the liquidus temperature due to increasing solute concentration is fairly small [26]. According to Lang's diagram in Figure 11 the increase of Cu content from 10wt% to 33wt% increased fluidity by 60%. Maximum fluidity is achieved at the eutectic composition. According to Lang's diagram in Figure 12, an increase in Mg content from 0wt% to 2wt% reduced fluidity by 55%, whereas the further increase of Mg content from 2wt% to 36wt% increased fluidity by 77%.

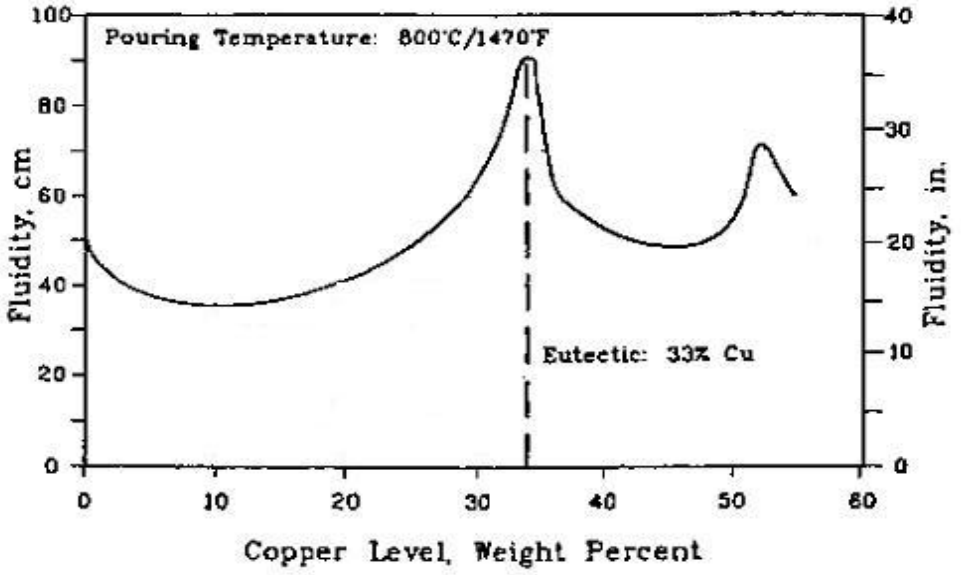


Figure 11 Effect of copper on fluidity of binary Al-Cu alloy [1].

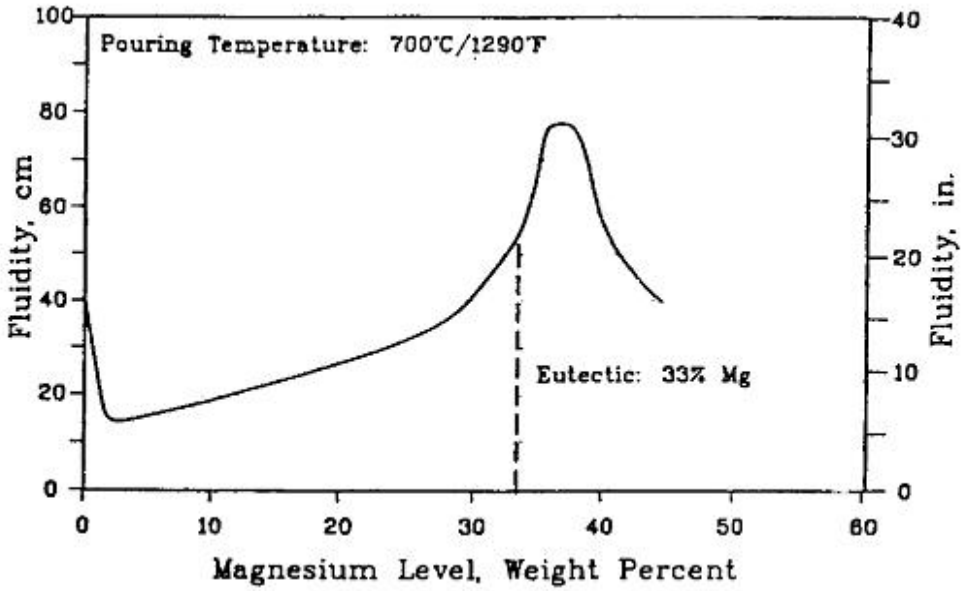


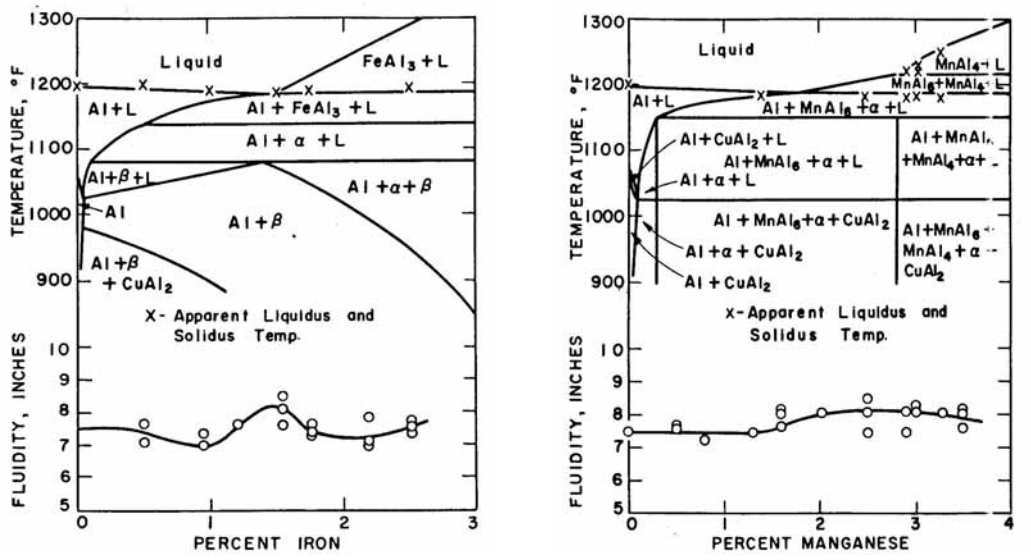
Figure 12 Effect of magnesium level on fluidity of binary Al-Mg alloy [1].

In the Al-Mg system, this increase in fluidity occurs prior to the maximum solubility of Mg in α-aluminium [23], which may be due to the solidification segregation and to the physical properties of the phases formed [1]. It is observed that the peak in fluidity for Al-Mg alloys occurs above the eutectic composition and this may be a related phenomenon [1].

Sheshradri *et al.* [27] studied the effect of alloying elements on fluidity of pure aluminium and found that Ti, Fe, Zr, Cr, Mn and Cu slightly decrease fluidity. Gowri and Samuel [28] studied a 380 alloy and observed that an increase in the Fe content decreases the fluidity of the alloy. The additions of 1.5 and 1.7wt% Fe caused a decrease in fluidity of 4% and 6%, respectively. The additions of 1.3wt% Zn to the same 380 alloy caused a decrease in fluidity of 5%. However, the additions of 1wt% Cu caused an increase in fluidity of 4%. No significant change in the fluidity of the 380 alloy was observed when 0.23 and 0.5 wt% Mg were added. Rooy [29, 30] reported similar reductions in fluidity of Al-Si based foundry alloys with the increase in Fe content. Wang *et al.* [31] reported a decrease in the fluidity of molten aluminium with increase of Fe without any appreciable change in the surface tension, due to an increase in the amount of insoluble Fe-bearing phases that form in the alloy [31, 32]. However, Pfeiffer and Sabath [33] observed that fluidity increased as the total combined concentration of Fe, Mn and Zn was increased in an Al-8wt%Si-3wt%Cu alloy.

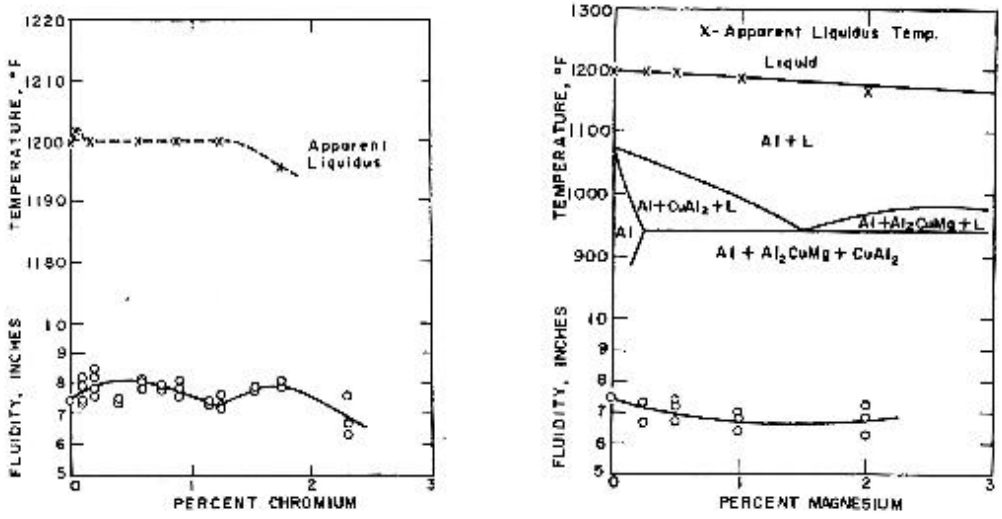
The results of these investigations have not shown any significant variation of fluidity with small additions of Fe, Zn, Cu, Mg and Mn. The change in fluidity was within the standard error of the experimental equipments used. Therefore, more investigations need to clarify the role of the alloying elements on fluidity of Al-Si foundry alloys.

Flemings *et al*. [10] studied the effect of Fe, Mn, Cr, Mg, Cu and Si on fluidity of an Al-4.5wt%Cu alloy. They cast the alloys at a constant melt superheat and measured fluidity with a vacuum fluidity test apparatus. They also evaluated the effect of these elements on the liquidus temperature. Figures 13 to 15 show the effect of iron and manganese, chromium and magnesium, copper and silicon, respectively, on the liquidus temperature and fluidity of an Al-4.5wt%Cu alloy. It was concluded that small additions of these elements do not significantly affect the fluidity of the alloy.



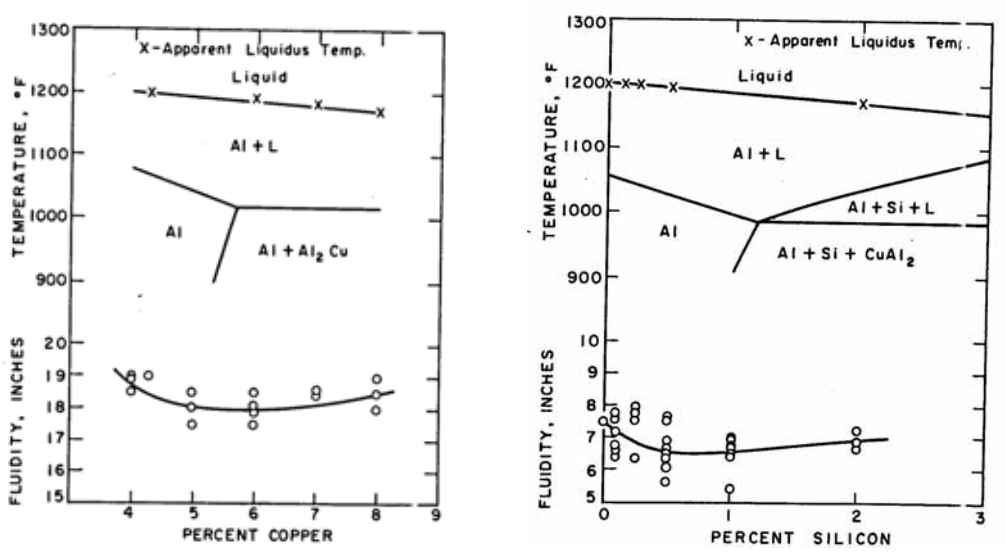
a) b)

Figure 13 Effect of a) iron and b) manganese on liquidus temperature (top) and fluidity (bottom) of Al-4.5wt%Cu alloy [10].



a) b)

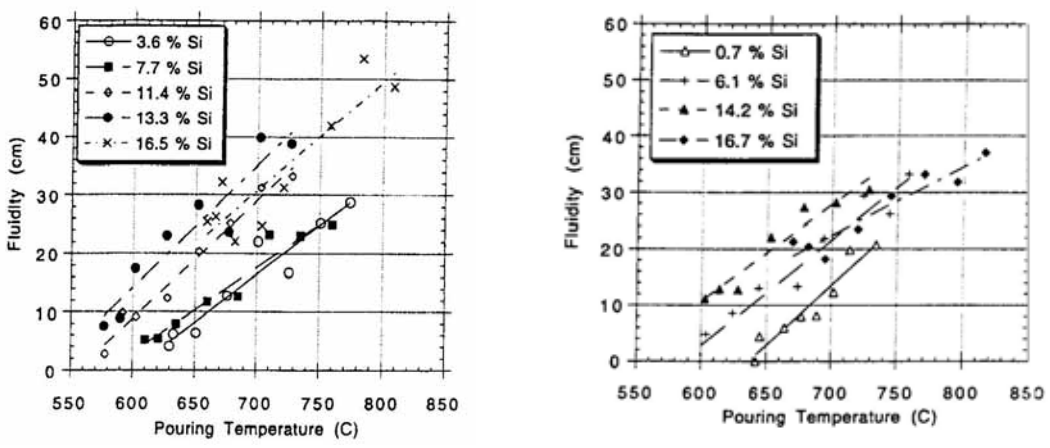
Figure 14 Effect of a) chromium and b) magnesium on liquidus temperature (top) and fluidity (bottom) of Al-4.5wt%Cu alloy [10].



a) b)

Figure 15 Effect of a) copper and b) silicon on liquidus temperature (top) and fluidity (bottom) of Al-4.5wt%Cu alloy [10].

The chemical composition of the alloys affects their solidification range, *i.e.* the interval between liquidus and solidus temperature. The solidification range plays an important role on castability because it influences casting properties and defects, *e.g.*, hot tearing. The solidification range strongly influences the mode of solidification, as shown by Flemings *et al.* [2, 9], and it has been shown that the mode of solidification significantly affects the fluidity of the melt [2, 10, 20]. Bastien *et al.* [34] showed that fluidity length is inversely proportional to the solidification interval of the alloy, *i.e.* "mushy" alloys which solidify with a large solidification range have lower fluidity than alloys which solidify with a short freezing range. However, it has recently been shown [35] that the fluidity of Al-Si alloys in High Pressure Die Casting (HPDC) process increases with decreasing solidus temperature (*i.e.* increasing solidification range) of the selected alloy. These two studies seem to indicate that the larger the solidification range of an alloy, the lower is its fluidity, with the exception being if the alloy is used in the HPDC process.



a) b)

Figure 16 Fluidity *versus* pouring temperature for a) different Al-Si alloys, namely Al-3.6wt%Si, Al-7.7wt%Si, Al-11.4wt%Si, Al-13.3wt%Si, Al-16.5wt%Si; and b) different Al-Si-3.5wt%Cu alloys (measured by a fluidity serpentine mould) [9].

2.5.2 Effect of superheat

Superheat, *i.e.* the difference between the casting temperature and the liquidus temperature, is also a key factor influencing fluidity. The fluidity increases with increasing superheat for a given alloy composition. Kolsgaard [36] reported that the fluidity length of Al-7wt%Si-0.6wt%Mg alloy reinforced with 10 to 30% SiC particles, measured with a spiral test in sand mould, increases linearly by increasing superheat. The increase in melt temperature by 1ºC, in the temperature interval 700-760ºC, increased the fluidity length by 1% [36]. Sahoo and Sivaramakrishnan [37] also measured the fluidity of an Al-8.3wt%Fe-0.8wt%V-0.9wt%Si alloy with a spiral test in sand mould. They reported an increase of 0.4% in the fluidity length when the melt temperature increased by 1ºC, in the interval 860-900ºC [37]. The effect of pouring temperature on the fluidity of Al-Si and Al-Si-3.5wt%Cu alloys was measured by Kim and Loper [9] using a fluidity test method (serpentine-shaped sand mould) and is shown in Figure 16. They studied five Al-Si alloys, namely Al-3.6wt%Si, Al-7.7wt%Si, Al-11.4wt%Si, Al-13.3wt%Si, Al-16.5wt%Si, and an Al-Si-3.5wt%Cu alloy with four different Si levels. A linear relationship between pouring temperature and fluidity was shown for all investigated alloys. Increasing the pouring temperature, and hence the melt superheat, delays the nucleation and growth of

fine grains at the tip of the flowing metal in the test channel, hence the fluidity length increases. For Al-Si hypereutectic alloys, it was found [11] that fluidity increases with increasing melt superheat up to about 100-150ºC, beyond which any further increase in superheat yielded no further gain in fluidity. This is probably due to increased turbulence in the flowing metal stream [11].

2.5.3 Effect of grain refinement

A considerable amount of experimental work has been done on the effect of grain refinement on fluidity of aluminium alloys, and the results are somewhat contradictory. Mollard *et al.* [21] showed a reduction in fluidity when 0.15 wt% Ti was added to an Al-4.5wt%Cu alloy, tested with a vacuum fluidity apparatus. Tiryakioglu *et al.* [8] found no effect of grain refinement on the fluidity of an A356 alloy tested in a sand spiral test, adding 0.04 wt% Ti as Al-5wt%Ti-1wt%B master alloy. Lang [22] found a significant increase in fluidity with boron additions in the range of 0.04-0.07wt% B to Al-Si alloys, tested with a bar die casting. Dahle *et al.* [38, 39] observed a more complex variation of fluidity with successive additions of Al-5wt%Ti-1wt%B in Al-7wt%Si-Mg and Al-11wt%Si-Mg alloys. Fluidity was reduced with grain refinement below 0.12wt% Ti, while it increased with additions above 0.12wt% Ti. The fluidity length decreased 5% with 0.01wt% Ti and up to 9% with a further addition of 0.12wt% Ti [39]. Al-Si alloys grain refined by boron showed the smallest grain size, the largest fraction solid at dendrite coherency and the best fluidity. The fluidity measurements by Dahle *et al.* [38, 39] were assessed using a vacuum fluidity test apparatus of about 7% relative reproducibility. For all alloys the fluidity was lower at the highest grain refiner content than in the unrefined alloy. Kwon and Lee [40] studied the effect of grain refinement on A356 alloy. The fluidity test apparatus consisted of a steel mould with eight thin channels and had 10% relative reproducibility. Whereas 0.03wt% Ti as Al-5wt%Ti-1wt%B grain refiner appreciably improved the fluidity at the lowest pouring temperature (700ºC), the addition of 0.2wt% Ti did not have any significant effect on the fluidity of the base alloy. Chai [41] investigated the effect of grain refinement on Al-4wt%Cu alloy with a vacuum fluidity apparatus and observed that the increase in grain refiner increased fluidity as well as coherency fraction solid.

The effect of grain refinement on the fluidity of Al foundry alloys is a complex matter which involves complex mechanisms [42-44]. The effect of grain refinement on fluidity depends on many factors: alloy composition, mode of solidification, type and amount of grain refiner, holding time and temperature in the furnace, *etc.* Among these factors, chemical composition, and hence solidification mode and morphology play a key role. Short freezing range alloys, such as Al-7wt%Si alloys, solidify with free equiaxed grains in the melt. They tend to run and feed well along the fluidity channel. Large freezing range alloys, such as Al-Mg alloys, solidify with mushy morphologies and dendrites which obstruct the flow. Grain refinement should, therefore, more likely have the greatest effect on solidification morphologies which solidify like Al-Mg alloys [44].

2.5.4 Effect of modification

The modification of Al-Si alloys is a common industrial practice. The addition of modifiers, *e.g.,* Sr and Na, to Al-Si alloys changes the eutectic structure from a lamellar to a fibrous morphology which improves the ductility of the alloys. The drawback of modification practice is that it has been reported to increase porosity [45]. Reported data [36, 46] show a slightly decreased fluidity with addition of modifiers. Kotte [47] found that both Sr and Na reduce fluidity to some extent, but the addition of Na causes a slightly more significant reduction in fluidity. Venkateswaran *et al.* [48] have studied the effect of different modifiers on the fluidity of eutectic Al-Si alloys. Fluidity decreased with the additions of Na, Na plus Sr, Ti, Na plus Ti, Na plus Sr plus Ti, while it increased with the additions of S, Sb, Sb plus Ti, S plus Ti [48]. Modification of Al-Si alloys reduced fluidity up to 10% [21]. Sheshradri *et al.* [27] found that the modification of Al-12wt%Si alloy reduced its fluidity between 5% and 7% in a sand mould and between 2% and 3% in a cast iron mould. Also Lang [22] found that Na decreases fluidity. Sahoo and Sivaramakrishnan [37] studied the effect of modification by Mg on the fluidity of Al-8.3wt%Fe-0.8wt%V-0.9wt%Si alloy. They found that the modified alloy had better fluidity than the unmodified alloy. High purity magnesium was added to the melt held at a temperature of 880ºC. The addition of 1wt% Mg gave 15% better fluidity than the unmodified alloy [37]. A reason for this effect may be that Mg forms phases which have high heat of fusion and hence delays the solidification of the alloy.

2.5.5 Effect of mould material, grain size, moisture content and binder

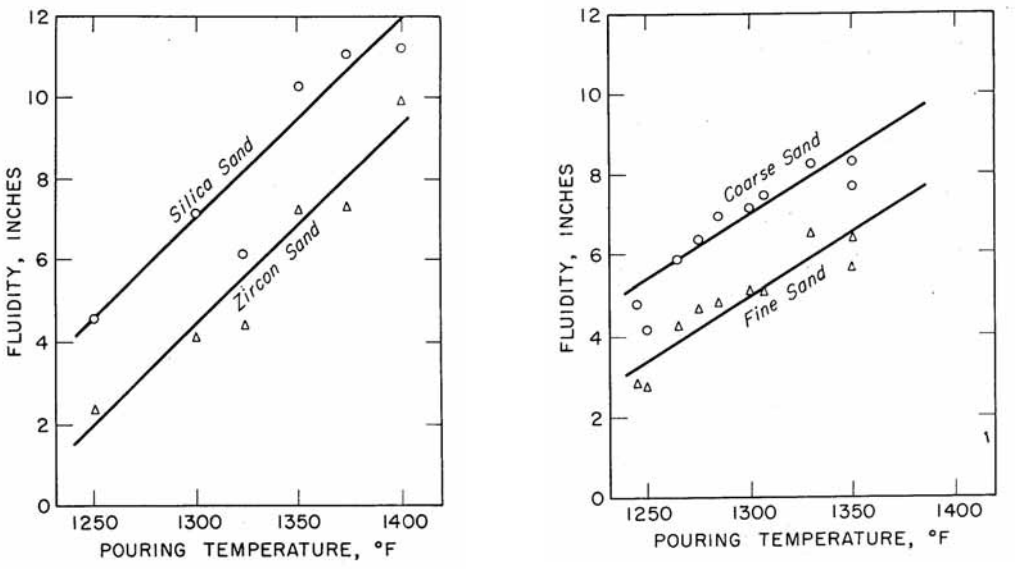
The effect of mould material has also been extensively studied [49-51]. Flemings *et al.* [49] studied the effect of mould materials (green-, core-, CO_2- and zircon sand) on the fluidity of an Al-4.5wt%Cu alloy. They found that the mould material significantly affects fluidity. For example, fluidity was 20 to 27% lower in core sand than in green sand; and 22 to 55% lower in zircon sand than in green sand. A comparison of the effect of silica sand and zircon sand moulds on fluidity is shown in Figure 17 a. Both sands were bentonite bonded, green and had a grain size of 110 AFS. The fluidity of castings in silica sand was higher than in zircon sand due to the greater thermal diffusivity of zircon sand [49].

Moreover, the effect of the grain size of the mould materials was investigated [49]. Two different grain sizes, namely a coarse (30 AFS) and a fine (140 AFS) silica sand (clay bonded and green) were studied on Al-4.5wt%Cu alloy [49]. The coarse sand mould gave better fluidity than the finer sand mould, as shown in Figure 17 b. Fluidity in fine sand was lower than that in coarse sand as the thermal diffusivity of fine sand is greater than for coarse sand [18]. In addition, a significant metal penetration is obtained in the coarse sand spirals and in the experiments by Flemings *et al.* [49] the penetration to 0.6mm on each face of the spiral was approximately 10% by weight. The added heat of fusion that needs to be extracted to solidify an extra 10% of metal may also account for the increase in fluidity observed [49].

