

# SIMULATION OF FLUIDITY IN AL-SI ALLOYS

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## **Abstract**

In this study, MAGMA soft™ commercial software package was used to simulate the fluidity of A356 alloy. Established an optimum mesh generation, the influence of important metallurgical parameters, such as heat transfer coefficient, casting temperature and coherency temperature, on fluidity were simulated. The simulation results were compared with fluidity laboratory tests carried out with spiral-shaped sand moulds and the results from the simulations 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 qualità e bassi costi costituiscono continue sfide per le moderne fonderie. I programmi di simulazione stanno acquistando sempre più importanza nelle fonderie come strumento per migliorare e ottimizzare i loro processi di produzione, sistema di controllo e qualità. In questo studio, MAGMA soft™ viene utilizzato per lo studio della fluidità/colabilità della lega A356. Lo scopo di questo lavoro è 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 T<sub>c</sub>). I risultati delle simulazioni sono stati confrontati con quelli sperimentali sulla lega A356. Lo strumento impiegato per misurare la fluidità è stato recentemente sviluppato al SINTEF in Norvegia. I risultati hanno dimostrato che le simulazioni riproducono molto bene i risultati sperimentali e che, quindi, MAGMA soft™ può essere un utile strumento per predire la fluidità/colabilità 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.

## 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 those 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-Stoke equation). 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. The physical and metallurgical phenomena are then described by theoretical equations, numerical analysis follows and, eventually, results lead to the description of the fluid-dynamic field, thermal field and microstructure evolution. Figure 1 presents the 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 the 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 aluminum foundry alloys, A356.