The effect of moisture content on fluidity was also investigated [49, 52]. The fluidity tests were performed in baked sand mould and green sand mould (moisture content up to 3.5%) and it was not observed any significant difference on fluidity [49]. These results were confirmed by Arnold *et al.* [52]. They varied the moisture content up to 9% and found no significant variation on fluidity [52].

Also the binder used in the mould preparation may influence fluidity. It was found [49] that in various core sands (including those bonded with sodium silicate and phenol formaldehyde) the fluidity was less than in green clay bonded sand. Differences in moisture content alone cannot account for this since it was shown [49] that moisture content has no effect on fluidity in clay

bonded moulds. The fluidity in green sand moulds was greater than that in core sand moulds due to a lower heat transfer in green sand [49].



a) b)

Figure 17 Fluidity of Al-4.5wt%Cu alloy *versus* pouring temperature when poured in a) silica and zircon sand (both sands were bentonite bonded, green and 110 AFS); and b) coarse (30 AFS) and fine (140 AFS) silica sand, clay bonded, green [49].

2.5.6 Effect of mould coating

Mould coating is a useful practice to enhance mould life and improve ejection of the cast products. Mould coating also plays an important role in enhancing fluidity because it reduces the heat transfer coefficient (HTC) between the casting and the mould. In the experiments by Flemings *et al.* [49] two coatings, such as hexachloroethane and carbon black, were examined and the alloy poured was Al-4.5wt%Cu with 0.18wt% Ti added as a grain refiner. Hexachloroethane was sprayed from an ether solution to a thickness of approximately 0.1mm. Carbon black was applied with a smoking acetylene torch. Two plates were mounted on the opposite side of a runner: one plate coated and the other uncoated. Clearly, the fluidity of the alloy in the coated mould was higher than in the uncoated mould. Both coatings improved fluidity

to about the same extend and neither had any deleterious effect on surface quality of the cast plates. It was shown [49] that the reduction of the heat transfer coefficient by less than a factor of four resulted in 200% increase in fluidity. Doubling HTC caused 40% decrease in fluidity measured by a vacuum fluidity test method [49].

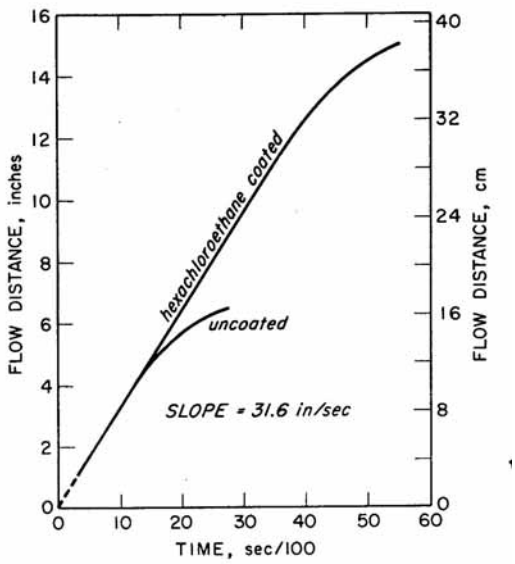


Figure 18 Flow distance *versus* time for hexachloroethane-coated and uncoated spiral for an Al-4.5wt%Cu alloy [49].

Figure 18 shows the fluidity distance *versus* time for a coated (hexachloroethane) and uncoated spiral. As shown in Figure 18, the initial flow velocity (given by the slope of the curves) was the same in the coated and uncoated spirals. Therefore, it was concluded that the hexachloroethane changes the heat transfer coefficient and does not have any influence on surface phenomena, such as surface tension, surface oxide films, *etc.* [49].

Niiyama *et al.* [50] showed that fluidity increases drastically when simultaneously casting in an argon atmosphere and using an organic mould surface coating. Argon showed no appreciable influence when used alone. Apart hexachloroethane and carbon black, also a zirconia coating enhanced fluidity [8, 49]. Syvertsen [53] has recently investigated the effect of mould

coating on fluidity of an A356 alloy. He tested four types of coatings and measured fluidity using a spiral test method in a laboratory scale Low Pressure Die Casting (LPDC) equipment. The equipment had a fairly good relative reproducibility. Coating A showed the highest fluidity length, good durability and there was no significant decrease in spiral length during casting of thirty spirals. Coating B exhibited a liner decrease of spiral length during the casting sequence due to a poor durability of the coating layer. Coating C and D also showed good fluidity lengths, though their durability was lower than coating A [53].

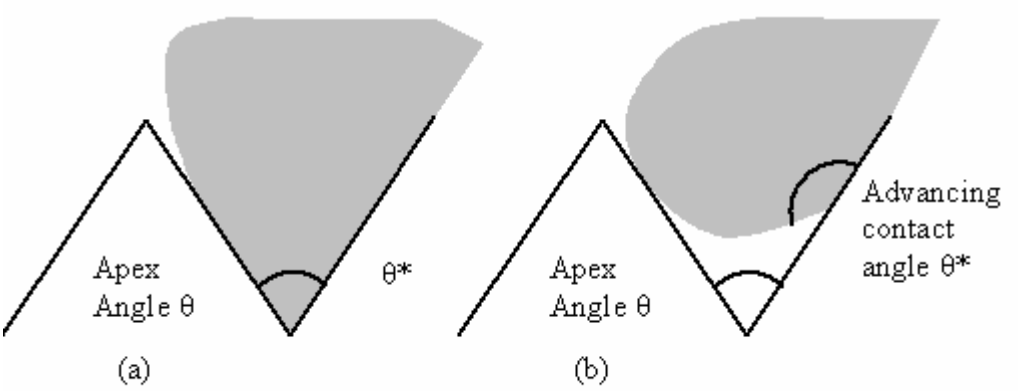


Figure 19 Schematic representation of the effect of coating and mould roughness on fluidity [54]: a) the advancing contact angle is less than the apex angle and the advancing liquid fills the surface roughness valley (poor fluidity); (b) the advancing contact angle is greater than the apex angle and a pocket of air is trapped between the advancing liquid and the rough surface (good fluidity).

Griffiths and Whitworth [54] examined the effect of die coating surface roughness and thermal conductivity on the fluidity of commercial purity aluminium. Their results showed that fluidity was slightly influenced by the die coating composition, hence thermal conductivity, and the coating surface roughness was found to have a more significant influence. The rougher the coating, the better the fluidity [54].

Figure 19 shows a schematic representation of the effect of coating and mould roughness on fluidity. If the advancing contact angle, θ* (*i.e.* the angle between the metal and mould), is less than the apex angle, θ, then the flowing metal fills the surface roughness valley. Otherwise, a pocket of air is trapped between the advancing liquid and the rough surface, an insulating layer forms which reduces the HTC and, therefore, increases fluidity [54].

2.5.7 Effect of pressure head, melt cleanliness and viscosity

Fluidity also depends on the pressure head which forces the liquid metal through the "pipe" that forms during solidification in a narrow channel. Thus, one may expect that the taller the sprue the greater the fluidity. However, Tiryakioglu *et al.* [8] found that small variations of metallostatic pressure, and hence pressure head, do not significantly affect fluidity. This is an interesting finding because it showed that increasing the sprue height would not be a good choice if fluidity must be increased. Unnecessarily long sprues and special pouring cups can be avoided, which will result in increase sand yield and reduced costs. In addition, small variations in the pressure are not expected to adversely affect fluidity [8].

Groteke [55] measured a significant effect of the melt cleanliness on fluidity. Up to 20% improvement in fluidity was observed when 319 and Almag alloys were cleaned by purging with inert and halogen gases. However, the use of inert gas alone was not as effective in removing inclusions from the melt as when halogen gases or mixtures were used [1]. Crepeau *et al.* [56] reported that fluidity of an A356 alloy significantly increased by removing suspended inclusions in the melt. At a pouring temperature of 704°C, fluidity improved by 40%. Recently, Kwon and Lee [40] have investigated the effect of oxide inclusions on the fluidity of Al-4.5wt%Cu-0.6wt%Mn and A356 alloys. They measured fluidity with a strip mould and oxide inclusions with an ultrasonic treatment. The results showed that pouring in air increased the amount of oxides in the melt and the fluidity of contaminated melt was decreased, particularly at a low pouring temperature. The fluidity in the contaminated melt decreased due to the reduction of the critical fraction solid to stop the flow, which depends on the amount of inclusions in the flow channel [40].

The viscosity of molten metals is quite low, for instance below 0.003 Pa s for Al-7wt%Si-Mg alloy [57]. Studies have shown that changes in viscosity with temperature and/or slight changes in composition are not great enough to account for the observed variation in fluidity. Viscosity does not affect the measurements when fluidity is tested with the commercially available fluidity tests and for most sand castings [49]. Also Bastien *et al.* [34] found that the fluidity of a molten metal, measured by a spiral test, does not depend on its viscosity. Therefore, the effects of viscosity as well as surface tension on fluidity in a casting mould can be neglected, as long as the metal maintains the liquid state during pouring [36, 57].

2.6 The importance of the Al-Si and Al-Mg-Si alloy systems

In this thesis work most of the experiments have been carried out using Al-Si (Al-7wt%Si and A356) and Al-Mg-Si (Mg content between 5 and 3 wt%; Si content between 2.5 and 0.5 wt%) alloys because these alloys are of major commercial importance. Both alloys have large applications in the automotive and aerospace industries. The extended use of hypoeutectic (Si content less than 12 wt%) Al-Si alloys, such as A356 and 319, for automotive components such as wheels, suspension and engine parts, has motivated studies for improving the mechanical performance of these alloys. The most used processes for casting hypoeutectic Al-Si alloys are sand casting and High Pressure Die Casting (HPDC). However, one major drawback of the cast components, if compared with forgings and extrusions, is the risk of porosity formation. Therefore, increased production stability and controlling defect formation are major challenges for the industry in order to realize cost efficient and competitive castings.

The Al-Si alloys owe their popularity to their good castability. Silicon increases the latent heat of the alloy and hence the solidification time. Silicon also reduces the shrinkage during solidification because it expands going from liquid to solid state [20]. Moreover, Al-Si alloys (Si content in the range 7-12 wt%) are not susceptible to hot cracking because of their short solidification range and the large amount of eutectic. The drawback with adding silicon is that it forms a brittle solid phase, which reduces the ductility of the alloy.

The Al-Mg-Si alloys are of great interest because they provide high strength without heat treatments. Magnesium increases the mechanical strength of the alloys through the precipitation hardening. Moreover, the addition of magnesium to the alloys, improves their ductility and corrosion resistance. Copper, iron, manganese, titanium, sodium and strontium are other important elements in the Al-Si and Al-Mg-Si alloys. Copper is added as well as magnesium to increase the mechanical strength of the alloy. Iron is usually considered an impurity, but for alloys used for HPDC, a certain iron content (0.9-1.15 wt% [58]) is required to prevent die soldering. Manganese is used to combine with aluminium, iron and silicon into phases that are less detrimental to mechanical properties than ternary Al-Si-Fe phases. Titanium acts as a dendritic grain refiner and, thus, enhances the castability and mechanical properties. Sodium and strontium are added to refine the morphology of the Al-Si eutectic, and thus increase ductility.

3 OBJECTIVES AND SURVEY OF THE ARTICLES

The objective of Article 1 was to present a new method for gravity casting of fluidity spirals in sand moulds. Measuring fluidity is not a straightforward task because the fluidity of an alloy is not a physical material property, but a complex technological property. Therefore, new methods with high repeatability, which can provide reliable data, are needed. The fundamental characteristic of the developed equipment was a constant pouring temperature, which allowed a constant melt superheat and, because the molten metal was poured in the spiral sand mould from a constant height, the equipment also allowed a constant initial pressure head and pouring velocity. The investigation also aimed at studying the effect of casting temperature on fluidity of an A356 alloy and it was shown that fluidity linearly increases with increasing casting temperature.

The objective of Article 2 was to study the influence of grain refinement and dissolved hydrogen on the fluidity of an A356 alloy. The addition of grain refiner is a common practice in foundries. However, inconsistent results on the effect of grain refinement on fluidity have been reported in the literature. The effect of dissolved hydrogen on fluidity of Al-Si alloys has not yet been reported in the literature. Therefore, this investigation aimed at clarifying the

effect of grain refinement and exploring the effect of hydrogen on the fluidity of Al-Si alloys. The fluidity was measured by the newly developed apparatus. It was found that the additions of Al-5wt%Ti-1wt%B grain refiner reduced the grain size throughout the spiral somewhat, particularly at the tip, but no significant influence on fluidity was observed. The hydrogen additions in the melt had no effects on fluidity, but, as expected, resulted in a significant increase in porosity.

The objective of Article 3 was to investigate the role of casting temperature and four alloying elements on fluidity of Al-7wt%Si alloys. The alloying elements investigated were Mg, Ti, Fe and Sr. The fluidity of the alloys was measured using a commercial fluidity mould. The Design Of Experiments (DOE) and Taguchi techniques were used to choose a limited set of experiments and to analyse the results. Each of the four alloying elements and the casting temperature was taken as independent variable with two levels. The main effect of each of the independent variables on the fluidity was quantified and Analysis Of Variance (ANOVA) was performed on the experiment matrices to validate the results and ensure their reliability. The results showed that casting temperature had the most pronounced influence on fluidity of molten metals. Among the alloying elements investigated, only Mg showed a significant detrimental effect on fluidity.

The objective of Article 4 was to study the role of oxide inclusions from recycled materials on fluidity of Al-7wt%Si alloys. Three alloys were investigated, namely a standard A356, A356 with 20% scrap addition and A356 with 50% scrap addition. The scrap additions consisted of contaminated alloy turning chips. Fluidity measurements were performed by using the experimental fluidity test and PoDFA (Porous Disc Filtration Apparatus) was used to quantify the oxide content. The results showed that recycled material increased the oxide content of the molten metal which significantly decreased its fluidity. However, for a same level of oxides, the percentage of recycled material did not influence fluidity.

The objective of Article 5 was to assess the fluidity of casting alloys by two fluidity test methods. The literature has shown that many fluidity test methods have been developed and used. The question that the present investigation addressed was whether fluidity results are affected by the type of fluidity test.

The work compared two fluidity tests which were used to evaluate the fluidity of three Al-Mg-Si alloys, namely Al-5wt%Mg-2.5wt%Si, Al-5wt%Mg-1.5wt%Si, and Al-3wt%Mg-0.5wt%Si. The fluidity of the alloys was measured using both a commercial and an experimental fluidity test methods. This investigation showed that both fluidity test methods are good means of assessing fluidity and give consistent results.

The objective of Article 6 was to perform numerical simulations of fluidity tests. MAGMAsoft commercial software package was used and the simulation results were compared with the experimental results of fluidity tests in spiral-shaped sand moulds. The simulation results were consistent with the experiments, and hence this study provided a basis for a more extensive use of simulations as a means of predicting fluidity and optimizing castability for aluminium alloy castings. The simulation results showed that an increase of the heat transfer coefficient and coherency temperature causes a decrease of the fluidity length for an A356 alloy. In addition, the fluidity measurements with the spiral test were consistent with those obtained with a vacuum fluidity test method.

4 CONCLUSIONS

The following conclusions can be drawn from this doctoral thesis work:

1. Chemistry of aluminium alloy plays an important role for fluidity. The Si content has a major importance. However, small variations in minor alloying elements do not significantly affect fluidity.

2. Casting temperature, and hence melt superheat, has a large influence on fluidity. At high melt superheats the role of alloy chemistry and mould coating is reduced.

3. Grain refiner additions to a previously refined Al-Si alloy do not significantly affect fluidity.

4. Dissolved hydrogen does not affect fluidity. Therefore, the practice of fluxing the molten metal does not change its fluidity. However, as expected, high hydrogen content increases porosity.

5. Oxide content reduces the fluidity of the alloys.

6. The results from different fluidity test methods may be quantitatively different but give a similar trend. Therefore, cast houses and foundries can measure fluidity with different test methods and still obtain consistent results.

7. Mould coating increases fluidity at all tested melt superheats. The conductivity of coating materials and their thickness as well as the mould roughness will also affect fluidity.

8. Commercial casting simulation software can be a useful tool for predicting fluidity.

5 CONCLUDING REMARKS AND FURTHER CHALLENGES

The results obtained in this doctoral thesis will have an industrial impact since the work has improved our understanding on several industrially relevant topics.

The practice of adding grain refiners, such as Al-5wt%Ti-1wt%B master alloy to a commercial Al-Si foundry alloy that already contains some grain refiner, *e.g.*, A356, does not affect the fluidity of the melt.

Mould coating significantly improves fluidity. It also improves indirectly the mechanical properties of the cast products because mould coating significantly increases fluidity and, hence, lower casting temperature can be used. In addition, the lowering of casting temperature, maintaining the same level of fluidity, gives benefits to mould life and hence has economical benefits.

Fluxing or degassing is a useful practice to decrease dissolved hydrogen and, hence, porosity formation in castings. However, if only the fluidity of the melt is a concern, there are no significant effects of dissolved hydrogen on fluidity.

Recycling of aluminium foundry alloys is also a useful and economical industrial procedure. It is recommended to maintain a low level of oxide during recycling procedures, since the oxide content has a significant deleterious effect on fluidity.

Numerical modeling can be a useful tool to predict solidification process, fluid flow and, thus, fluidity. There is a need for reliable data on heat transfer coefficient values at the casting interfaces. Also knowledge of the boundary conditions is important. The criteria for flow stoppage need further investigations and numerical modeling should also account for the effect of oxide content and coating which have shown to have a significant effect on fluidity.

The development of a standard fluidity test method which can be used both in research laboratory and foundry is highly recommended in order to directly compare fluidity measurements from different sources.

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PART 2

ARTICLES

ARTICLE 1

AN IMPROVED METHOD FOR FLUIDITY MEASUREMENT BY GRAVITY CASTING OF SPIRALS IN SAND MOULDS

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International Journal of Cast Metals Research, vol.18, 59-62, 2005

AN IMPROVED METHOD FOR FLUIDITY MEASUREMENT BY GRAVITY CASTING OF SPIRALS IN SAND MOULDS

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ABSTRACT

This study describes a new equipment for gravity casting of fluidity spirals in a sand mould. The fundamental characteristic of the equipment is a constant pouring temperature, which gives a constant melt superheat and, since the molten metal is poured into the spiral sand mould from the same height, the equipment gives a constant initial pressure head and pouring velocity. By comparing the data from the earlier version of the equipment, an improvement in the reproducibility has been shown. The effect of melt superheat on fluidity has been measured by the new improved equipment and has been confirmed to increase linearly with increasing melt superheat.

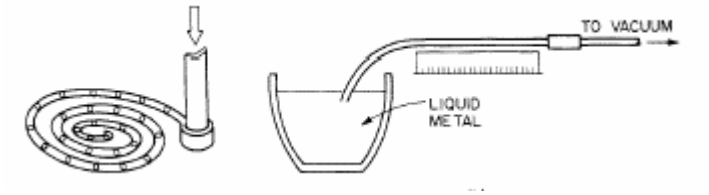
Keywords: Fluidity, Spirals, Casting

1. INTRODUCTION

Fluidity of molten metals, in the foundry environment, is defined as the length the metal flows before it is stopped by solidification [1]. Since fluidity limits the geometry of a casting that can be successfully filled [1], the study of fluidity is important for, particularly, the aerospace and automotive industries in order to realise thinner and lighter products. Therefore, in recent years, many foundries and metal suppliers have invested time and money in the study of the fluidity of their foundry alloys. There are many standard tests available for measuring fluidity. The two most common fluidity tests are the vacuum fluidity and the

spiral tests. Figure 1 shows a schematic representation of the two tests. In the vacuum fluidity test, the melt is sucked into a glass tube under a known reduced pressure. The length of flow is measured and used to evaluate the fluidity [2]. In the fluidity spiral test, the melt is poured into a spiral-shaped channel with a small cross-sectional area.

The fluidity of metals is affected by many parameters [3] and reliable fluidity data for aluminum casting alloys are not presently available, even though such data are very important in the optimisation of the casting properties of the alloys [4]. The need for an improved spiral fluidity test method has been mentioned by several authors [4-7]. It is important to reduce the influence of variables that are difficult to control in the experiment so as to improve the reproducibility of the measured fluidity. Therefore, the aim of this study is to present a new apparatus and method for a reliable spiral fluidity test and quantify its reproducibility.



a) b)

Fig. 1 Schematic representation of two fluidity tests: a) spiral test; b) vacuum test [1].

2. EXPERIMENTAL

2.1 Original apparatus and method

The first version of the equipment, which may be considered to represent a standard setup for spiral tests, consisted of a pouring basin, a rectangular tapered sprue in the cope, and a double spiral cavity in the drag. The spirals were moulded in quartz sand with an average grain size of 0.15 mm. The moulds were prepared manually with a phenolic binder (Alphaset). Figure 2 shows the pouring basin and the sand mould. The two Archimedian spirals, each with a cross section of 4 x 10 mm^2, consisted of 3.5 turns, giving a maximum running length of 1.2 m each. Both spiral ends were fully vented.

The molten metal was poured manually from the furnace to the pouring basin with a ladle. The temperature of the metal was measured by the operator with a calibrated thermocouple (K-type, ±1ºC accuracy) in the ladle, before pouring into the basin. The aim was to pour the molten metal into the basin as fast as possible and to fill up the basin completely, in order to have the same initial metallostatic pressure head on the flowing metal.

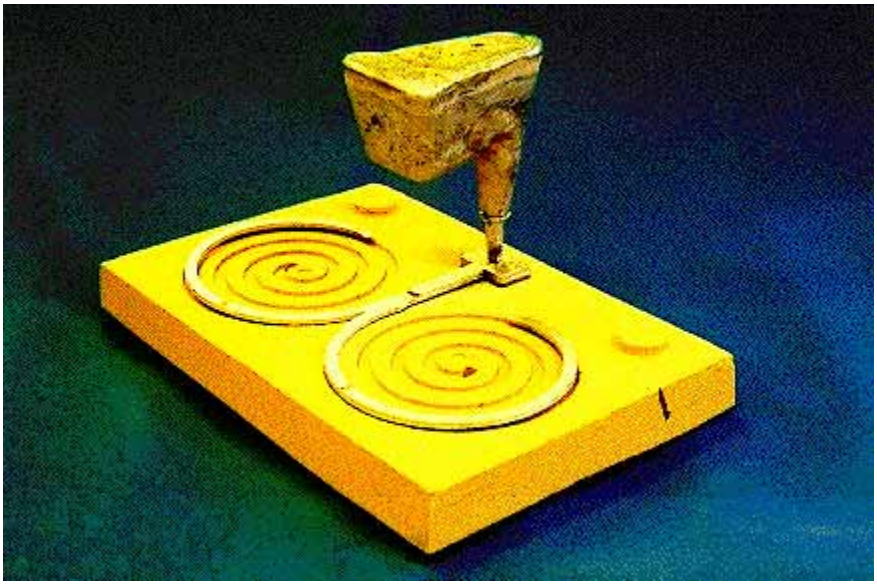


Fig. 2 Pouring basin and double-spiral mould of the original version of spiral fluidity test equipment.

2.2 New apparatus and method

The improved version of the equipment consisted of a gating system, a stopper rod connected to a pneumatic cylinder and a quartz sand mould with an average grain size of 0.15 mm. Figure 3 shows the main components of the new version of the equipment. The gating system consisted of a pouring cup (90 mm internal diameter and 133 mm height) and a short circular tapered sprue. Figure 4 shows both side and top views of the equipment. The moulds were made with a core shooter (Cold Box) and they had a cope (flat sand mould) and a drag (single Archimedian spiral shape). Those two parts were tightly fixed together with four metal clamps. The cope had a vent at the end of the spiral cavity (diameter 18 mm). The Archimedian spiral had a cross section of 4 x 10 mm^2, consisted

of 3.5 turns and a maximum running length of 1.2 m. A calibrated thermocouple (K-type, ±1ºC accuracy) measured the temperature at a specific location (35 mm from the gating system) inside the insulated pouring cup and was connected to a computer data acquisition and control system.

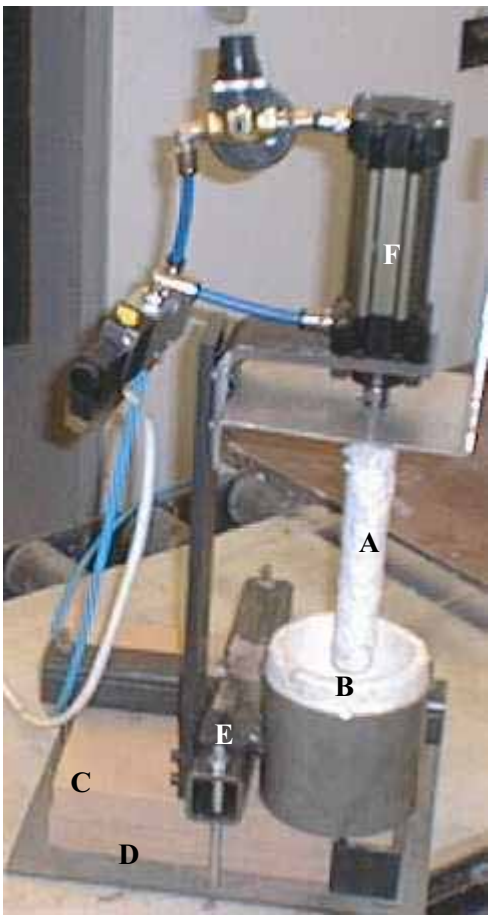


Fig. 3 Main components of the new equipment: stopper rod (A); pouring cup (B); cope (C); drag (D); metallic clamps (E); pneumatic cylinder (F).

A moving stopper rod closed the bottom of the pouring cup and automatically opened the gate to the spiral when the molten metal temperature reached a preset value. A pneumatic cylinder, controlled by the computer system, actuated linearly to effect the opening and closing of the stopper rod. The stopper rod

was a graphite cylinder (150 mm length), which was covered with an insulating tube in order to prevent heat loss from the metal. The pouring cup, the insulating tube cover and the sand mould were replaced for each spiral. The sand moulds and the pouring crucible were not preheated and were kept at room temperature.

The software, used for controlling the experiments and collecting the temperature data, was written for the present work. The software recorded the temperature of the metal in the pouring cup. Using a ladle, the operator filled the pouring cup to the height h of 120 mm (the same height was used for each test).

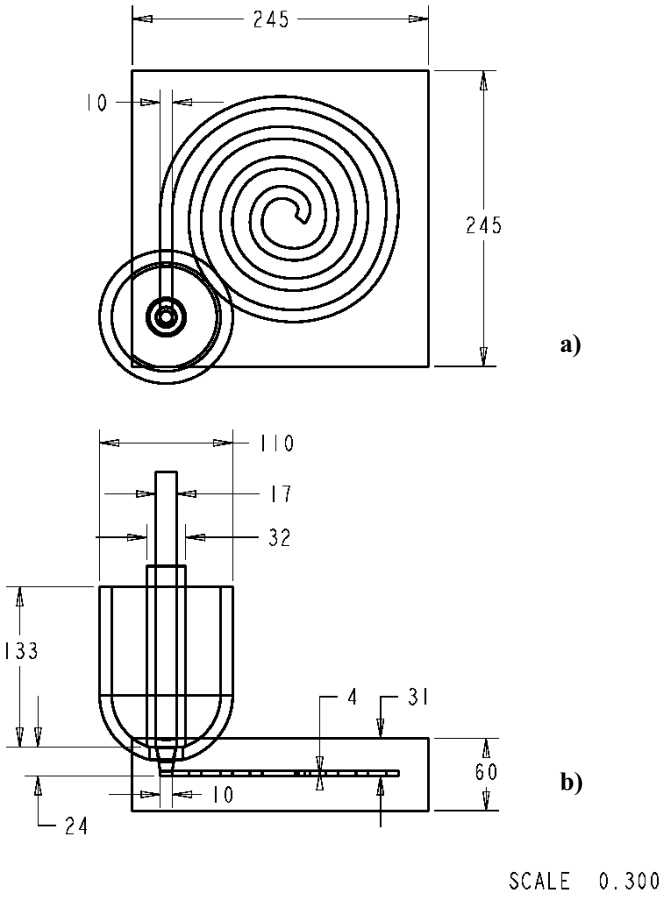


Fig. 4 Drawing of new equipment showing a) plan view of pouring cup and b) side section through stopper rod and sand mould (all dimensions are in mm).

The computer immediately started recording the temperature and when this fell to the preset value, the pneumatic cylinder lifted the stopper rod and the metal entered the mould to fill the spiral. Therefore, in contrast with the previous equipment, the new equipment gave a constant melt superheat (defined by the preset opening temperature for the stopper rod), and a constant initial metallostatic pressure given by $P = \rho g h$, where g is the acceleration due to gravity, h is the constant height of the metal inside the pouring cup and ρ is the density of the alloy. Moreover, in contrast with the previous equipment, the new equipment allowed the mould cavity to be filled slowly and smoothly with a constant initial velocity, given by the height (24 mm) of the sprue (Fig.4).

2.3 Casting experiments and materials

Two Al-7Si alloys were used in the experimental work, one for the original equipment and the other for the new version. The chemical compositions of these alloys are given in Table 1. The reproducibility of the original and improved versions of the equipment was assessed through series of N repeated measurements. The reproducibility of the earlier version of the apparatus was studied by casting twelve double spirals at a temperature of 720ºC. The reproducibility of the new version of the apparatus was studied by casting twenty spirals at a constant temperature of 715ºC (constant melt superheat of 102ºC). Furthermore, the effect of the melt superheat on the fluidity length was evaluated with the improved equipment, by casting ten spirals for each temperature: 700, 715 and 730ºC.

Table 1 Chemical composition (wt-%) of alloys used with original equipment (Alloy A) and new version (Alloy B).

Alloy	Si	Mg	Fe	Sr	Ti	Ga	Cu	Mn	Zn	Ca
A	7.2	0.35	0.11	0.001	0.12	0.016	0.01	0.01	0.01	0.001
B	6.6	0.38	0.198	0.021	0.059	0.01	0.004	0.004	0.005	0.003

2.4 Statistics

For the spiral measurements the following parameters and equations were used [8]:

(i) Mean value of a set of n measurements x_i: $\bar{x} = \frac{\sum_i^n x_i}{n}$

(ii) Standard deviation of sample: $s=\left(\frac{1}{n}\sum_{i}^{n}(x_i-\overline{x})^2\right)^{1/2}$

(iii) Standard deviation of the distribution of single measurements (estimate of reproducibility):

$$\sigma=\left(\frac{n}{n-1}\right)^{1/2}s$$

(iv) Standard deviation of the distribution of the means of measurements (estimate of uncertainty in the mean value):

$$\sigma_m=\left(\frac{1}{n-1}\right)^{1/2}s$$

(v) Relative reproducibility: $\left(\frac{\sigma}{\overline{x}}\right)\cdot 100$

(vi) Relative uncertainty in the mean value: $\left(\frac{\sigma_m}{\overline{x}}\right)\cdot 100$

3. RESULTS and DISCUSSION

3.1 Reproducibility of the original and new versions of the equipment

Table 2 shows the average length of the fluidity measurements and the calculated standard deviation for both the original and new equipment. The average length for twenty-four spirals (twelve double spirals from the previous equipment) and the standard deviation have indicated that the previous equipment has a reproducibility of 9%. The average length of the twenty spirals (new equipment) and the standard deviation have indicated that the new equipment has a reproducibility of 5.5%. Thus, it has been shown that compared with the original equipment, the reproducibility of the new version has increased by a factor of almost two, as a result of improved control of the metal velocity and superheat. The pouring of the molten metal into the mould

was automatic and was not dependent on the operator's skill. The pouring temperature was automatically controlled by the thermocouple connected to the data acquisition and control system.

Table 2 Average length of the fluidity measurements for twenty-four spirals (twelve double spirals for the original equipment) and twenty spirals (new equipment), and standard deviation.

Total number of spirals	**Average length,** $\bar{x}$ **[mm]**	**Standard Deviation,** σ **[mm]**
24	582	53
20	540	30

3.2 Effect of the melt superheat on the fluidity

The improved method of spiral test was used to evaluate the effect of melt superheat on the fluidity of an Al-7Si alloy (alloy B in Table 1). It was tested at three different temperatures (700, 715 and 730ºC) by casting ten spirals for each temperature. The averages of the spiral lengths and the standard deviations in the mean value (σ_m) were calculated for each temperature (see Table 3). The average length of the spirals for the three different temperatures increased linearly as shown in Figure 5. The best fit relation was found to be:

$$L_f = 5.6T - 3480$$

where L_f is the fluidity length in mm and T is the casting temperature in ºC. Consequently, increasing the pouring temperature by 1ºC, in the interval 700-730ºC, has given an increase in the fluidity length approximately equal to 1%. This result is close to those of previous authors [9-11].

Table 3 Results of the temperature influence on fluidity.

Temperature [ºC]	**Number of spirals**	**Average length,** $\bar{x}$ **[mm]**	**Standard deviation in mean value,** σ_m **[mm]**
700	10	460	10
715	20	542	7
730	10	630	10

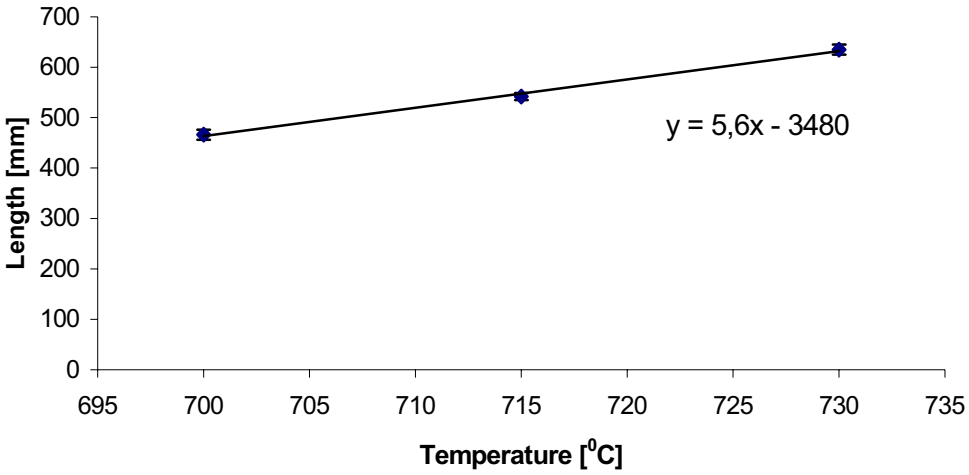


Fig. 5 Average length of spirals versus pouring temperature (equation of best fit line is shown).

4. CONCLUSIONS

1. The present work has described a new equipment for gravity casting of fluidity spirals in sand moulds, in which the reproducibility is improved by nearly a factor of two.
2. The fluidity length of the spirals has been found to increase linearly by approximately 1% when increasing superheat by 1ºC in the interval 700-730ºC.

ACKNOWLEDGEMENTS

Thanks are due to Mr. Alf Sandberg for help with casting, Mr. Inge Sandaunet for the data acquisition and control system development and Dr. Øyvind Nielsen for the scientific support. The present work was funded by the project NorLight Shaped Castings of Light Metals, with the following partners: Alcoa Automotive Castings, Scandinavian Casting Center ANS; Elkem Aluminium ANS; Fundo Wheels AS; Hydro Aluminium Metal Products; Hydro Magnesium; the Netherlands Institute for Metals Research; Norwegian University of Science and Technology; and SINTEF. The authors thank the industrial partners and the Norwegian Research Council for financial support.

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ARTICLE 2

EFFECT OF GRAIN REFINEMENT AND DISSOLVED HYDROGEN ON THE FLUIDITY OF A356 ALLOY

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International Journal of Cast Metals Research, vol. 18, 181-186, 2005

EFFECT OF GRAIN REFINEMENT AND DISSOLVED HYDROGEN ON THE FLUIDITY OF A356 ALLOY

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ABSTRACT

The influence of grain refinement and dissolved hydrogen on the fluidity of A356 alloy has been investigated. A spiral casting test method, recently developed, has been used to measure fluidity in a reproducible way. The grain refinement reduces the grain size of the spirals, particularly at the tip, but no significant influence on the fluidity has been revealed. The hydrogen additions in the melt have not affected the fluidity but have, of course, significantly increased the porosity.

Keywords: Fluidity, Grain refinement, Hydrogen effect, Porosity, Grain size, Inclusions

1. INTRODUCTION

Fluidity is an important feature of aluminium alloys because it restricts their applicability for casting purposes. The knowledge of the parameters influencing fluidity is important in order to achieve good quality and thin walled castings. Fluidity has been investigated by many researchers and is affected by many factors. Portevin and Bastien [1] have shown that fluidity varies inversely with solidification range (liquidus minus solidus temperatures) in most alloy systems. The larger is the solidification range, the lower the fluidity of the alloy system [1]. The maximum fluidity of a binary system is obtained at the pure component and eutectic compositions [2]. The Al-Si system, however, shows maximum fluidity at a hypereutectic composition [3] owing to the high heat of fusion of silicon and a skewed coupled zone in the Al-Si system [4, 5]. Melt superheat (the difference between the melt temperature and the liquidus temperature) is also a key factor influencing fluidity. Many authors [6-8] have

reported that, for a given alloy composition, the fluidity increases linearly with increasing melt temperature. Kolsgaard [8] has reported that an increase of 1ºC in the melt temperature gives an increase of 1% in the fluidity length of Al-7wt%Si-0.6wt%Mg alloy reinforced with 10-30% SiC particles. This finding has been confirmed by recent work [9] on A356 alloy.

Controversial results on the effect of grain refinement on fluidity have been reported in the literature. Mollard *et al.* [10] showed a reduction in fluidity when 0.15 wt% Ti was added to an Al-4.5wt%Cu alloy, tested with a vacuum fluidity apparatus. Tiryakioglu *et al.* [11] found no effect on grain refinement in A356 and 319 alloys, adding 0.04 wt% Ti as AlTi5B1 master alloy tested in a sand moulded spiral. Lang [12] found a significant increase in fluidity with boron additions in the range of 0.04-0.07 wt% B to Al-Si alloys tested with a bar die casting. Dahle *et al.* [13] observed a more complex variation in fluidity with successive additions of AlTi5B1 in Al-7wt%Si-Mg and Al-11wt%Si-Mg alloys tested with a sand moulded spiral. The reproducibility of the test apparatus was about 10% and the fluidity was reduced with grain refinement below 0.12 wt% Ti, while it increased with additions above 0.12 wt% Ti. The fluidity length decreased 5% with 0.01 wt% Ti and increased up to 9% with a further addition of 0.12 wt% Ti [13]. Moreover, Dahle *et al.* [14] studied five levels (0, 0.01, 0.03, 0.05, and 0.12wt%) of AlTi5B1 grain refiner additions to Al-1wt%Mg, Al-5wt%Mg, Al-2wt%Cu, and Al-4wt%Cu alloys. The fluidity measurements were assessed using a vacuum fluidity test apparatus of about 7% reproducibility. For all alloys the fluidity was lower at the highest grain refiner content than in the unrefined alloy. Kwon *et al.* [15] studied the effect of grain refinement on A356 alloy. The fluidity test apparatus consisted of a steel mould with eight thin channels and had 10% reproducibility. Whereas 0.03 wt% Ti as AlTi5B1 grain refiner appreciably improved the fluidity at the lowest pouring temperature (700ºC), the addition of 0.2 wt% Ti did not have appreciable effect on the fluidity of the base alloy. Kwon *et al.* [15] also reported that oxide inclusions in the melt decreased the fluidity, especially at a low pouring temperature.

The effect of dissolved hydrogen on fluidity in Al-Si and Al-Si-Cu alloys has not yet been published.

A new version of the spiral test method has recently been developed and shown to give results with improved reproducibility [9]. The purpose of the present study is to use this improved test method to investigate the influence of grain refinement and hydrogen additions on the fluidity of one of the most commercially important Al-Si alloys, A356 alloy.

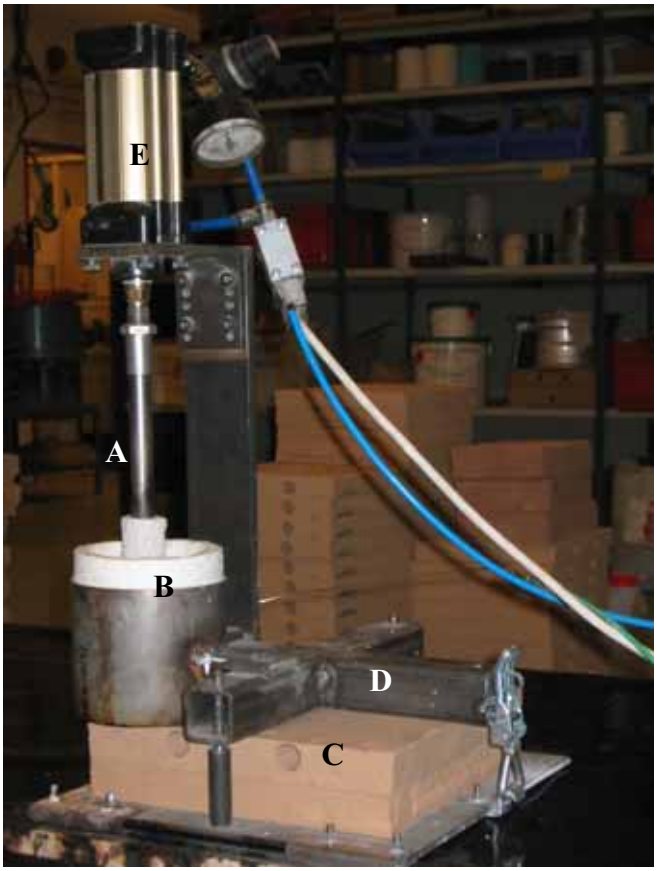


Fig.1 Fluidity test apparatus. The main parts are: A- stopper rod, B- pouring cup, C- sand mould, D- metallic clamps, E- pneumatic cylinder.

2. EXPERIMENTAL

2.1 Fluidity test apparatus and alloy

The main parts of the fluidity test apparatus are shown in Fig. 1. It consisted of a pouring cup, a short circular tapered sprue, a stopper rod connected to a pneumatic cylinder, and a silica sand mould made with a core shooter using the cold box process (phenolic urethane resin cured with amine vapour).

The movable stopper rod initially closed the bottom of the pouring cup and automatically opened the gate when the molten metal temperature reached a preset value, measured by a thermocouple in a fixed position in the pouring cup. The pneumatic valve, controlled by a PC, regulated the movement of the stopper rod. When the gate opened, the metal filled the spiral sand mould. In this way the equipment provided an accurate melt superheat. A more detailed description of the test apparatus and its reproducibility was previously presented [9]. The alloy used in the experiments was A356 with the chemical composition shown in Table 1. A batch of 50 kg of the alloy was melted at 760ºC in a resistance furnace. The spiral length was taken as the fluidity value.

Table 1 Chemical composition (wt-%) of A356 alloy.

Al	Si	Mg	Fe	Sr	Ti	Ga	Cu	Mn	Zn	Ca
Bal.	6.6	0.38	0.198	0.021	0.059	0.01	0.004	0.004	0.005	0.003

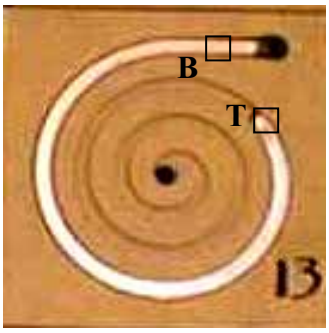
2.2 Addition of grain refiner

In order to study the effect of grain refinement on fluidity, three different amounts of an AlTi5B1 rod type grain refiner were added to the molten A356 alloy. The chemical composition of the grain refiner is given in Table 2. Grain refiner was added to increase the Ti content by 0.01, 0.02 and 0.04 wt%. Because the alloy contained Ti as received, the total amount of Ti became 0.07, 0.08 and 0.1 wt%, respectively. Ten spirals each were cast at 715ºC with 0.01, 0.02 and 0.04 wt% Ti addition. Four spirals for the unrefined alloy and four spirals for each addition of grain refiner were studied. For each investigated spiral, two samples were subjected to metallographic study: one from the base (close to the pouring cup) and one from the tip of the spiral.

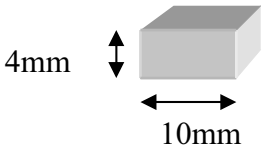
Table 2 Chemical composition (wt-%) of grain refiner AlTi5B1.

Alloy	Si	Fe	Ti	B	Va
AlTi5B1	0.07	0.11	4.8	1.0	0.06

Figure 2 shows an as-cast spiral in a sand mould, the two locations where the samples were taken, and the cross-section (4 x 10 mm^2) of each investigated spiral. The samples were polished down to 1 μm and anodized in a solution of HBF_4. A series of images were taken using optical microscopy without (Fig. 3) and with (Fig. 4) polarized light. The grain sizes were measured using the linear intercept method [16].



a)



b)

Fig. 2 a) As-cast spiral in sand mould and two locations where the samples were taken for each investigated spiral (B- base of the spiral, close to the pouring basin; T- tip of the spiral) and b) Cross-section of the spiral.

2.3 Hydrogen addition

In order to study the effect of hydrogen on fluidity, three levels of hydrogen were chosen. The first level was chosen as the initial hydrogen level in the melted alloy, the second was measured after purging pure argon (99.99 wt% Ar) with a rotating impeller for 45 minutes. During purging the melt temperature was kept between 700 and 720ºC, which is known to give a high efficiency during degassing [17]. The third hydrogen level was measured after plunging pieces of wood beneath the surface of the molten metal. The three hydrogen levels obtained were 0.13, 0.15 and 0.43 ml/100g for the argon purged (P), as-received (A) and hydrogen up-gassed (H) melts, respectively. Spirals were cast under the same atmospheric condition (same relative air

humidity and room temperature). The hydrogen concentration in the melt was measured with an Alscan^{TM} apparatus. For each hydrogen level, ten spirals were cast at 700ºC. Optical microscopy and porosity studies were made on the selected samples. The tendency to porosity formation was evaluated qualitatively with a reduced pressure test (RPT) [18, 19] during the cast trials, and quantitatively from the density measurements. The selected samples were weighed in air and water, and the density was calculated according to Archimedes' principle. The percentage porosity was defined by the relationship:

$$\%Porosity = \frac{(\rho_{\max} - \rho)}{\rho_{\max}} \cdot 100 \qquad (1)$$

where ρ_{max} was the density of the fully dense material (alloy density) and ρ was the experimentally observed density given by:

$$\rho = \frac{W_a}{|W_w|} \cdot \rho_o \qquad (2)$$

where W_a is the weight in air, W_w is the weight in water, and ρ_0 is the density of water at room temperature.

PoDFA tests [20] were performed to correlate the level of inclusions to fluidity measurements. For the PoDFA tests, two samples were taken after argon purging and hydrogen addition, respectively. Backscattered electron micrographs were taken as well as microprobe analyses of the selected area of the samples, taken from the filter cake just above the filter.

Table 3 Average length of fluidity measurements and standard error in mean values for ten spirals cast without and with grain refiner additions.

Grain refiner additions, wt-% Ti	Average length $\pm \sigma_m$, mm
0	540 ± 10
0.01	550 ± 10
0.02	560 ± 10
0.04	550 ± 20

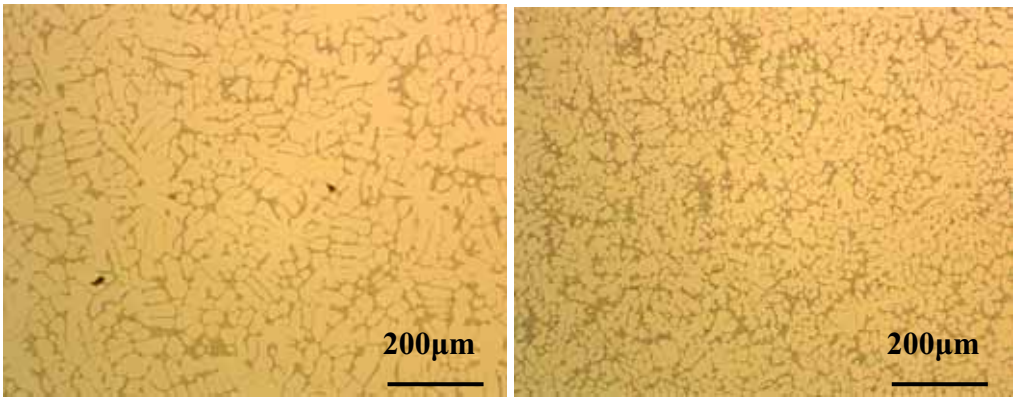
Table 4 Grain size measurement averages from base and tip of each spiral, and their average length $\pm \sigma_m$ (standard error in mean values).

Grain refiner additions, wt-% Ti	Base grain size average, μm	Tip grain size average, μm	Average length $\pm \sigma_m$, μm
0	358	247	300 ± 30
0.01	302	238	270 ± 30
0.02	244	192	215 ± 30
0.04	204	160	180 ± 25

3. RESULTS

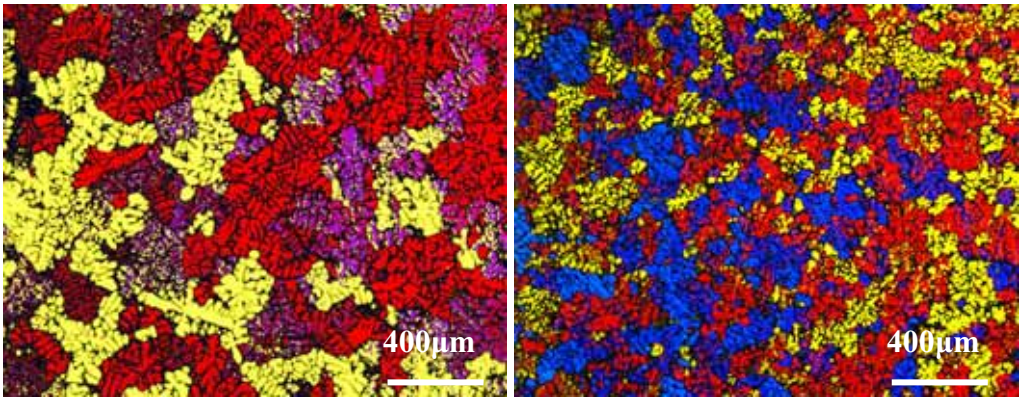
Table 3 shows the average length of the fluidity measurements and standard error in the mean values for ten spirals cast without and with grain refiner additions. Table 4 shows the grain size measurements from the base and tip of each investigated spiral. The average of the grain size measurements for each investigated spiral and the standard error in the mean values were also calculated. Figures 3 and 4 are optical and anodized micrographs, respectively, of the same spiral sample taken from the base (Figs. 3a and 4a) and tip (Figs. 3b and 4b) of the spiral.

Table 5 shows the average length of the fluidity measurements for the three hydrogen levels and the standard error in the mean values. Figure 5 shows two samples from the reduced pressure test (RPT) that were taken after purging, giving a hydrogen level of 0.13 ml/100g, and after hydrogen addition, giving 0.43 ml/100g.



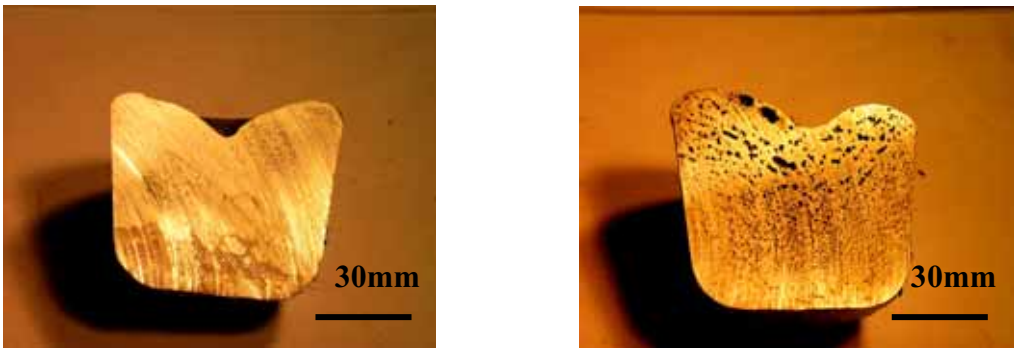
a) b)

Fig. 3 Optical micrographs of refined sample 1R2 (0.01 wt% Ti) from a) base and b) tip of spiral.



a) b)

Fig. 4 Polarised light image of refined sample 1R2 (0.01 wt% Ti) from a) base and b) tip of spiral.



a) b)

Fig. 5 Samples from the reduced pressure test: a) after purging (hydrogen level 0.13 ml/100g); b) after hydrogen addition (hydrogen level 0.43 ml/100g).

Table 6 shows the porosity calculated from the density measurements for selected spirals and standard error in the mean values, σ_m (%), for the three hydrogen levels.

The volume concentration of inclusions for low and high levels of hydrogen was calculated from the PoDFA samples in Table 7. Microprobe analyses were performed to identify the type of inclusions in the samples. Figure 6 shows backscattered electron micrographs of the microstructure of the purged and up-gassed samples. The type of inclusions present in both samples is also indicated.

Table 5 Average length of the fluidity measurements for the three hydrogen levels and the standard error in the mean values for ten spirals with three hydrogen levels (P-after purging with Ar, A-as received, H-after wood addition to the melt).

Hydrogen content, ml/100g		Average length $\pm \sigma_m$, mm
P	0.13	420 ± 20
A	0.15	420 ± 30
H	0.43	430 ± 40

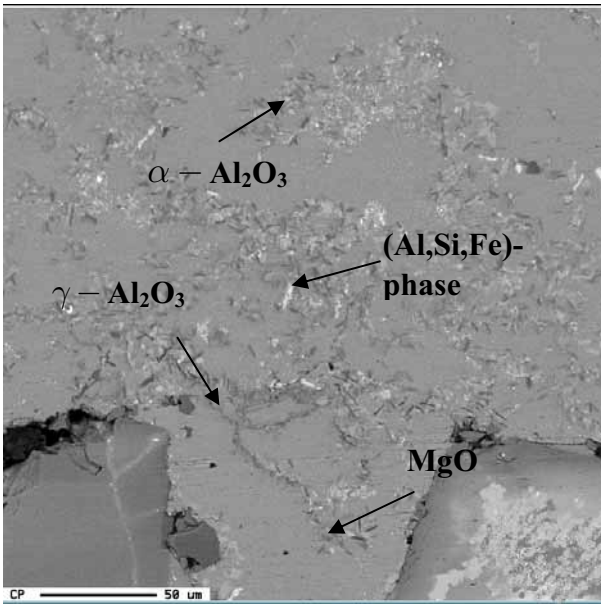
Table 6 Porosity (%) calculated from density measurements for selected spirals and standard error in mean values, σ_m(%), for three hydrogen levels.

Hydrogen, ml/100g		Porosity, %	σ_m, %
P	0.13	1.9	0.1
A	0.15	1.4	0.4
H	0.43	3.7	0.2

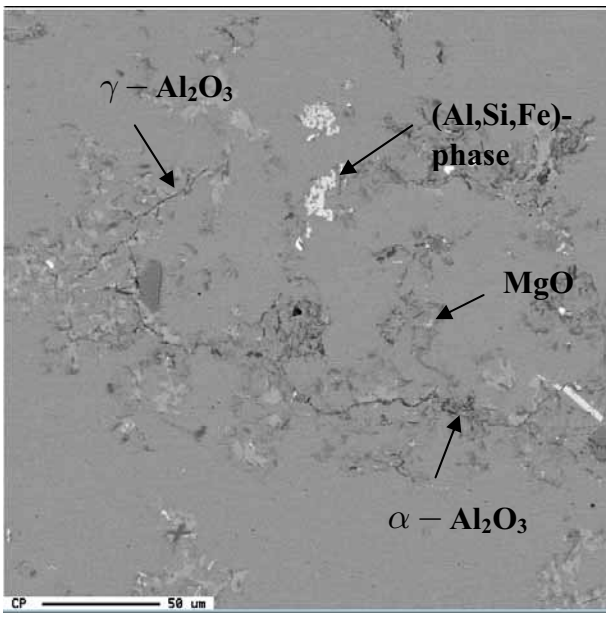
Table 7 Volume concentration of inclusions for low and high level of hydrogen, P and H, respectively.

Sample	Oxide film, ppm (vol.)	Fine dark inclusions, ppm (vol.)	Larger dark inclusions, ppm (vol.)	Larger grey inclusions, ppm (vol.)	Total ppm (vol.)
P	0.07	2.1	0.03	n.d.*	2.2
H	0.03	1.4	0.10	0.03	1.5

*n.d. = not detected



a)



b)

Fig. 6 Backscattered electron micrographs of a) purged sample with low hydrogen content (0.13 ml/100g) and b) up-gassed sample with high hydrogen content (0.43 ml/100g).

4. DISCUSSION

The fluidity measurements for three additions of AlTi5B1 reveal that fluidity does not significantly change with these additions. Table 3 shows that the difference between the average fluidity lengths for the three additions is within the standard error in the mean values. Therefore, no statistically significant effect of grain refinement on the fluidity of A356 can be concluded. The result is in accord with Tiryakioglu *et al.* [11] who, for the same alloy and a similar test method, made the same conclusion. Also Kwon *et al.* [15, 21], using a different test method, found no appreciable variation on fluidity of A356 when measured above 700ºC for 0.2 wt% Ti addition.

The reason why the grain refinement does not affect fluidity is not yet well understood. For instance, some influence on fluidity by the grain refinement process might be expected, since it has been shown [6] that fine particles are more effective in stopping a flowing stream than an equivalent percentage by weight of coarse particles. In this case, fluidity might be expected to decrease with grain refinement. Conversely, however, it has also been shown [13] that

grain refinement postpones the dendrite coherency point, which can be supposed to be related to fluidity [9, 22]. The flow of the liquid stream can be assumed to be impaired when the dendrites at the tip become coherent, which means that a late coherency would be expected to give a better fluidity. Therefore, in this case, fluidity might be expected to increase with grain refinement. However, for the levels of Ti investigated, the coherency point varies between 24% and 25% [13], which is likely to give no significant effect on fluidity.

As suggested by Easton and St John [23], because aluminium casting alloys such as A356 already contain high solute levels and high growth restriction factor, GRF (the GRF of 7 wt% Si is equivalent to that of 0.17 wt% Ti [24]), the optimum grain refiner only needs to contain nucleant particles, such as TiB_2 in the case of AlTi5B1 grain refiner (but no additional alloy to confer additional growth restriction). The microstructure investigations of A356 alloy (Figs. 3 and 4) show no morphological changes associated with increased Ti additions and the alloy has remained as fine equiaxed dendrites. Easton and St John [23] observed the same morphology in the unrefined and refined A356 alloy. The microstructure analyses (Figs. 3 and 4) and the grain size measurements (Table 4) show that the grain refinement affects the grain size of the spirals. However, the decrease in grain size achieved after the additions is not dramatic because the A356 alloy already contains 0.059 wt% Ti. In confirmation of this behaviour, it has been reported [24] that small amounts of grain refiner at high superheat, comparable with that used in the present work, produced significant grain size reductions, but further additions only produced minimal additional benefit.

Table 4 shows that the tip of the spirals has a finer structure than the base, as might be expected because of the increase in the cooling rate from the base towards the tip and possibly as a result of dendrite fragmentation.

Table 5 shows the average length measurements of the spirals for three hydrogen levels. Clearly, there is no statistically significant effect of hydrogen on fluidity of the A356 alloy. In contrast, and, of course, as is to be expected, the reduced pressure test (Fig. 5 and Table 6) shows greatly increased porosity after the addition of hydrogen. The PoDFA samples (Table 7) have shown a similar concentration of inclusions, 2.2 and 1.5 ppm (by volume), for the

purged (P) samples and the increased hydrogen (H) samples, respectively. It has been shown [25] that degassing with a rotating impeller can, in some circumstances, increase the oxide content in the melt. Therefore, whereas purging the molten A356 alloy with pure Ar for 45 minutes decreased the hydrogen content, in this case it appeared to increase the concentration of oxides. Micropobe analyses have shown that the inclusions present in both samples are dispersed oxides in various forms: γ-Al_20_3 as elongated films and α-Al_20_3 as thicker films. MgO is also present as dispersed clusters in addition to the mixed oxide, spinel $MgAl_2O_4$. Non-oxides include carbides Al_4C_3 in the matrix as tiny platelets or small chunks and TiB_2 in the form of clusters of tiny particles.

This brief look at the inclusions present in the alloys has indicated the complexity of the subject. Clearly, a significant study, beyond the scope of the presented work, will be required to identify the role they play in the limitation of fluidity.

5. CONCLUSIONS

1. The fluidity length of A356 aluminium casting alloy without grain refiner and with three additions of 0.01, 0.02 and 0.04 wt% Ti as AlTi5B1 grain refiner has been measured. No statistically significant effects of grain refiner addition on fluidity are revealed, but there is a grain size reduction of the spirals from the base to the tip.
2. The fluidity length for three hydrogen levels (0.13, 0.15 and 0.43 ml/100g) has been measured (showing the volume concentration of inclusions to be substantially similar). The hydrogen content did not significantly affect the fluidity of A356 alloy, although, as to be expected, porosity was increased.

ACKNOWLEDGEMENTS

The authors thank Dr. Freddy Syvertsen and Mr. Arne Nordmark for help with the experimental work. Dr. Øyvind Nielsen is gratefully acknowledged for proof-reading the manuscript. The present work was funded by the project NorLight Shaped Castings of Light Metals, with the following partners: Alcoa Automotive Castings, Scandinavian Casting Center ANS; Elkem Aluminium ANS; Fundo Wheels AS; Hydro Aluminium Metal Products; Hydro

Magnesium; the Netherlands Institute for Metals Research; Norwegian University of Science and Technology; and SINTEF. The authors thank the industrial partners and the Norwegian Research Council for financial support.

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ARTICLE 3

INFLUENCE OF TEMPERATURE AND ALLOYING ELEMENTS ON FLUIDITY OF Al-Si ALLOYS

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TMS 2005, Shape Casting: The John Campbell Symposium, Ed. by M. Tiryakioglu and P.N. Crepeau, 193-202, 2005

INFLUENCE OF TEMPERATURE AND ALLOYING ELEMENTS ON FLUIDITY OF Al-Si ALLOYS

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ABSTRACT

The goal of the work is to study the influence of casting temperature and four alloying elements: Mg, Ti, Fe and Sr, on fluidity of Al-7wt.% Si alloys. The fluidity of the alloys was measured using a fluidity mold produced by N-Tec Ltd., U.K. The experiments were designed using three orthogonal L_8 Taguchi matrices. Each of the four alloying elements and the casting temperature was an independent variable with two levels. Three interactions between the variables were identified and analyzed. The two levels of Mg were 0.003wt.% and 0.45wt.%; Ti levels were 0 and 0.2wt.%, Fe levels were 0.006wt.% and 0.24wt.%, and Sr levels were 0 and 0.023wt.%. Superheats were 70°C and 130°C over the respective liquidus temperatures of the experimental alloys. The main effect of each of the independent variables on the fluidity was quantified and Analysis Of Variance (ANOVA) was performed on the experiment matrix. The results were verified and validated to ensure robustness of the experiment design. The results of the Taguchi design of experiments show that casting temperature has the most pronounced influence on fluidity of the molten metal. Among the alloying elements chosen, only Mg has an appreciable effect on fluidity. Increasing Mg in the melt from 0.003wt.% to 0.45wt.% decreases the fluidity of the molten metal.

Keywords: Fluidity, Al-Si alloys, Alloying Elements, Taguchi Design of Experiments

INTRODUCTION

The increasing demand of light weight, high strength cast alloys has triggered a substantial increase in the world production of Al alloy castings in the past two decades. In addition to properties and part performance, castability has become an important parameter in the development of Al cast alloys [1]. Melt fluidity is one of the critical properties influencing castability of an alloy and is affected by many variables, as John Campbell has shown in a comprehensive review [2]. Many combinations of alloying elements such as Si, Cu, Mg, Fe, *etc.*, are being added to Al alloys to improve castability and performance. However, the influence of these elements on the fluidity, and in turn castability of Al alloys, has not been systematically quantified partly due to the lack of experimental methodologies. The N-Tec[1] fluidity mold was used for this study in order to quantify melt fluidity in a repeatable and reproducible way. The aim of this work was to understand and quantify the effect of key alloying elements such as Mg, Ti, Fe and Sr on fluidity of Al-Si alloys. The Taguchi method of experimental design and analysis was used [3, 4].

Role of Alloying Elements on Fluidity

The fluidity of a solidifying melt is dependant on the interplay of the following parameters:

- Velocity of the melt through the flow channels in the mold.
- Velocity of the primary solidifying front: primary Al dendrites.
- Composition of solute enrichment ahead of the solidifying dendrites.
- Rate of change of fraction solid in the two-phase region of the alloy.

The viscosity of the melt affects melt velocity; in addition to Si, temperature and alloying elements such as Mg and Sr drastically affect viscosity of the melt [5]. Apart from the rate of heat extraction from the melt by the mold wall, the velocity of the solidifying front is dependant on the composition of the solute field ahead of the dendrites and the composition gradient of the elements in the solute field. The alloying elements in the melt such as Mg and Fe will have a

[1] The N-Tec fluidity mold is a product of the MetalHealth® System for molten metal characterisation which is owned by N-Tec Limited, Oxford (U.K.) and manufactured under licence by Metaullics Systems, Ohio (USA).

strong influence on the rate at which the fraction solid changes with time: the solidification rate, df_s/dt. In addition, elements such as Mg and Fe form various intermetallic phases in the two-phase region thus, directly influencing fluidity [6]. Ti is added in hypoeutectic Al-Si alloys to reduce the size of the primary Al phase. The size of the Al grains will directly affect the nature and velocity of the solidifying front and hence, affect fluidity of the melt. Past works [7, 8, 9] have shown conflicting viewpoints on the qualitative effect of Ti on melt fluidity.

In this study, the effect of critical elements in Al-Si alloys such as Mg, Ti, Fe, and Sr will be quantified. Efforts are underway to establish the mechanism by which the above-mentioned solidification parameters affect fluidity.

EXPERIMENTAL PROCEDURES AND TAGUCHI DESIGN

Experimental Evaluation of Fluidity

Figure 1 shows the fluidity mold used in this study, which consists of the following parts.

-Drag consisting of five channels (*fingers*) of identical lengths and different cross sectional areas.
-Flat mold cope.
-Gating system split in two semi-cylinders.
-Kalpur™ sleeve[2], held in place by a clamp ring on the top of the gating system.

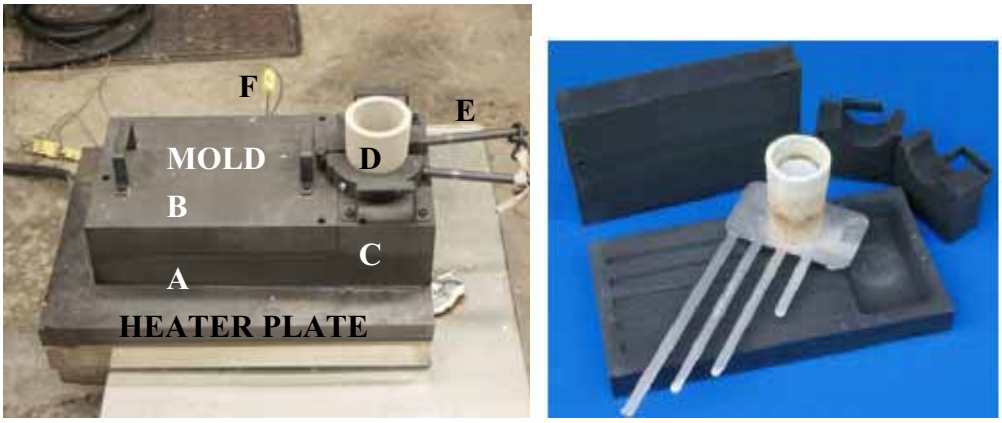
The fluidity mold was placed on a heater plate[3] in order to pre-heat the mold and precisely control the temperature cycle of the mold during the experiments. The mold temperature was measured by a calibrated 'K' type thermocouple placed in the middle part of the drag. The total volume of the solidified alloy in the five channels was calculated and reported as a fluidity index.

$$V = \sum_{i=1}^{5} A_i \cdot L_i \qquad (1)$$

[2] Manufactured by Foseco Metallurgical Inc, Ohio, USA.

[3] Manufactured by Metaullics Systems, Ohio, USA.

where V is the total volume, A and L are the cross sectional area and the length of each channel, respectively.



a) b)

Figure 1. a) N-Tec mold and heater plate. The main components of the fluidity mold are: A drag, B cope, C gating system split in two semi-cylinders, D Kalpur sleeve held in place by E clamp ring, and F thermocouple in the drag; b) Open mold and a sample from a fluidity test. (Courtesy N-Tec Limited)

Design of Experiments

Taguchi design of experiments was used in this study and Table I shows the list of variables used in the experiments. Five independent variables were used in two levels each, respectively. Two L_8 Taguchi experimental matrices were designed. Each of the matrices used four independent variables, namely, Sr, Ti, Fe and Mg at two levels each, respectively. Experiments in each of the two L_8 matrices were conducted at two levels of temperature and hence, two levels of melt superheat (difference between pouring temperature and liquidus temperature). Apart from four elements as independent variables, three interactions were also considered in each of the two experimental matrices, namely, SrXTi, SrXFe, and FeXTi.

A third L_8 Taguchi matrix was derived from the two matrices designed. The Temperature column (T), with the two levels shown in Table I, replaced the Fe

column since the two experimental matrices showed that the effect of Fe levels on fluidity is negligible (refer to Results and Discussion section).

Table I. List of variables, constants and their respective levels used in the experiments.

Independent Variable			Constant		Dependant Variable
Variable	Level		Constant	Level	
	Level 1	Level 2			
T	70ºC Superheat	130ºC Superheat	Mold	H-13	Total volume of metal filled in five channels
Sr	0 wt.%	0.023 wt.%	Mold Coating	Dycote 36	
Ti	0 wt.%	0.2 wt.%	Mold Pre-heat	295ºC	
Fe	0.006 wt.%	0.24 wt.%	Pouring Velocity	Maintained by Kalpur sleeve	
Mg	0.003 wt.%	0.45 wt.%			

Experimental Procedures

Alloys for the eight experiments were prepared in an induction furnace with standard aluminum master alloys. Alloy compositions were determined by a spark emission spectrometer. Thermal analysis during solidification for each of the eight alloys was carried out with a 'K' type thermocouple. The liquidus temperature of the eight alloys was established from the analysis of the thermal data. The two pouring temperatures (70°C and 130°C above the liquidus temperature, respectively) used in the experimental matrices were calculated from the determined liquidus temperatures.

Procedure for Analysis of results

The Signal to Noise (S/N) ratios were calculated for the total volume of metal in the five channels of the fluidity mold. ANOVA was performed using STATISTICA software[4] and the calculated S/N ratios were graphically plotted against the levels of the independent variables. Calculation of the Mean Squared Deviation (MSD) values used the 'larger the better' criteria [1,2],

[4] STATISTICA, Volume IV: Industrial Statistics, StatSoft Inc., 1995, Tulsa, OK, USA.

meaning that the larger the value of the total volume of metal in the five channels in each experiment, the better is the fluidity of the alloy. The greater the S/N ratio, the more effect (qualitatively) the independent variable has at that level on fluidity of the alloy melt. ANOVA presented quantitative results of the effect of each of the independent variables on fluidity.

RESULTS AND DISCUSSION

Experimental Matrix with Fe as a Variable

Figures 2 and 3 present the main effect of the independent variables on fluidity for castings made with 70°C and 130°C superheat, respectively. There are two significant features in the results shown, one being the slope of the line between the corresponding S/N ratios for each variable, and the other the nature of the slope (positive or negative). The larger is the slope of the line, the more pronounced is the effect of the independent variable on fluidity. A positive slope indicates that changing the variable level from the first to the second favorably increases fluidity and *vice-versa*. In Figures 2 and 3, Mg has a negative slope between 0.003wt.% and 0.45wt.% indicating that increasing Mg value decreases fluidity. Moreover, the slope of Mg is the highest among the independent variables used, showing that Mg has the largest influence on fluidity as compared to Sr, Ti and Fe. Fe has a negligible effect on fluidity. Sr and Ti have nominal effects. Moreover, the effect of Mg for both superheat values is negative, which means that increasing Mg for both 70°C and 130°C superheats decreases fluidity. Sr and Ti have a positive effect on fluidity for a 70°C superheat and a negative effect on fluidity for a 130°C superheat. The different effect of Sr and Ti on fluidity by changing superheat may be due to morphological changes associated with temperature for Sr and Ti phases. Further work is required to verify this assumption. Figures 4 and 5 show the effect of the interactions on fluidity at superheats of 70°C and 130°C, respectively. Each line is drawn from the S/N ratios for the two variable levels. If the two lines in an interaction cross each other, then the interaction is said to have an effect on fluidity. If the interaction lines are parallel, then it does not have an effect on fluidity.

In Figure 4 (a)-(b) the interaction lines cross each other and hence, SrXTi and SrXFe interactions have an effect on fluidity. In Figure 4 (c) the interaction

lines are parallel to each other and hence, FeXTi interaction does not have an effect on fluidity. Similarly, in Figure 5 (a), the interaction lines cross each other and hence, SrXTi interactions have an effect on fluidity. In Figure 5 (b)-(c) the interaction lines do not intersect each other and hence, SrXFe and FeXTi interactions do not have an effect on fluidity.

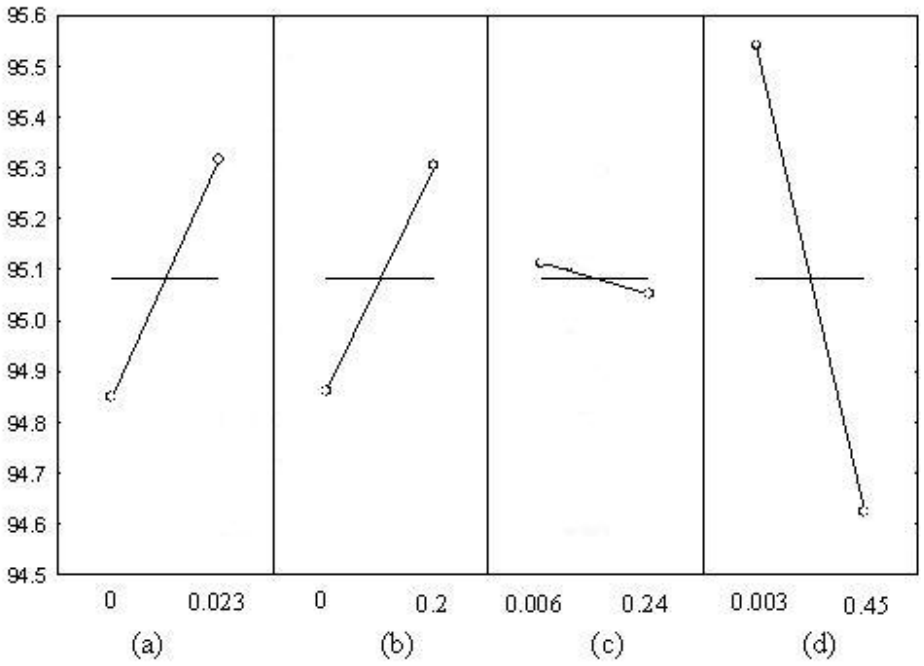


Figure 2. The S/N ratios are plotted against the levels of the independent variables at 70°C superheat and show the main effects of: (a) Sr (positive); (b) Ti (positive); (c) Fe (negative); (d) Mg (negative).

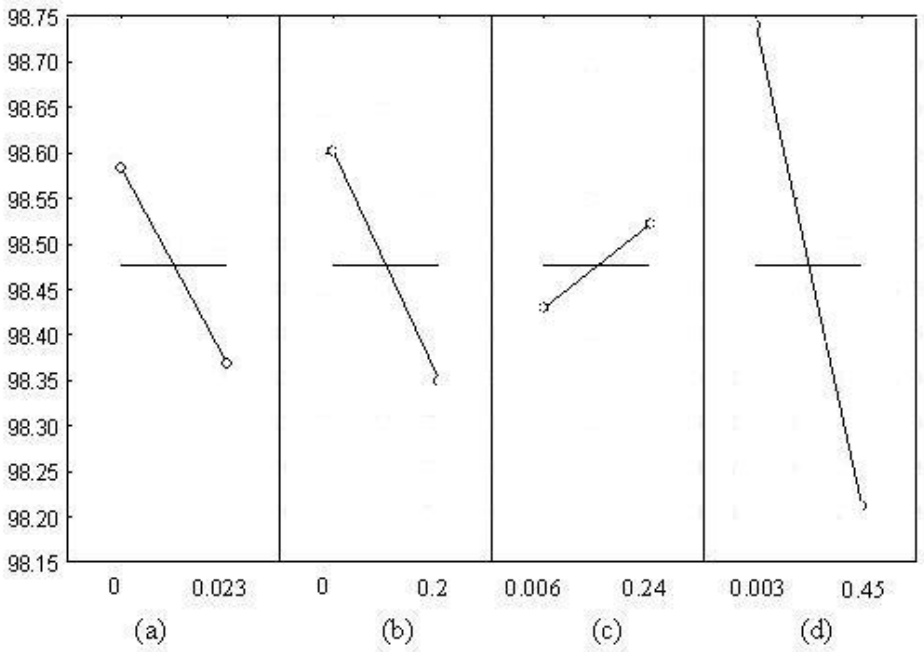


Figure 3. The S/N ratios are plotted against the levels of the independent variables at 130°C superheat and show the main effects of: (a) Sr (negative); (b) Ti (negative); (c) Fe (positive); (d) Mg (negative).

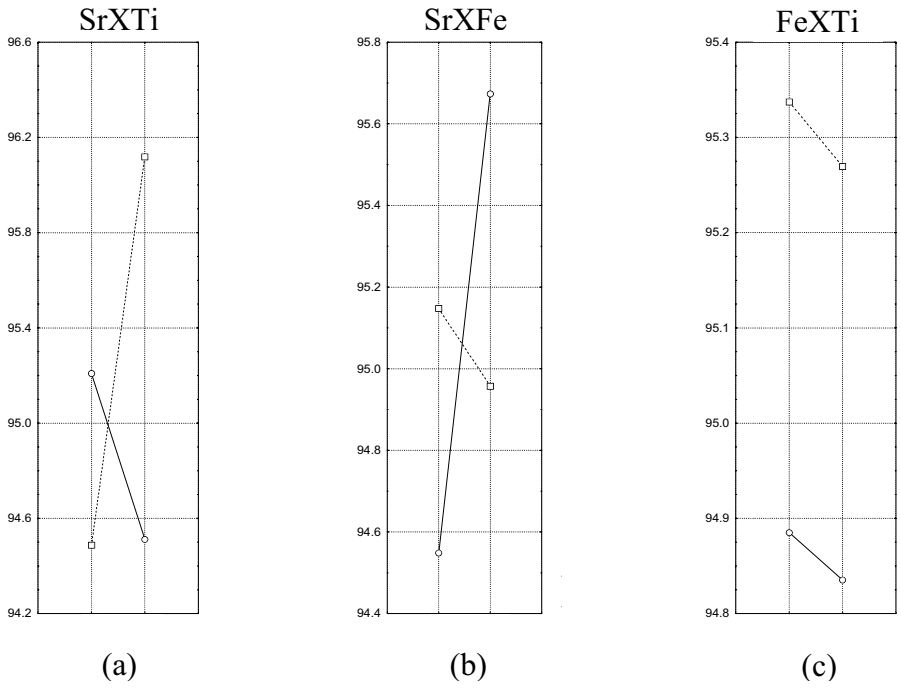


Figure 4. Effect of interactions on fluidity at 70°C superheat. Each line is drawn from the S/N ratios for the two variable levels. The interactions are: (a) SrXTi, (b) SrXFe, and (c) FeXTi.

Table II shows the results of the pooled ANOVA performed for the two pouring temperatures with 70°C and 130°C superheat, respectively. Pooling of ANOVA eliminates the effect of variables having a negligible effect on fluidity. These variables have less than 1% contribution on the fluidity of the melt. The percent contribution is a quantitative evaluation of the effect of the independent variables, while the trend is a qualitative evaluation (refer to Figures 2 and 3). The error term in Tables II is a particularly informative term. The percentage contribution of the error term indicates whether the experiment was performed correctly and consistently. If the percentage contribution of the error term after pooling is greater than 20%, then the experiments were not conducted properly; it may, for example, infer that some critical variable(s) having an overwhelming effect on the results has (have) been omitted in the experiments [1,2].

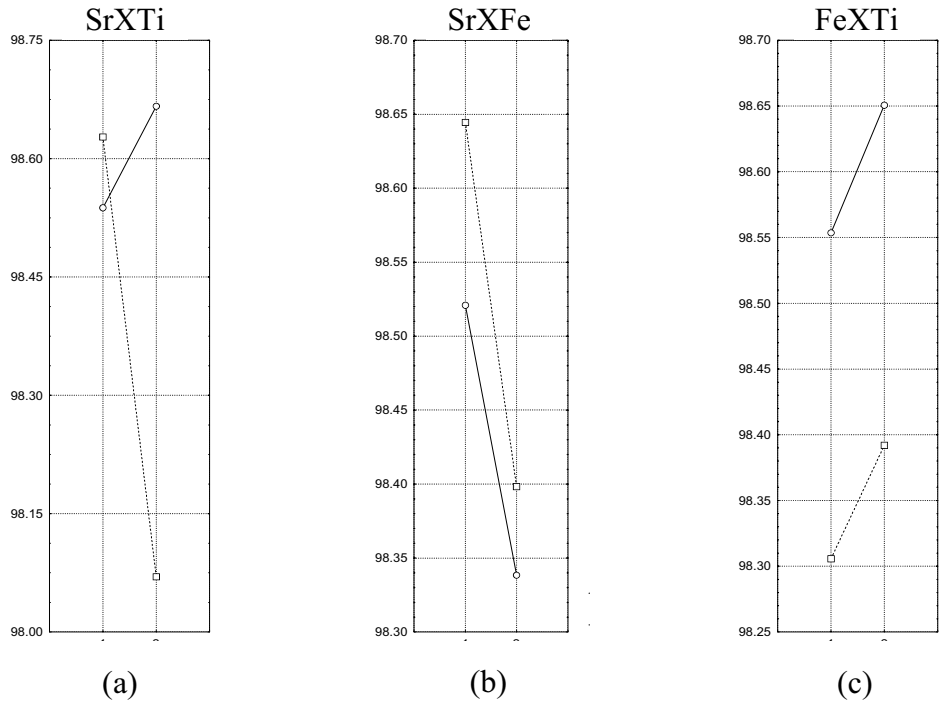


Figure 5. Effect of interactions on fluidity at 130°C superheat. Each line is drawn from the S/N ratios for the two variable levels. The interactions are: (a) SrXTi, (b) SrXFe, and (c) FeXTi.

In Table II, the percentage contributions of the error term (after pooling) are 55% and 61% for experiments with 70°C and 130°C superheats, respectively. These values are far greater than 20%, which does not suggest any confidence that the experimental design and the procedures followed were robust and accurate. Hence, the results presented so far may only be accurate from a qualitative point of view. However, re-designing the Taguchi matrix by replacing Fe (negligible effect on fluidity) with temperature (T) resulted in a different picture with respect to the error term.

Table II. Pooled ANOVA - quantitative and qualitative analysis of independent variables on fluidity.

Parameters	70°C Superheat		130°C Superheat	
	Contribution (%)	Trend	Contribution (%)	Trend
Sr	3.2	+	3.42	-
Ti	2.89	+	4.78	-
SrXTi	19.95		8.77	
Fe	**Pooled**		**Pooled**	
SrXFe	6.37		**Pooled**	
FeXTi	**Pooled**		**Pooled**	
Mg	12.35	-	20.77	-
Error	55.16		61.55	

Experimental Matrix with Temperature as a Variable

Analysis of the Taguchi experimental matrix with Fe revealed that the error term was far greater than 20%. Accordingly, a new matrix was derived wherein the Fe variable was substituted with the Temperature variable and the results of the new experimental matrix showed confidence in the results (error term less than 20%). Figures 6 and 7 show the main effect of the independent variables on the S/N values, and the effect of the interactions on fluidity, respectively. Temperature has the most pronounced positive effect on fluidity followed by Mg which has a negative effect. Sr and Ti do not show an appreciable effect on fluidity. SrXTi is the only interaction that shows an appreciable effect on fluidity. Table III shows the quantitative and qualitative results of the analysis by ANOVA. The error term in Table III has a 16% contribution, which means that the results of the Taguchi experimental matrix are dependable and possess a high confidence level.

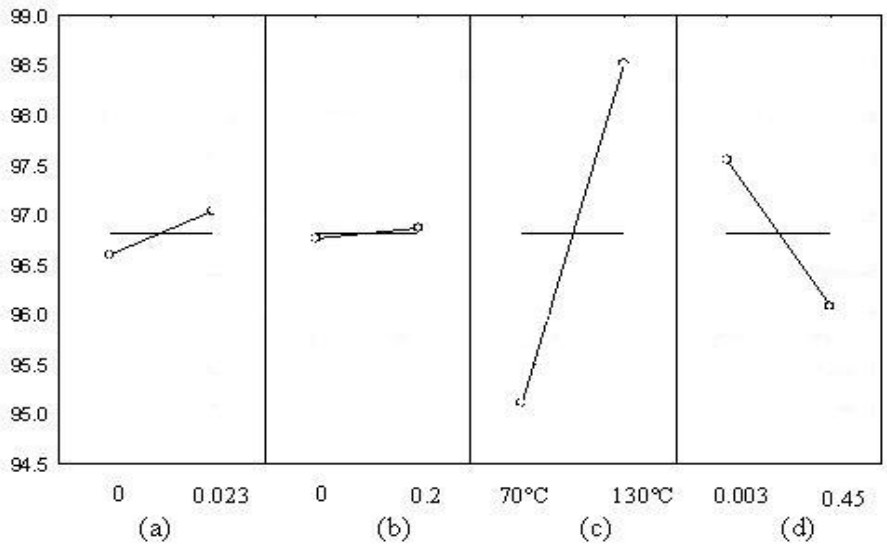


Figure 6. The S/N ratios are plotted against the levels of the independent variables with Temperature as a variable and show the main effects of: (a) Sr (positive); (b) Ti (positive); (c) T (positive); (d) Mg (negative).

Qualitative and quantitative analyses of the results reveal that among the alloying elements considered as independent variables, only Mg has a pronounced effect on fluidity of Al-7wt.%Si alloy melt. Increasing Mg decreases fluidity of the melt at the pouring temperatures (superheats) examined. Increasing pouring temperature drastically increases fluidity of the alloy melt. The optimum condition, *i.e.*, the combination of levels of each factor which gives the highest fluidity, has been calculated and is 0.023wt.%Sr, 0.2wt.% Ti, 0.003wt.% Mg and a superheat level of 130°C.

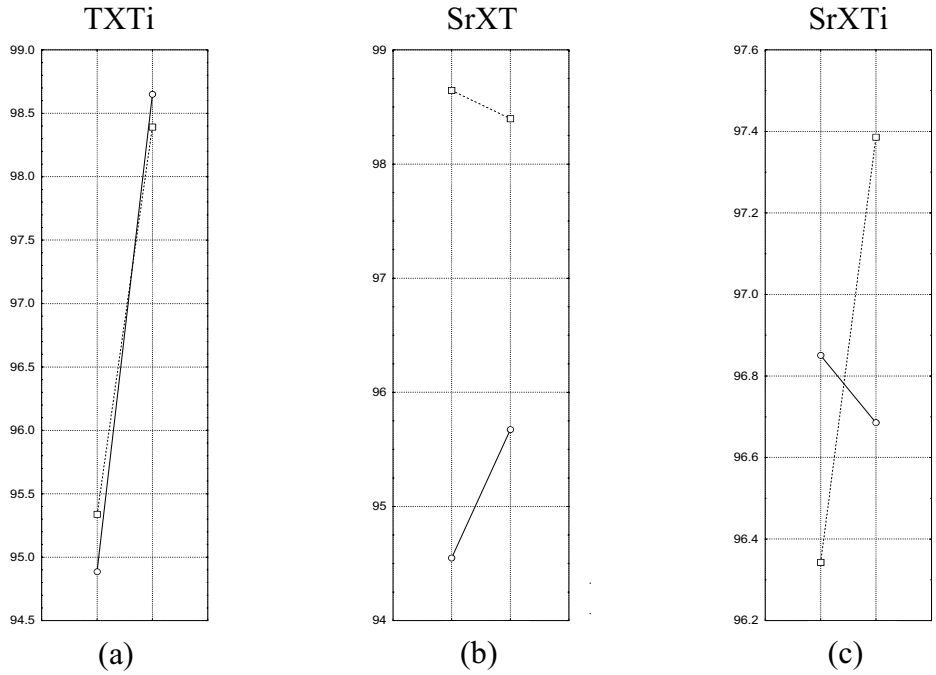


Figure 7. Effect of the interactions on fluidity. Each line is drawn from the S/N ratios for the two variable levels. The interactions are: (a) TXTi, (b) SrXT, and (c) SrXTi.

Table III. Pooled ANOVA - quantitative and qualitative analysis of independent variables on fluidity.

Parameters	Contribution (%)	Trend
Sr	1.1	+
Ti	**Pooled**	
SrXTi	2.5	
T	65.4	+
SrXT	**Pooled**	
TXTi	**Pooled**	
Mg	13	-
Error	16	

CONCLUSIONS

The following conclusions can be drawn:

- Variation in casting temperature presents the most pronounced change in fluidity of the melt. Higher casting temperature results in higher fluidity.
- Within a family of Al-Si alloy such as 356, Mg is the only element with a pronounced effect on the fluidity of the melt. Increasing Mg content decreases the fluidity of the melt.
- Addition of Sr, as a chemical modifier, and Ti, as a grain refiner, does not have an appreciable effect on the fluidity of the melt.
- Fe content, within the limits of composition tested, does not have any effect on fluidity.

Further experiments are underway to understand the effects of additional elements in the melt and the effect of other parameters on fluidity.

AKNOWLEDGEMENTS

The authors wish to thank Dr. Libo Wang for helping in the experimental trials and for scientific support; Dr. Phil Enright from N-Tec Ltd., Dr. Phil Sandford from Foseco, and Dr. David Neff from Metaullics, for providing tools and interesting discussions. The work was funded by the project NorLight Shaped Castings of Light Metals, in Norway, and also the ACRC at WPI, in USA. The authors thank the industrial partners and the Norwegian Research Council for their financial support.

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ARTICLE 4

THE INFLUENCE OF OXIDE INCLUSIONS ON THE FLUIDITY OF Al-7wt.%Si ALLOY

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Presented at the International Conference on Advances in Solidification Processes, Stockholm, Sweden, June 7-10, 2005.
Accepted for publication in Materials Science and Engineering A, June 2005

THE INFLUENCE OF OXIDE INCLUSIONS ON THE FLUIDITY OF Al-7wt.%Si ALLOY

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ABSTRACT

Recycling of aluminium alloys often increases the amount of oxide inclusions and this may influence the castability of the material. In this study, the fluidity of three Al-7wt.%Si alloys, namely a standard A356, A356 with 20% scrap addition and A356 with 50% scrap addition, is reported. The scrap additions consist of contaminated alloy turning chips. Fluidity measurements were performed in an experimental fluidity test consisting of gravity casting of spirals in sand moulds with good reproducibility. The influence of oxide content and percentage of recycled material on the fluidity of the alloys were studied. The results show that recycled material increases the oxide content of the molten metal which significantly decreases its fluidity. Comparisons between the fluidity measurements on 20% and 50% scrap additions, however, do not show significant differences.

Keywords: Al-Si alloys, Fluidity, Oxide inclusions, Recycling

1. INTRODUCTION

Recycling of aluminium is important due to several economic and environmental reasons. Recycling of aluminium requires only 5% of the energy for primary aluminium production and saves raw materials such as carbon and alumina. Moreover, waste products can be recycled instead of being sent to landfill and this conserves the natural resources [1, 2]. During the last decades interest has been focused on recycling of aluminium, particularly aluminium beverage cans. Recycling 1 kg of aluminium beverage can save up to 8 kg of bauxite, 4 kg of chemical products and 14 kWh of electricity [3]. The European average of beverage can recycling in 2004 was 40% with an increase of 10% in the last decade. Currently, a large number of foundries meticulously collect

process scrap at all stages and sort them by alloy. Recently, efforts are made by the automotive industry to enable cars with aluminium components to be easily dismantled and the scrap sorted and re-used for new parts. One of the main concerns, when recycling aluminium scrap, is to avoiding oxide inclusions, which dramatically affects the castability of the material.

Many researchers [4, 5] have studied the role of oxide films/oxide inclusions on the properties of aluminium castings. They concluded that oxide films/oxide inclusions influence the amount of defects such as pores and cracks, and hence the mechanical properties of the aluminium castings. Generally, the oxide films may originate from two main sources: the melt preparation and the filling process. The former produces the so-called "old" oxide films and they usually enter the mould when using a ladle for pouring [6]. However, they can be avoided to some extend by careful melt preparation. The latter produces the so-called "young" oxide films and they are formed in the molten aluminium stream as it flows through the runner system to enter the mould in a short time period. They can be avoided to some extend by careful design of the running system. Recycled materials, scraps and turnings, are also sources of oxide films/oxide inclusions.

Many parameters affect the fluidity of aluminium alloys [7]. Di Sabatino and co-workers have studied the effect of the casting temperature [8] and the effect of minor alloying elements [9], concluding that the alloy superheat, *i.e.* casting temperature minus liquidus temperature, plays the most important role in enhancing fluidity, while minor alloying elements do not have appreciable effects. Kwon and Lee [10] have investigated the effect of oxide inclusions on fluidity, concluding that increasing oxides content decreases fluidity, particularly at a low pouring temperature.

The work presented in this study focuses on the effect of recycling aluminium turnings and increasing the oxides level on the fluidity of one of the most popular aluminium-silicon alloy for foundry applications, *i.e.* Al-7wt.%Si.

2. EXPERIMENTAL

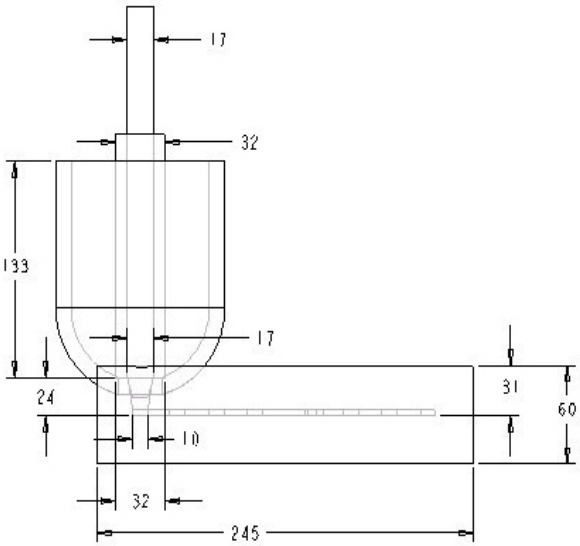
Three alloys were investigated: a standard A356, and the same alloy with 20% and 50% scrap additions. The chemical composition is shown in Table 1. The

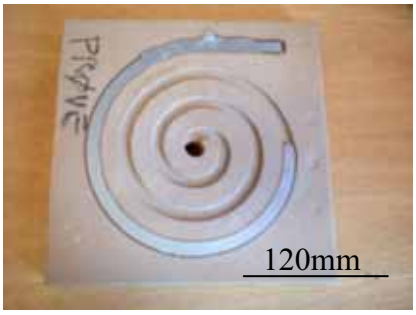
scrap additions consisted of turning chips recycled from Al-7wt.%Si and Al-11wt.%Si alloys for wheel production provided by Fundo Wheels AS (Høyanger, Norway). High purity aluminium (99,999%) was added in order to adjust the chemical composition, because the main goal was to obtain three alloys with the same major chemistry, *i.e.* Al-7wt.%Si alloys.

Table 1. Chemical composition of the three alloys for the experimental study (wt.%).

Alloy	Si	Fe	Mg	Ti	Cu	Sr	Na	Al
A356	6.81	0.118	0.36	0.103	0.0001	0.0013	0.0001	Bal.
A356+20%	6.78	0.119	0.31	0.102	0.0004	0.0036	0.0001	Bal.
A356+50%	6.70	0.119	0.26	0.089	0.0005	0.0053	0.0001	Bal.

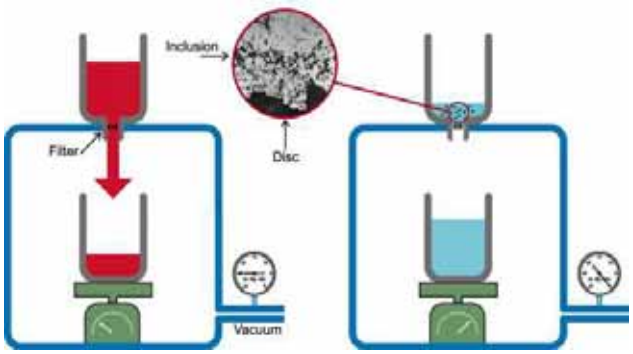
A batch of 20 kg of each alloy was melted in an induction furnace which was held at 730 ± 10 °C and five castings were made for each alloy. Fluidity was measured with an experimental apparatus that has recently proved to have high reproducibility [8]. The geometry of this apparatus is shown in Figure 1a and b shows the open mould with as cast spiral. Fluidity was measured as the length of the metal flow in the spiral sand mould. The silica sand moulds were made with a core shooter using the cold box process (phenolic urethane resin cured with amine vapour) and consisted of two parts tightly fixed together with four metal clamps: a cope (single Archimedian spiral shape) and a drag (flat sand mould). The cope had a vent at the end of the spiral cavity and the Archimedian spiral had a cross section of 4x10 mm^2 with a maximum running length of 1.2 m. The gating system consisted of a pouring cup and a short circular tapered sprue. A calibrated thermocouple (K-type, ±1 K for ΔT accuracy) measured the temperature of the molten metal inside the insulated pouring cup and was connected to a computer data acquisition and control system. A moving stopper rod closed the bottom of the pouring cup and automatically opened the gate to the spiral when the molten metal temperature reached a preset value of 700 ºC. This opening temperature was constant for all the casting trials. The molten metal was poured by the operator from the induction furnace directly to the pouring cup of the fluidity equipment with a coated ladle. The dross skin on top of the melt was manually removed by a rake prior to sampling.





(a) (b)

Figure 1. (a) Geometry of the equipment for the fluidity measurements (dimensions in mm); and (b) open mould showing as cast spiral.



(a) (b)

Figure 2. (a) PoDFA equipment [11]: the molten metal is poured in a crucible and placed on top of the vacuum chamber; (b) schematic illustration of the process: the metal is sucked by the vacuum and forced to flow through the porous filter disc which is cut and prepared for the microscopy investigation.

PoDFA (Porous Disc Filtration Apparatus) tests [11] were performed to analyse the level of inclusions and Figure 2 shows the equipment. The molten metal is poured in a pre-heated crucible, placed on top of the vacuum chamber, sucked by the vacuum and forced to flow through the porous filter disc. Inclusions and oxides are retained on the surface of the disc which is cut and prepared for the microscopy investigation. Apart from the cast series with standard A356, two samples were selected from each cast series, one sample being taken at the beginning and one at the end of the fluidity tests. For the standard A356 alloy, only one sample was taken for the PoDFA test, because the alloy was "clean" as received. Optical microscopy and scanning electron microscopy were used for the microstructure investigation.

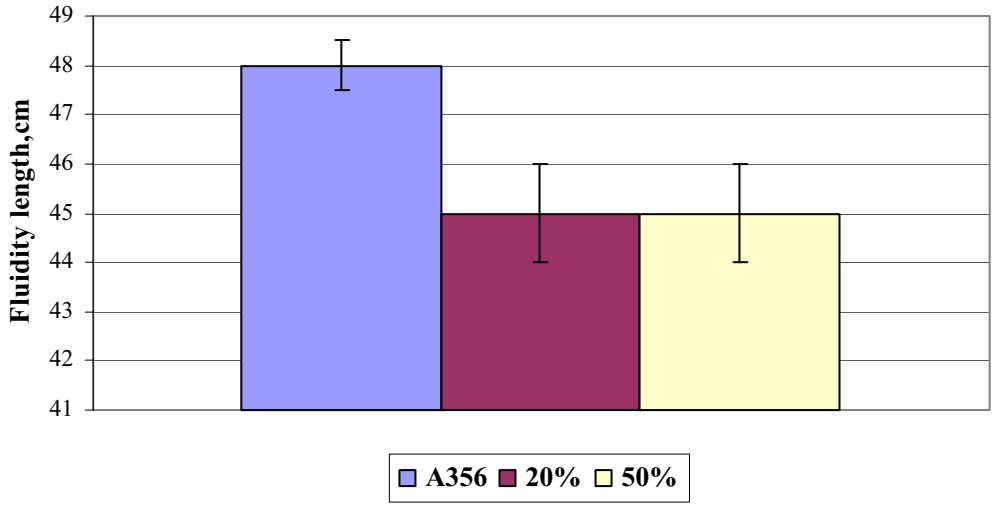


Figure 3. Fluidity measurements for three alloys: standard A356, A356 + 20% scrap additions and A356 + 50% scrap additions. The standard error bar is shown.

3. RESULTS AND DISCUSSION

Figure 3 shows the fluidity measurements from the spiral test. The standard error, calculated from the standard deviation in the mean values [8], is also shown. Clearly, A356 alloy has a much higher fluidity length than the alloys with 20% and 50% scrap additions. The decrease in fluidity length due to scrap addition to the melt is about 7%. However, the fluidity measurements on 20% and 50% scrap additions do not show any difference. Table 2 lists the amounts

of filtered metal in the PoDFA samples. For the alloys A356+20% and A356+50%, there are two values corresponding to the sample taken before starting and after the fluidity experiments. The results of PoDFA analysis, the total content of inclusions and oxides are shown in Table 3. Inclusions and oxides are measured in mm^2/kg and N/kg, respectively, where the area of inclusions trapped (mm^2) and the total number of oxide particles (N) are rated *versus* the amount of metal passed through the filter (kg). The A356 alloy is very clean: both total amounts of inclusions and oxides are small, while the additions of 20% and 50% scrap significantly increase both inclusions and oxides.

Table 2. PoDFA sampling. Amount of filtered molten metal for three alloys.

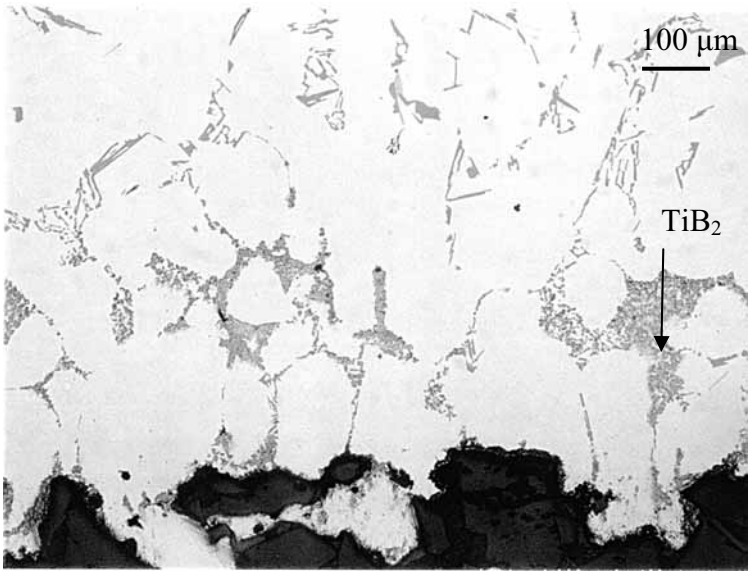
Alloy	**Filtered metal, kg**	
A356	0.91	-
A356+20%	1.51	1.52
A356+50%	1.52	1.40

Table 3. Analysis from the PoDFA tests. The results show the inclusions and oxide content for A356, A356+20% scrap addition before and after casting series, and A356+50% scrap addition before and after casting series.

	A356	**A356+20%**		**A356+50%**	
		Before	After	Before	After
Inclusions, mm^2/kg	0.438	0.825	1.109	1.408	1.203
Oxides, N/kg	2	28	64	11	39

The samples taken after the fluidity experiments have a higher content of oxides than at the beginning. This may be due to holding the melt for a longer period of time and introducing some turbulence during sampling. Nevertheless, the alloys with the addition of turnings (A356+20% and A356+50%) have a similar content of inclusions and oxides. Adding 20% turning chips to the standard A356 alloy have increased the number of oxides by a factor of about twenty. However, a further addition (50%) of turning chips has not proportionally increased the oxide content. This may be due to the fact that some oxides are retained by the melt in the furnace and/or to the tendency of oxides to float to

the surface. Generally, inclusions can be lighter or heavier than the molten metal. The former float to the molten metal surface where they are collected by a slag or dross phase; the latter accumulate as a slurry at the bottom of the furnace [12]. Moreover, it can be expected that the inclusion content of the melt was influenced by the turbulence due to the induction field. Further systematic investigations are, however, needed to clarify this. No significant difference in the oxide content may be the reason for no significant difference in the fluidity measurement for these alloys (Figure 3). The percentage of recycled aluminium alloys does not significantly affect fluidity for the same content of inclusions and oxides. Therefore, recycling aluminium alloys is possible at an industrial level and does not deteriorate casting properties such as fluidity, once operators manage to keep the inclusions and oxide contents at a low level. These findings are consistent with the industrial observations [13] at Fundo Wheels AS that has been adding about 40% of turning chips to their production of alloys with no difference in the wheels strength, porosity level and scrap rate.



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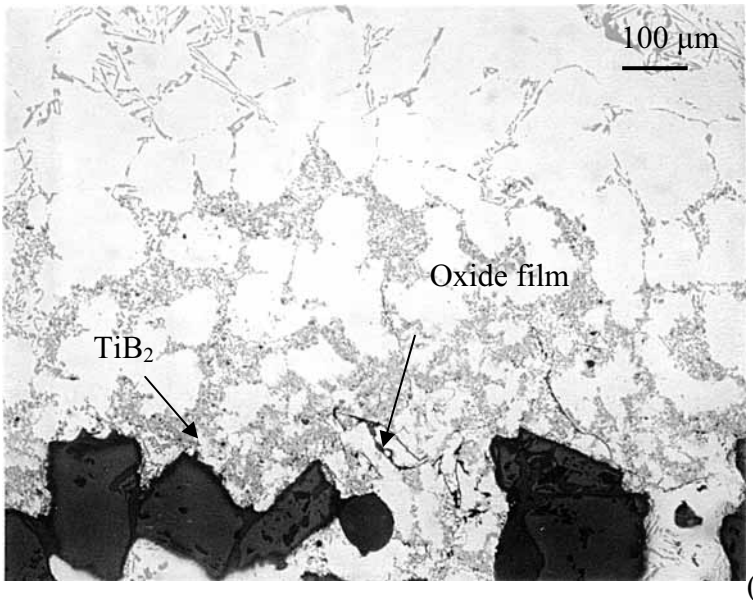

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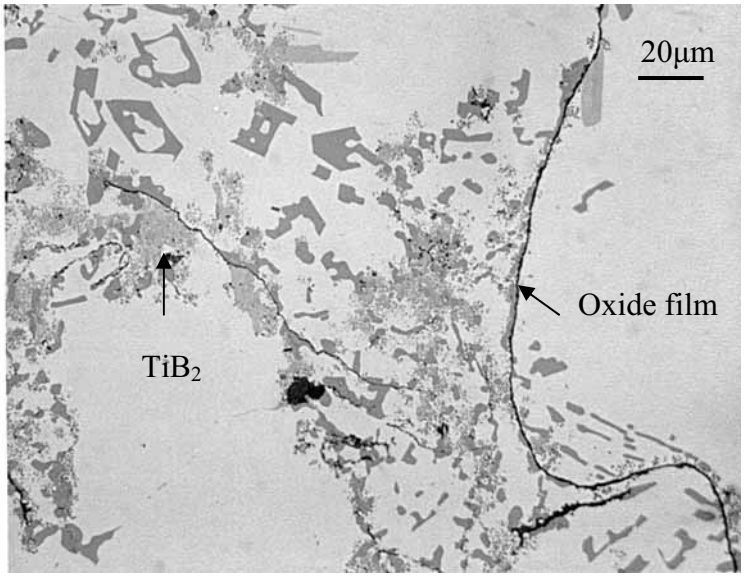

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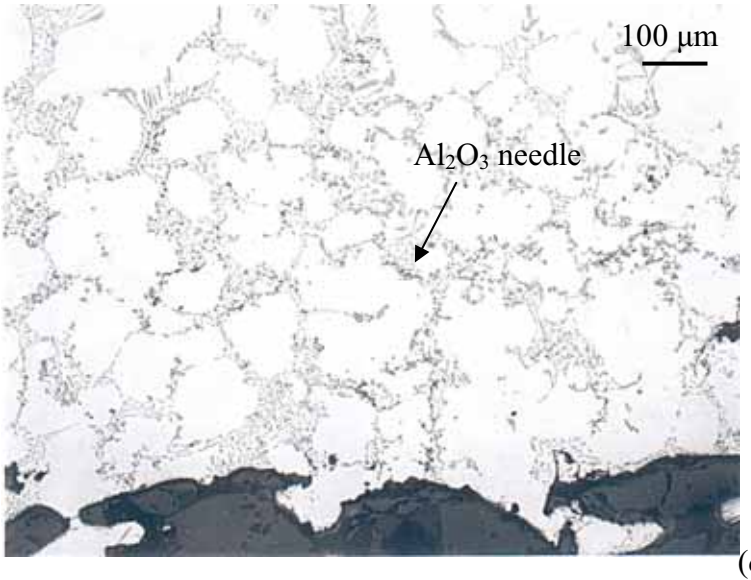

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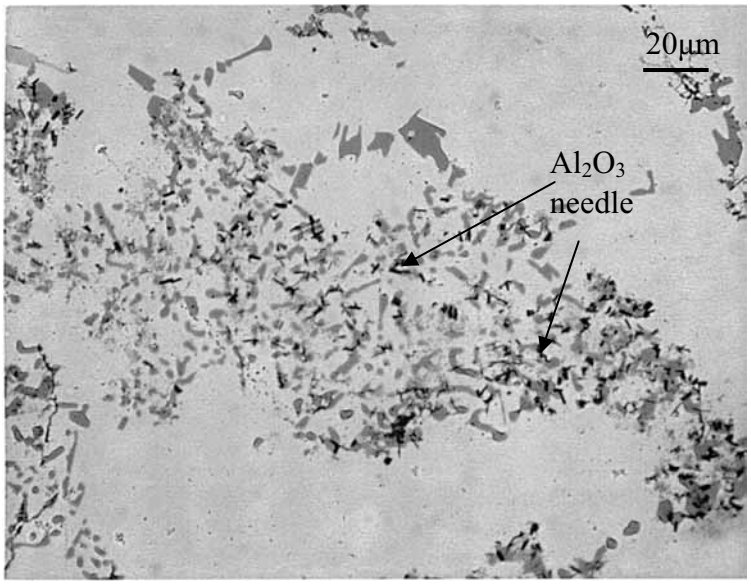

(e)

Figure 4. Optical micrographs of the investigated samples from the PoDFA tests: (a) A356; (b) A356+20%; (c) A356+20% (high magnification); (d) A356+50%; (e) A356+50% (high magnification).

The optical investigation has revealed that the A356 alloy is extremely clean with respect to oxide films and other inclusions. The only inclusion present in significant quantity is titanium diboride (TiB_2) because the alloy contained AlTi5B1 grain refiner as received. In the A356+20% and A356+20% alloys, adding scrap to the base metal reduces its cleanliness. Oxide film content increases as well as the level of fine particulate. The fine particles are a mixture of TiB_2 and alumina needles (Al_2O_3). The samples also show small amounts of $MgAl_2O_4$-spinel. Figure 4 shows optical micrographs of the sample taken during PoDFA tests; the inclusions and oxide films are indicated.

4. CONCLUSIONS

This experimental work has shown that:

1. Inclusions play an important role on fluidity. Increasing inclusions and oxide content decreases fluidity.

2. Adding contaminated alloy turning chips significantly increases inclusions and oxide content. However, the percentage of recycled aluminium alloys does not significantly affect fluidity for the same content of inclusions and oxides.

ACKNOWLEDGEMENTS

The authors wish to acknowledge Mr. Alf Sandberg for his help with castings; Dr. Alan Cushway at N-Tec Limited (England) for the analysis of the PoDFA specimens. The present work was funded by the project NorLight Shaped Castings of Light Metals with the following partners: Alcoa Automotive Castings, Scandinavian Casting Center ANS; Elkem Aluminium ANS; Fundo Wheels AS; Hydro Aluminium Metal Products; Hydro Magnesium; the Netherlands Institute for Metals Research; Norwegian University of Science and Technology; and SINTEF. The authors thank the industrial partners and the Norwegian Research Council for financial support.

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ARTICLE 5

FLUIDITY EVALUATION METHODS FOR Al-Mg-Si ALLOYS

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Accepted for publication in International Journal of Cast Metals Research, August 2005

FLUIDITY EVALUATION METHODS FOR Al-Mg-Si ALLOYS

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ABSTRACT

Much work has been carried out to assess the fluidity of casting alloys by various fluidity test methods. This study compares two fluidity tests which have been used to evaluate the fluidity of three Al-Mg-Si alloys for High Pressure Die Casting (HPDC) processes: Al-5Mg-2.5Si, Al-5Mg-1.5Si, and Al-3Mg-0.5Si (composition in wt%). The fluidity of the alloys has been measured using (i) a commercially available strip fluidity test method, and (ii) an experimental test method using a spiral sand mould. Reproducibility and fluidity measurements obtained using the two methods are reviewed and discussed. The experimental results show that both fluidity test methods give internally consistent results.

Keywords: Fluidity, Al-Mg-Si alloys, High Pressure Die Casting

INTRODUCTION

A number of methods have been devised to measure the fluidity of molten metals. Common to all tests is that the molten metal is made to flow into a narrow channel. Fluidity is reported as a measure of the length or volume of the mould filled by the metal stream before it freezes.

As early as 1902, West [1] investigated the flow characteristics of molten metals cast into sand moulds; he poured metal into a horizontal wedge and considered the length of the metal flow as a measure of its fluidity. Ruff [2] poured metal in a long cylindrical channel and used the length of the flow as a measure of

fluidity, but the test was particularly sensitive to errors in levelling. Evans [3] tried an inverted *"U"* type of test where vertical sections of various cross-sectional areas fed from a common channel and were considered as a measure of fluidity. Saito and Hayashi [4] in 1919 were the first to try a fluidity spiral test. Many investigators have improved this spiral test. The major modifications of the spiral test are those by Saeger and Krynitsky [5] for cast iron, and Taylor, Rominski and Briggs [6] for steel. Eastwood and Kempf [7], and later on Sicha and Boehm [8] developed a spiral casting with a flat cross-section for studying fluidity of aluminium and its alloys. Further developments of the spiral fluidity test were made by Kondic [9]. Ragone, Adams and Taylor [10, 11] developed a vacuum fluidity test in which the liquid metal was drawn into a pyrex glass tube by means of vacuum. Ragone's method has been widely used to measure the fluidity of pure magnesium and its alloys [12], and of aluminium alloys [13, 14].

Until 1950, interest in metal fluidity was largely focused on ferrous metals. Fluidity testing of aluminium alloys was until recently quite complicated and/or yielded results difficult to reproduce. The relative reproducibility of the early fluidity spiral test was about 25% [8, 15]. Di Sabatino *et al.*[16] have recently developed a new test method for gravity casting of spirals in sand moulds with 5% relative reproducibility. Additionally, during the last two decades multi-channel die moulds have been used for fluidity evaluation. The multi-channel die moulds used by Kwon and Lee [17] and Di Sabatino *et al.* [18] have shown to have a relative reproducibility of about 10%.

Results from various different experimenters on fluidity are difficult to compare in a comprehensive way because investigators have introduced variants of the fluidity test, and tests have not been conducted in a consistent manner. However, results on the effect of temperature and heat of fusion on fluidity have been confirmed by several authors. Results obtained for the Al-Cu system by Floreen and Ragone [13] are in agreement to those obtained by Courty [19]. The latter used a fluidity spiral test which had a bottom pouring basin stopped with two fusible lead plugs, whereas Floreen and Ragone used the vacuum fluidity test. Campbell [20] has shown that different types of fluidity tests in the same mould materials give consistent results, provided that the surface tension and casting modulus (casting volume/cooling area ratio) effects are taken into account. The effect of the size and shape of the channel section is rationalised in terms of:

(i) the effective reduction in head pressure because of the back pressure due to surface tension;
(ii) the effective modulus of the section, since this directly affects its solidification time.

Therefore, if efforts are made to keep a certain level of standardization in terms of test parameters, results from different researchers using different test methods may be comparable. In this context, two distinctly different fluidity test methods were evaluated with three different Al-Mg-Si alloys.

EXPERIMENTAL

Materials and thermal analysis

Al-Mg-Si alloys, which have been shown [21, 22] to be particularly interesting for the High Pressure Die Casting processes, were used for this investigation. The experimental work was carried out at two different laboratories. The first series of experiments was performed at the Metal Processing Institute (MPI), WPI, Worcester, MA (USA). Fluidity was measured by a commercial test involving the filling of a series of thin rectangular section strips [23]. The alloys were prepared in an induction furnace that was held at a temperature range of 720-750ºC. Eighteen kilograms of each alloy were prepared and the chemical composition was measured with spark emission spectroscopy. Alloy 1 (Al-5Mg-2.5Si) was also grain refined with 2 kg/ton of Al-5Ti-1B rod-type master alloy and is indicated as alloy 1-GR. After the grain refiner addition, the melt was stirred for about 10 minutes.

The second series of experiments was performed at SINTEF Materials and Chemistry, Trondheim (Norway). Fluidity was measured with an experimental apparatus developed by SINTEF [16] and the alloys were manufactured by Hydro Aluminium, Sunndalsøra (Norway).

Table I shows the chemical composition of the alloys evaluated. Alloys 1, 2, 3, 1-GR were prepared in the casting laboratory at MPI for the tests made using the strip mould. Alloys A, B, C, D were provided by Hydro Aluminium. Thermal analysis for each alloy was conducted with one-thermocouple test. A

calibrated thermocouple (K-type with accuracy ±1ºC) was held in the centre of a preheated graphite crucible, and the temperature *versus* time curves were recorded. Table II shows T_l, the liquidus temperature measured by the thermal analysis, and T, the pouring temperature, equal to 70ºC above the liquidus temperature (melt superheat). Before each casting, the melt was degassed with dry Argon for 30 minutes at 720ºC using a rotary degassing unit.

Table II: Chemical composition (weight %) of alloys evaluated for fluidity.

Alloy	**Si**	**Fe**	**Mn**	**Mg**	**Ti**	**Al**
1	2.4	0.01	0.8	4.0	<0.001	Bal
A	2.6	0.11	0.88	5.23	0.0063	Bal
2	1.35	0.02	0.7	4.7	<0.001	Bal
B	1.34	0.14	0.93	5.24	0.0047	Bal
3	0.4	0.02	0.8	3.1	<0.001	Bal
C	0.52	0.17	1.02	3.0	0.0043	Bal
1-GR	3.1	0.02	0.8	4.5	0.014	Bal
D	2.6	0.13	0.81	5.1	0.02	Bal

Table III: Measured liquidus temperature (T_l) and pouring temperature (T) obtained *via* thermal analysis.

Alloy	**T_l, ºC**	**T, ºC**
1	623	693
2	625	695
3	640	710
A	614	684
B	622	692
C	640	710

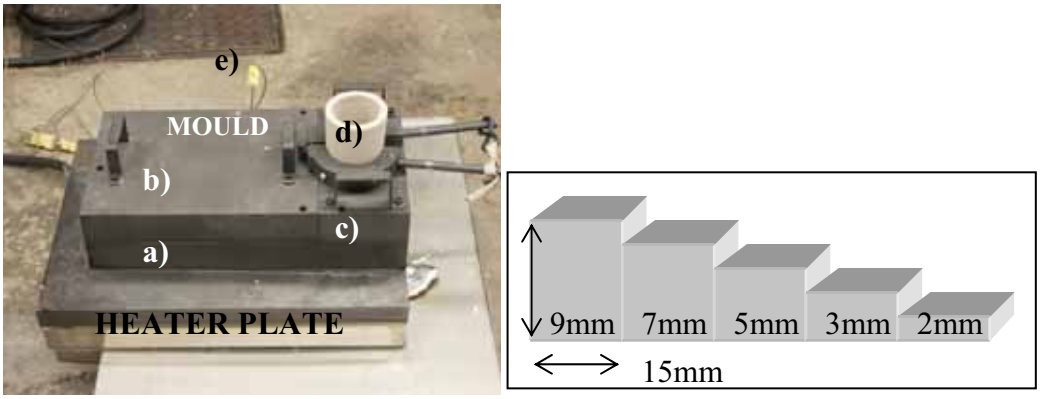
Fluidity strip mould

The fluidity strip mould is currently used as part of a commercial package on offer for checking the quality of liquid aluminium alloys [23] and shown in Figure 1(i). The mould is constructed from steel (H13) and has three parts: a base mould (drag) with five channels (fingers) of the same length and different cross sectional areas as shown in Figure 1(ii); a flat mould (cope) located above the base mould; and the gating system split in two semi-cylinders. Figure 2 shows

top and front views of the mould. A commercially available ceramic fibre sleeve [24] was held in place by a clamp ring on top of the gating system. The sleeve was placed at a constant distance (50mm) from the bottom of the mould using a spacer tube. A coated ladle, 2kg weight, was used during the experiments. The mould was coated with a proprietary die coating [24]. The fluidity mould was placed on a heater plate [25] in order to preheat the mould to a uniform target temperature. The mould temperature, measured by a calibrated thermocouple placed in the middle part of the base mould, was kept constant at 295ºC. The fluidity was calculated as the total volume of the five fingers:

$$V_{tot} = \sum_{i=1}^{5} (A_i \bullet L_i) \qquad (1)$$

where A_i and L_i are the cross sectional area and the finger length for each finger, respectively.



(i) (ii)

Figure 1: (i) Strip mould [23] and heater plate [25]. The main components are: a) drag, b) cope, c) gating system split in two semi-cylinders, d) ceramic sleeve and e) thermocouple in the drag; (ii) cross section of the five fingers of the strip mould.

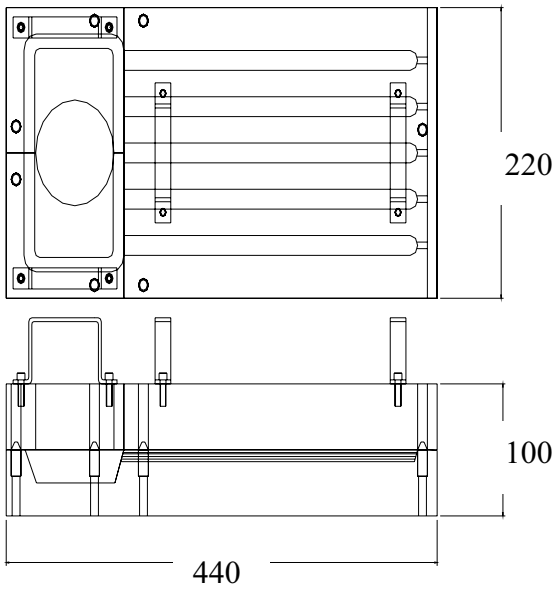


Figure 2: Top and front views (dimensions in mm) of the mould (Courtesy N-Tec Limited [23]).

Experimental spiral mould

The experimental spiral mould consisted of a pouring cup, a short circular tapered sprue, a stopper rod connected to a pneumatic cylinder, and a quartz sand mould. A detailed description of the test apparatus and its reproducibility has been previously presented [16].

Reproducibility

The reproducibility of both equipments was assessed through a series of N repeated measurements. The standard deviation and the relative reproducibility were calculated.

Effect of melt temperature

The effect of melt temperature was tested by casting a standard A356 alloy at three different temperatures, 700, 715 and 730°C, both for the strip mould and

spiral mould. The averages of the total volumes and spiral lengths as well as the standard deviations in the mean values (σ_m) were calculated for each temperature.

Effect of coating

The effect of coating on fluidity was studied by casting molten A356 alloy with and without coating the strip mould. The first set of experiments was carried out on the uncoated mould at two casting temperatures: 684ºC and 744ºC.

For the second set of experiments a die coating was applied. The coat consisted of a mixture of talc, mica and alumina with a sodium silicate binder. The coating was applied using the following procedure [26]. The mould was evenly heated to 260ºC and cooled at 150ºC by spraying with water. Thin, dilute coating layers were evenly applied with a spray gun to give a final coat thickness of about 0.2 mm. Before the experiments began, in order to assess the homogeneity of the results, about fifteen castings were run [27]. The castings for the experiments recorded here were then poured at the same temperatures (684ºC and 744ºC) as for the uncoated mould experiments. For each experimental condition, three repetitions were carried out.

Casting modulus

The casting modulus is an important casting parameter because it influences the solidification time of the molten alloys [28]. The casting modulus, defined as the ratio of the volume of a casting and its cooling area, has been calculated for both fluidity test methods.

RESULTS

Reproducibility

The results from the reproducibility study are shown in Table III. The relative reproducibility has been calculated from the average length of the measurements and the standard deviation. The relative reproducibilities for the strip mould and the fluidity spiral mould are 11% and 5%, respectively.

Table III: Fluidity measurements and relative reproducibility for the strip mould and spiral sand mould tests.

N repetitions		**Fluidity**	**Relative reproducibility**
Strip	21	57242±6468 [mm^3]	11%
Spiral	20	540±30 [mm]	5%

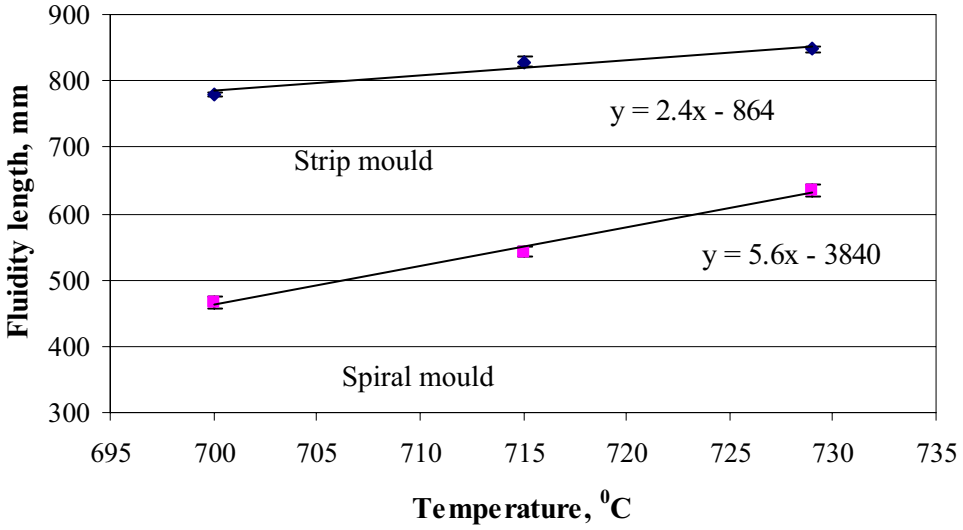


Figure 3: Fluidity length as a function of temperature for both the strip mould (upper graph) and spiral sand mould (bottom graph).

Effect of melt temperature

The average volume of the fingers from the strip mould and the average length of the spirals for all three different temperatures increased linearly, as shown in Figure 3. For the strip mould tests, a general equation for the fluidity measurements and temperature was observed:

$$L_f = 2.4T - 864 \qquad (2)$$

where L_f is the fluidity length, in mm, and T is the casting temperature, in °C. Consequently, increasing the pouring temperature by 1ºC, in the interval 700-730ºC, gives an increase in the fluidity length by 0.3%.

For the experimental fluidity spiral test, the following relation was found [16]:

$$L_f = 5.6T - 3480 \qquad (3)$$

Thus increasing the pouring temperature by 1ºC, in the interval 700-730°C, gives an increase in the fluidity length by 1%.

Effect of coating

Table IV shows the results of the fluidity measurements for the A356 alloy with and without coating for both low and high casting temperatures, 684ºC and 744ºC. The fluidity increase due to coating has been calculated and is equal to 26% and 22% for low and high casting temperatures, respectively.

Table IV: Fluidity measurements with and without coating for two different casting temperatures.

Casting temperature, ºC	**Fluidity volume, mm^3**	
	With Coating	**Without Coating**
684	$88*10^3$	$65*10^3$
744	$103*10^3$	$80*10^3$

Fluidity measurements

The measurements of the fluidity volume, for the strip method, and the fluidity length, for the spiral method, are presented in Figure 4 as well as the standard deviations in the mean values (σ_m).

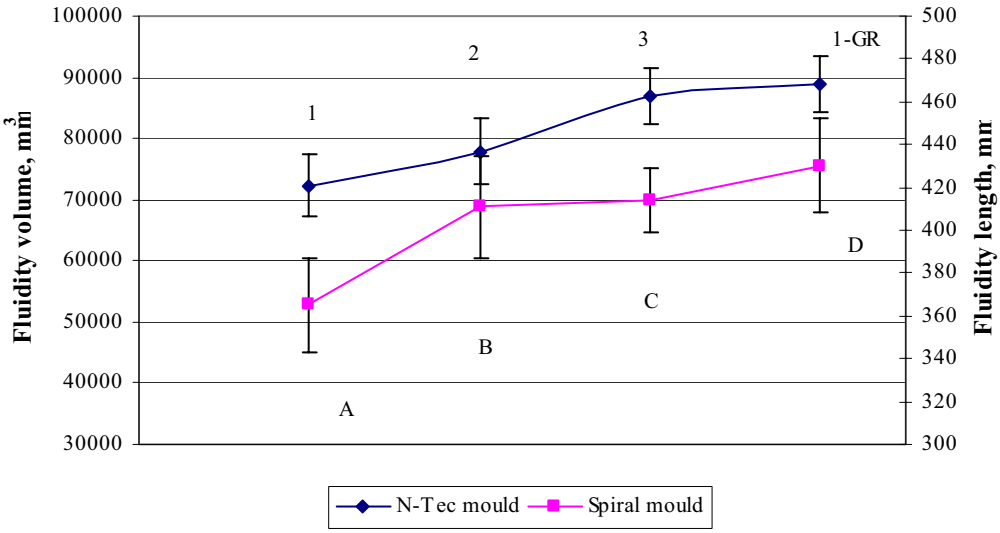


Figure 4: Fluidity measured by the strip (N-Tec) mould (scale on the left hand side in mm^3) and spiral sand mould (scale on the right hand side in mm). The standard deviations in the mean values (σ_m) are also shown.

DISCUSSION

The lower reproducibility of the strip mould is due to errors introduced during the fluidity tests. The spiral sand mould had a stopper rod that automatically lifted when the temperature reached the preset value, whilst in the strip mould the temperature was manually measured by the operator. Therefore, errors due to the operator and lower degree of automation make the results from the strip mould less repeatable. However, these are issues which can be modified for commercial use. Although the spiral test is particularly designed to reduce the effect of unwanted variations in temperature, the variability of the strip test results seems unlikely to be from this source because of the significantly lower sensitivity of the strip test to temperature variations.

The investigation of the strip mould has shown that the applied coating increased fluidity, probably due to a decreased heat transfer coefficient at the metal/mould interface. For all experiments with low (684°C) and high (744°C) casting temperature, the fluidity volume increased by 26% and 22%,

respectively. The experimental results clearly demonstrate that coating the mould is a useful practise to increase fluidity, particularly at low casting temperatures.

Although the fluidity measurements by both test methods have shown that the Al-5Mg-2.5Si+Ti may have the highest fluidity, whilst the Al-5Mg-2.5Si may have the poorest fluidity, Figure 4 shows that the differences between the investigated alloys are small and not significant.

The results from the fluidity measurements by two different equipments and methods are consistent. Campbell [20] reported that the results from different fluidity tests can be compared if they have similar casting modulus and the mould materials are the same. In this investigation, the casting moduli of the two fluidity test methods have the same order of magnitude; being 5.2mm for the strip mould and 4mm for the spiral mould. However, the two mould materials are completely different. According to Campbell's approach [20, 29], one may introduce a correction for the chilling power (*i.e.* thermal conductivity) of the mould material and thus an exact comparison could be made. Further investigation would be required to prove this.

The two fluidity test methods provide a good means of assessing castability of alloys from the perspective of fluidity. It is important to note that the ease of use of these methods is an advantage and will have value to the practitioner.

CONCLUSIONS

The fluidity sand spiral mould and the strip test mould are both reliable methods to assess fluidity of Al based foundry alloys. The need for the standardization of fluidity tests has often been urged. While this may be desirable, this work has shown that different fluidity test methods are in any case useful, giving results that are internally consistent and giving the same trends.

ACKNOWLEDGEMENTS

The authors thank Dr. Libo Wang, Dr. Freddy Syvertsen and Mr. Arne Nordmark for their help during the experimental work; Dr. Phil Enright and his

staff at N-Tec Limited for valuable discussion and for providing the strip mould equipment. ACRC (Advanced Casting Research Center) at WPI is gratefully acknowledged. The project was funded by NorLight Shaped Castings of Light Metals with the following partners: Alcoa Automotive Castings, Hydro Aluminium, Hydro Magnesium, Fundo Wheels, Elkem, the Netherland Institute of Metals Research, NTNU, SINTEF and the Norwegian Research Council.

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ARTICLES 6

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Accepted for publication in Metallurgical Science and Technology,
Ed. by Teksid Aluminum, July 2005

SIMULATION OF FLUIDITY IN Al-Si ALLOYS

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ABSTRACT

In this study, MAGMAsoft® commercial software package was used to simulate the fluidity of A356 alloy. Established an optimum mesh generation, the influence on fluidity of important metallurgical parameters, such as heat transfer coefficient, casting temperature and coherency temperature, was simulated. The simulation results were compared with fluidity laboratory tests carried out with spiral-shaped sand moulds and these simulations results were found to be consistent with the experiments. Therefore, this study sets a basis for more extensive use of simulations as a means for predicting and optimizing the fluidity of aluminium alloys. In addition, the results from the spiral-shaped mould tests were compared with vacuum fluidity tests carried out using an A356 alloy and the two techniques showed consistent results.

Riassunto

Materiali di elevate caratteristiche, prodotti di alta qualitá e bassi costi costituiscono sfide continue per le moderne fonderie. I programmi di simulazione stanno acquistando sempre piú importanza nelle fonderie come strumento per migliorare e ottimizzare i loro processi di produzione, sistemi di controllo e qualitá. In questo studio, MAGMAsoft® viene utilizzato per lo studio della fluiditá/colabilitá della lega A356. Lo scopo di questo lavoro é determinare l'influenza del coefficiente di trasferimento di calore (chiamato "Heat Transfer Coefficient" o HTC), la temperatura di colata e la temperatura per cui i grani coesivamente bloccano il flusso di metallo (chiamata "coherency temperature" o Tc). I risultati delle simulazioni sono stati confrontati con quelli sperimentali sulla lega A356. Lo strumento impiegato per misurare la fluiditá é stato recentemente sviluppato al SINTEF in Norvegia. I risultati hanno

dimostrato che le simulazioni riproducono molto bene i risultati sperimentali e che, quindi, MAGMAsoft® puó essere un utile stumento per predirre la fluiditá/colabilitá delle leghe di alluminio. Inoltre due differenti tecniche di misurazione sono state confrontate: il metodo della spirale e la tecnica del vuoto. Le due tecniche di misurazione hanno prodotto risultati molto simili.

1. INTRODUCTION

The foundry industry is continuously facing new challenges concerning high performance materials, high quality products and constrained costs. Computer simulations are gaining increasing importance in foundries to help them in optimizing processes, control system and product quality. In a survey in 1999, the American Foundrymen Society found that more than 1200 foundries, on a worldwide basis, are using numerical simulation for studying, setting up and optimizing their processes [1]. The study of metallurgical processes, such as those in the foundry, by means of mathematical models usually follows three steps [1]:

- Identifying the phenomena driving the process;
- Mathematically formalizing the effects of these phenomena on the physical parameters in equations;
- Solving the formalized equations (differential equations or systems of them).

In a typical foundry process, firstly the molten metal fills the cavity and this is described by fluid-dynamics laws (Navier-Stokes equations). Solidification and cooling of the alloy occur and they follow the heat transfer laws (Fourier equation). Eventually, solid state transformations may occur controlled by thermodynamics and kinetics, which are described by physical metallurgy (Avrami equation). The physical and metallurgical phenomena are then described by theoretical equations, numerical analysis follows and, eventually, results lead to the description of the fluid-dynamics field, thermal field and microstructure evolution. Figure 1 presents the flow chart of the main steps in modeling foundry processes [1].

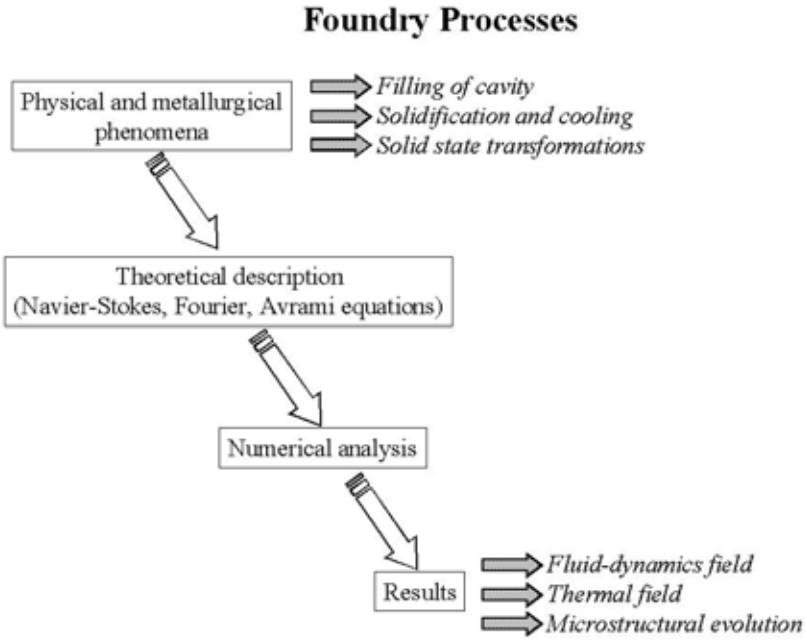


Figure 1. Flow chart of the main steps in modeling foundry processes [1].

Finite element modeling has been applied to the casting processes in order to optimize runner and gating systems, as well as process parameters [2]. Moreover, the most developed thermal and fluid-dynamic calculation codes allow prediction of shrinkage and gas porosity formation as well as evaluation of solidification residual stresses.

Fluidity is a key property in optimizing casting processes because it strongly influences the soundness of the casting and its final properties. The measurement of fluidity in casting alloys is not a straightforward task because it depends upon many variables [3]. Accordingly, many researchers [4, 5, 6] have studied the parameters influencing fluidity. In this study, simulations are applied to study the fluidity of one of the most common aluminium foundry alloys, A356.

During simulation, for a given set of conditions, the number of elements in the simulation process may change the results. The effect of mesh generation on the

simulation results was taken into account and, once an optimum mesh generation was established, the influence on fluidity of important metallurgical parameters, such as heat transfer coefficient, casting temperature and coherency temperature, was simulated.

The heat transfer coefficient (HTC), *i.e.* the rate of the heat loss through the metal/mould interface, is an important parameter influencing fluidity and has been widely investigated [7, 8, 9]. However, HTC is not a simple material property and is dependent upon chemical and physical interfacial conditions, mould and casting material properties, casting geometry, *etc.* There is a need for accurate and reliable data of HTC for aluminium foundry alloys. The selection of HTC values as well as boundary conditions at the metal/mould interface affects the accuracy of the simulations [10]. In the present investigations, HTC values were approximated such that the computer simulations and the experimental measurements were in agreement.

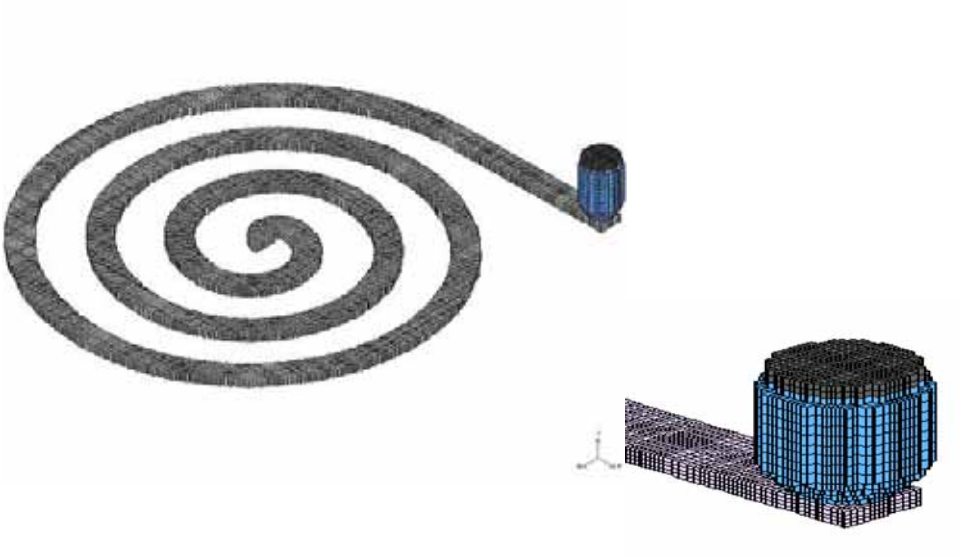
Casting temperature is one of the most important parameter influencing fluidity, as recently shown by Di Sabatino *et al.* [11] who found that increasing the casting temperature has the most pronounced beneficial effect on fluidity, while minor alloying element additions do not significantly affect fluidity.

The dendrite coherency temperature was also investigated in this study. The dendrite coherency point is defined as the instant, in the solidification process of an alloy, at which the individual dendrites start impinging upon their neighbours [12], which means that a solid network forms and hence the fluid flow stops. The temperature at this point is called dendrite coherency temperature (Tc) or simply coherency temperature [13]. A low coherency temperature means that the coherency point is postponed [14] which may mean that fluidity increases, and *vice-versa.*

2. NUMERICAL SIMULATIONS AND EXPERIMENTAL TESTS

The investigations carried out in the present work consisted of both numerical simulations and experimental fluidity tests. MAGMAsoft® commercial software package was used for numerically simulating the fluid flow of molten metal into spiral-shaped sand moulds. MAGMAsoft® is a Finite Difference Volume (FDV) method and the simulation procedure can be described by the following

steps [1]: geometry definition, mesh generation, material and process parameters definition, simulation/solution of the governing equations, and evaluation of the results. The geometry and mesh used for the simulations are shown in Figure 2. Table 1 shows the list of variables, their levels and constants used in the experimental trials.



a) b)

Figure 2. Geometry and mesh: a) inlet, pouring cup and spiral; b) higher magnification to show the mesh quality.

Firstly, the investigation focused on the mesh generation to achieve optimum simulation condition. Thereafter, simulations were carried out to evaluate the influence of heat transfer coefficient, casting temperature, and coherency temperature on the fluidity of the A356 alloy. Table 2 shows the physical constants and properties of the A356 alloy [15] for the experimental trials. Coldbox at 20 ºC was chosen as sand mould material in the MAGMAsoft®'s database. Table 3 shows the mesh generation. An automatic method was used for the mesh generation and a mesh size of about three millions control volumes (CVs, *i.e.* the overall number of elements) and hundred thousand metal cells

(*i.e.* the number of mesh elements that lied within the melt). The filling process was dependent on the metallostatic pressure, which was calculated from the geometry of the equipment and experimental conditions; the stop criteria was based on the coherency temperature, Tc. Based on previous works [12, 16], it was assumed that the dendrites start impinging and form a network that prevents further flow at a fraction solid of 30%, which (for the investigated alloy) corresponds to a Tc of 600ºC [17].

Table 1 List of variables, their levels and constants for the four series of casting trials.

Series	**Variable**				**Constants**
1	Mesh generation, # elements				Alloy: A356 HTC: 3500 W/m^{2}K Casting Temp.: 700°C Tc: 600°C (f_c=30%)
	1 *10^6	1.5 *10^6	3 *10^6	3.5 *10^6	
2	Heat Transfer Coefficient, HTC, W/m^{2}K				Alloy: A356 Casting Temp.: 700°C Mesh: 3 *10^6 elements Tc: 600°C (f_c=30%)
	3500	2000	1000		
3	Casting temperature, °C				Alloy: A356 HTC: 3500 W/m^{2}K Mesh: 3 *10^6 elements Tc: 600°C (f_c=30%)
	650	700	750		
4	Coherency Temperature, Tc, °C				Alloy: A356 HTC: 3500 W/m^{2}K Casting Temp.: 700°C Mesh: 3 *10^6 elements
	560	580	600		

Table 2 Physical constants and properties of the A356 alloy for the experimental trials [15].

Density of liquid (kg/m^3)	2340
Density of solid (kg/m^3)	2520
Liquidus (°C)	614
Solidus (°C)	542
Viscosity of liquid metal (Pa s)	1.3x10^{-3}

Table 3 Mesh generation for the simulation runs.

Mesh generation		
Method	Automatic	
Mesh size	Control Volumes, CVs	2 984 618
	Metal cells	112 539

In detail, the simulations consisted of four series of "virtual casting" trials that can be summarized as follows:

- First series: optimum mesh generation
- Second series: effect of heat transfer coefficient
- Third series: effect of casting temperature
- Fourth series: effect of coherency temperature

The simulation results were compared to the fluidity measurements of the A356 alloy. To evaluate the influence of casting temperature on fluidity, ten spirals were cast with the experimental fluidity equipment at three different casting temperatures, namely 700, 715 and 730 ºC. The experimental equipment for the fluidity tests was recently developed by SINTEF, in Norway, and a drawing of its geometry is shown in Figure 3. A thorough description of the equipment was given elsewhere [18] and the main parts were:

- Sand mould consisting of two parts: a cope with an Archimedian spiral cavity and a flat drag.
- Pouring cup.
- Stopper rod.

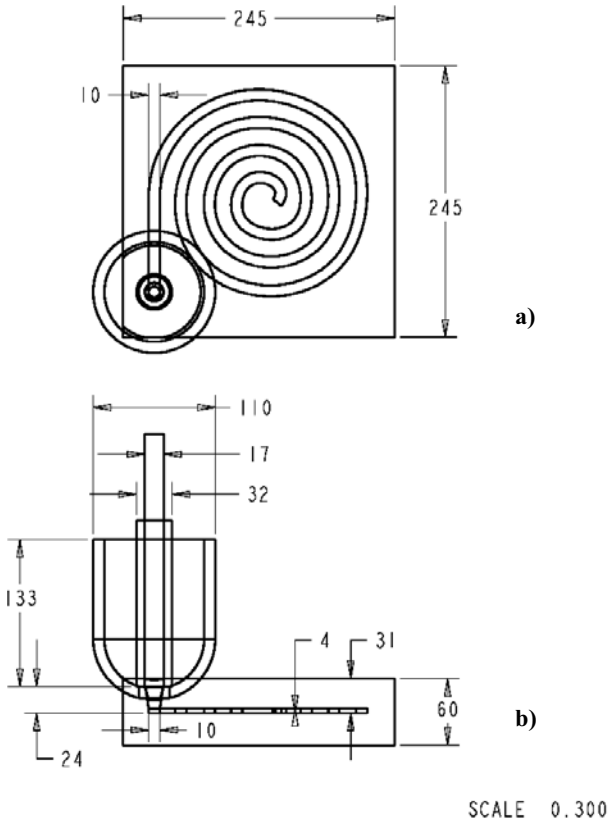


Figure 3. Drawing of the equipment for the fluidity tests: a) plan view of the pouring cup and sand mould, and b) side section through the stopper rod and the sand mould (all dimensions are in mm).

The molten metal was poured into a pouring cup and when its temperature, measured by a thermocouple placed in the cup, reached a preset value, the gating system automatically opened by a stopper rod and the metal entered the spiral cavity in the sand mould. The equipment has a high reproducibility [18] because it allows good control over the casting temperature (hence alloy superheat) and has highly reproducible pouring velocity.

Furthermore, the results from the fluidity tests were compared to those recently achieved by Bonollo *et al.* [19] using an A356 alloy tested by the device shown in Figure 4. It consisted of a crucible connected by means of a tube to a vacuum system. When the vacuum was applied, the molten alloy filled the tube until

solidification occurred and the distance that the alloy flowed before being stopped by solidification was taken as the fluidity length. The testing temperatures were between 620°C and 800°C.

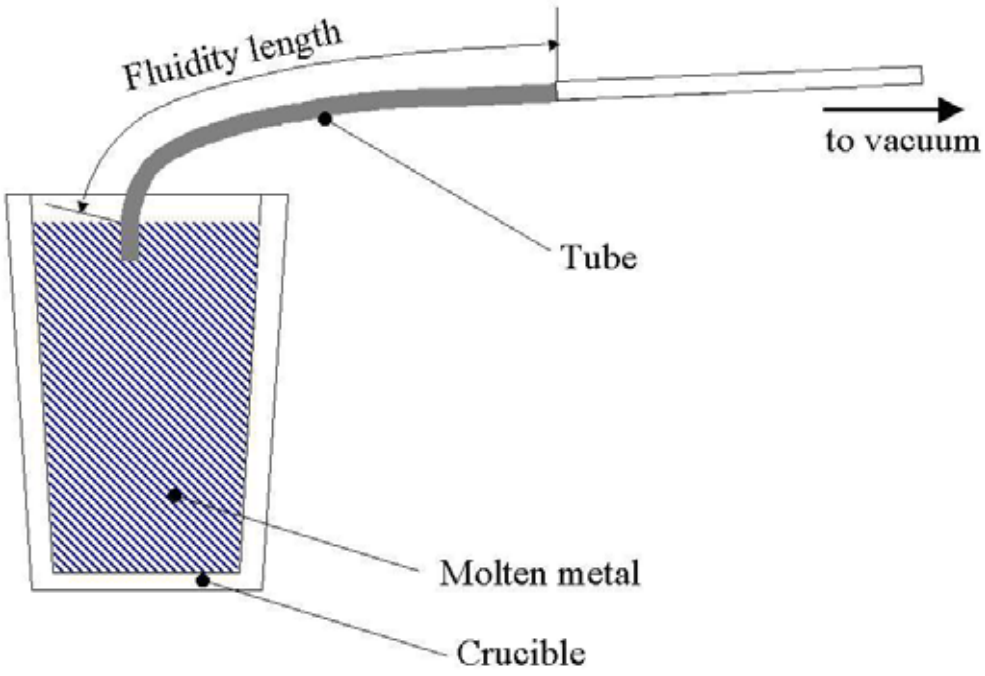


Figure 4. Schematic representation of the device for the evaluation of vacuum fluidity length.

3. RESULTS AND DISCUSSION

Simulation

Figure 5 shows the results of the simulations with the mesh size as a variable and the other parameters (alloy, HTC, casting temperature, coherency temperature) constant. It was found that three millions control volumes must be used as mesh size because from this value the fluidity length *versus* mesh curve

shows a *plateau*, *i.e.* further increase on the mesh will not significantly affect the results.

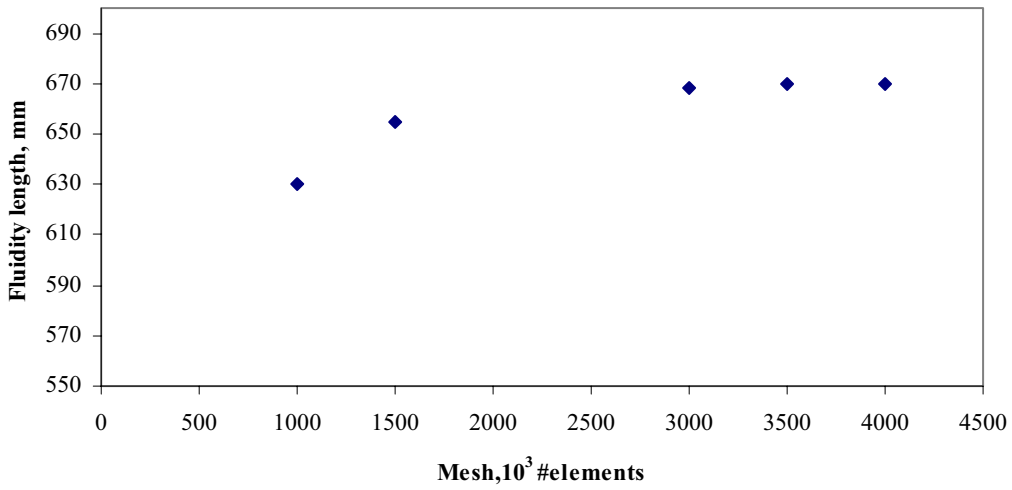


Figure 5. Results of the simulations of the fluidity test with the mesh as a variable.

Figure 6 shows the influence of the heat transfer coefficient (HTC) on fluidity. The increase in the value of the heat transfer coefficient decreases fluidity. The HTC describes the rate at which heat is lost through the casting and the mould. High HTC means that the casting freezes faster and hence fluidity decreases, and *vice-versa*. Figure 7 shows the influence of casting temperature on fluidity of the A356 alloy. According to the simulation results, the fluidity increases with the casting temperature in the range 700-730°C. Figure 7 also shows the line of best fit (trend line) which suggests the following equation for the calculation of the fluidity length:

$L_f = 3.3T - 1660$ (1)

where L_f is the fluidity length, in mm, and T is the casting temperature, in °C. Consequently, an increase in the pouring temperature by 1ºC, in the interval 700–730ºC, gives an increase in the fluidity length equal to approximately 0.6%.

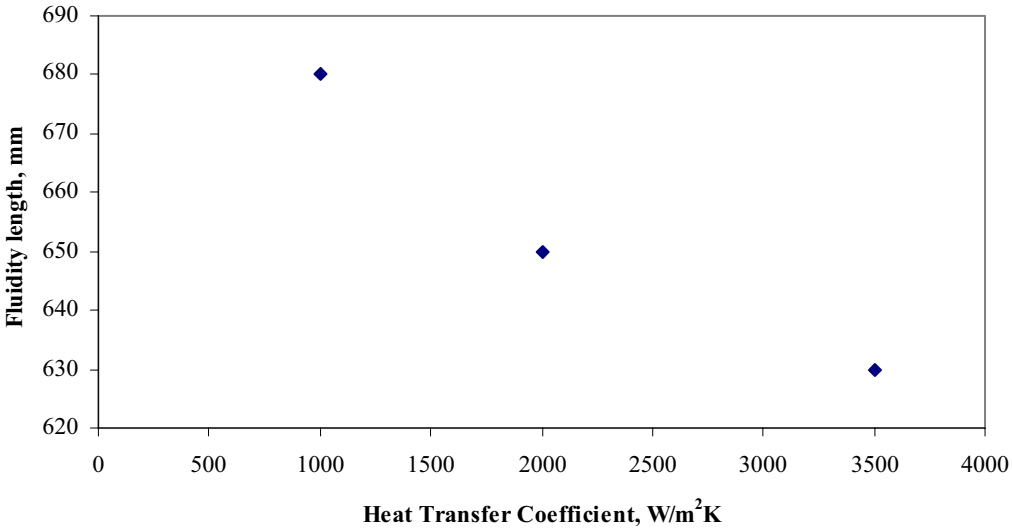


Figure 6. Results of the simulations of the fluidity test when the heat transfer coefficient at the casting/sand mould interface is a variable.

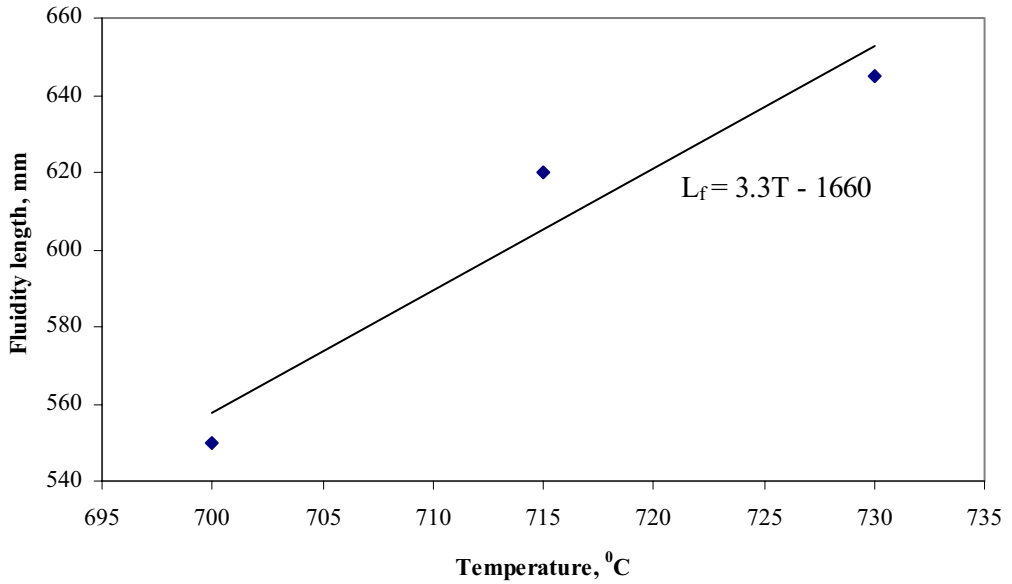


Figure 7. Results of the simulations of the fluidity test with the casting temperature as a variable.

Experimental fluidity tests (spiral cavity)

Figure 8 shows the experimental results of the influence of casting temperature on fluidity of the A356 alloy. The experimental results show that fluidity linearly increases with the temperature and the trend line is:

$L_f = 5.6T - 3480$ (2)

Consequently, the increase in the pouring temperature by 1ºC, in the interval 700–730ºC, has given an increase in the fluidity length equal to approximately 1%. This value is close to the results from previous authors [20, 21, 22].

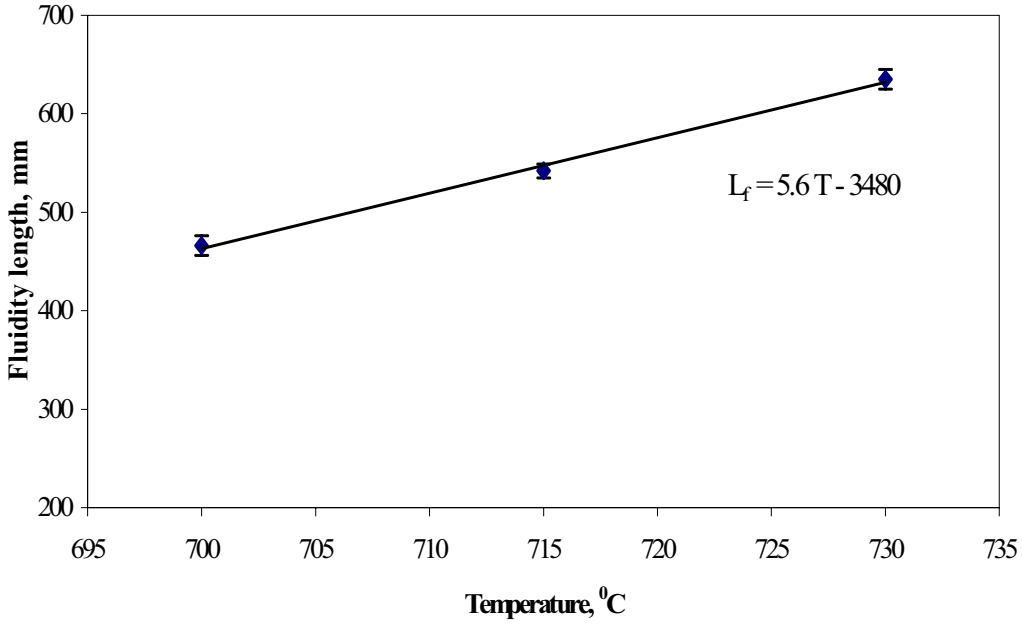


Figure 8. Experimental results of the fluidity measurements with the spiral moulds showing the fluidity length *versus* temperature curve. The statistical error bar and the best fit equation (trend line) are also shown.

Spiral cavity *versus* vacuum fluidity tests

The results of the vacuum fluidity tests on the A356 alloy are shown in Figure 9. With respect to the spiral fluidity test, the absolute values of the fluidity lengths, defined in the vacuum case as L_f', are different, due to the intrinsic

difference between the two methods. However, a similar linear dependence of fluidity with temperature is shown. This study has, therefore, confirmed that different fluidity test methods, such as the spiral test and vacuum test, may give consistent results. For the vacuum fluidity test, in the 700-730°C temperature interval, a 1°C increase in temperature produces an average increase in fluidity of about 0.9%.

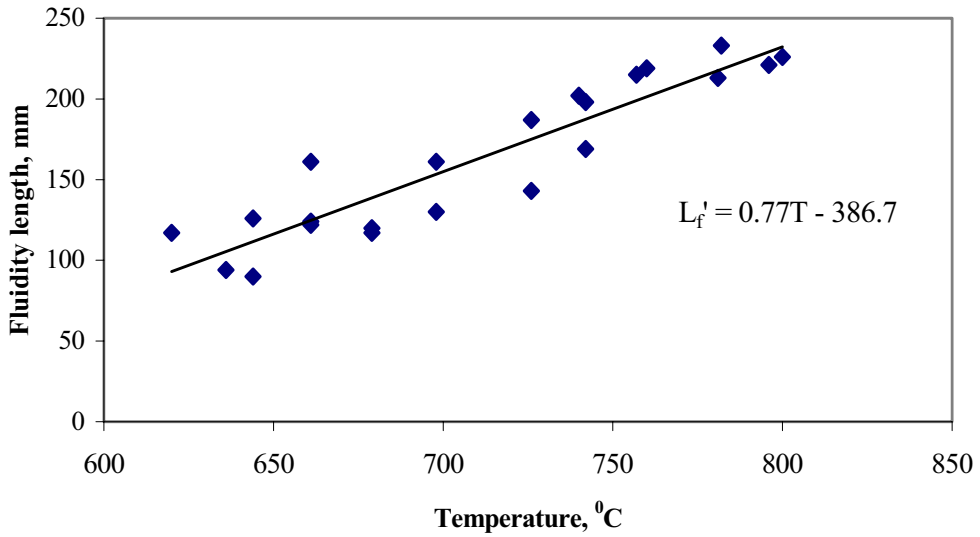


Figure 9. Experimental results of the fluidity measurements with the vacuum method, showing the fluidity length *versus* temperature curve and its trend line for the A356 alloy investigated.

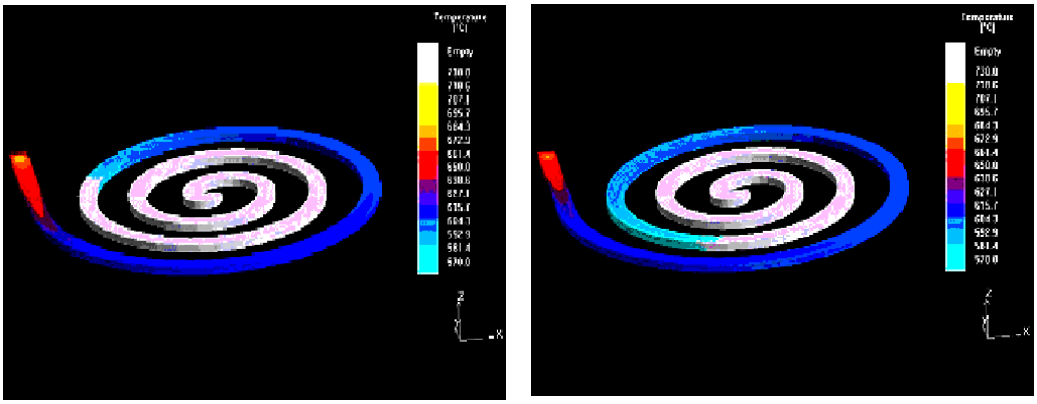
Simulation *versus* spiral cavity fluidity test

Table 4 compares the results from the simulation runs and spiral tests. The length of simulated spirals, the average length of the experimental spirals with their standard deviation in the mean values, σ_m, were measured. Clearly, the simulation predictions fit well with the experimental results as it is shown in Figures 10 and 11. The results from the simulation runs at 700ºC and 730ºC are consistent with the experimental results from the spiral tests at the same casting temperatures. Figure 12 shows the influence of the coherency temperature (Tc) on fluidity. Three values of Tc have been investigated, namely 560, 580 and 600ºC. These temperatures for the A356 alloy investigated correspond to

coherency fraction solid (f_c) of 90%, 46% and 30%, respectively. Increasing the coherency temperature causes the dendrites to impinge earlier during solidification and hence the formation of a solid skeleton, which stops the metal flow, happens earlier. Accordingly, the increase in the value of Tc decreases fluidity.

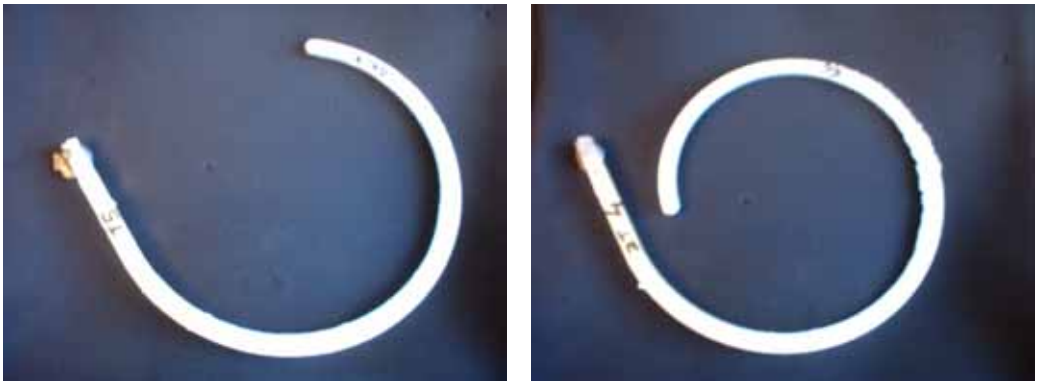
Table 4 Comparison between the results from the simulation runs and spiral tests. The results from three casting temperatures are compared: the length of simulated spirals, and the average length of the experimental spirals with their standard deviation in the mean values, σ_m, are measured.

Temperature [°C]	**Simulation runs** **Length,** $\bar{x}$ **[mm]**	**Spiral tests** **Average length,** $\bar{x} \pm \sigma_m$ **[mm]**
700	550	460±10
715	620	542±7
730	645	630±10



a) b)

Figure 10. Simulation results of fluidity at a) 700ºC, fluidity length 550mm; and b) 730ºC, fluidity length 645mm.



a) b)

Figure 11. Experimental results from the spiral tests at a) 700ºC, fluidity length 460 mm; and b) 730ºC, fluidity length 630mm.

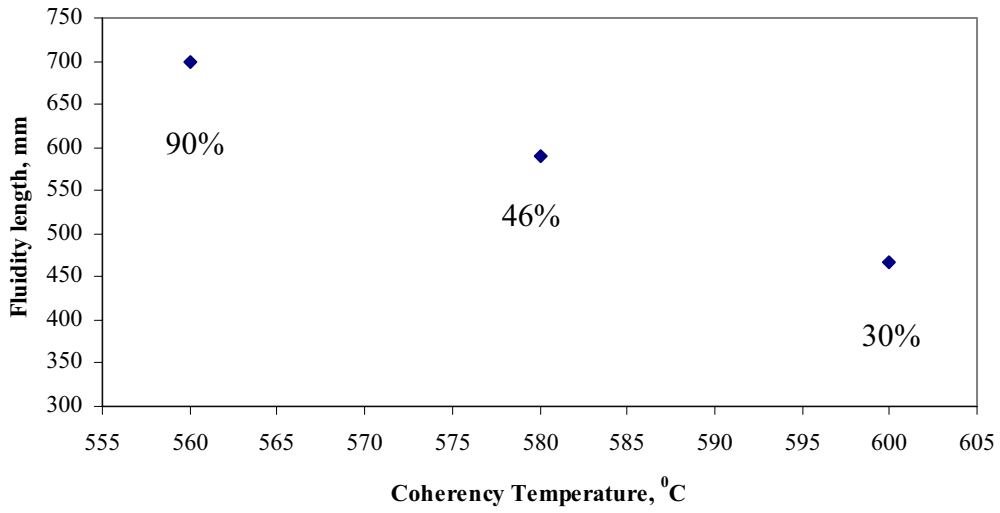


Figure 12. Results of the simulations of the fluidity test with coherency temperature as a variable. Three coherency temperatures are used and the corresponding coherency fraction solid (f_c) are shown.

4. CONCLUSIONS

This investigation has led to the following conclusions:

1. The simulation predictions fit well with the experimental results and, therefore, numerical simulations can be a useful tool for predicting the fluidity of Al alloys.
2. Increasing the casting temperature increases the fluidity length of the A356 alloy. The simulation results are in agreement with the experimental results using both the spiral test and the vacuum test methods.
3. The increase of the heat transfer coefficient and coherency temperature causes a decrease in the fluidity length of the A356 alloy.

ACKNOWLEDGEMENTS
Dr. Freddy Syvertsen and Mr. Raimo Helenius are acknowledged for helping with MAGMAsoft® simulations. The present work was funded by the project NorLight Shaped Castings of Light Metals with the following partners: Alcoa Automotive Castings, Scandinavian Casting Center; Elkem Aluminium; Fundo Wheels; Hydro Aluminium Metal Products; Hydro Magnesium; the Netherlands Institute for Metals Research; Norwegian University of Science and Technology; and SINTEF. The authors thank the industrial partners and the Norwegian Research Council for financial support.

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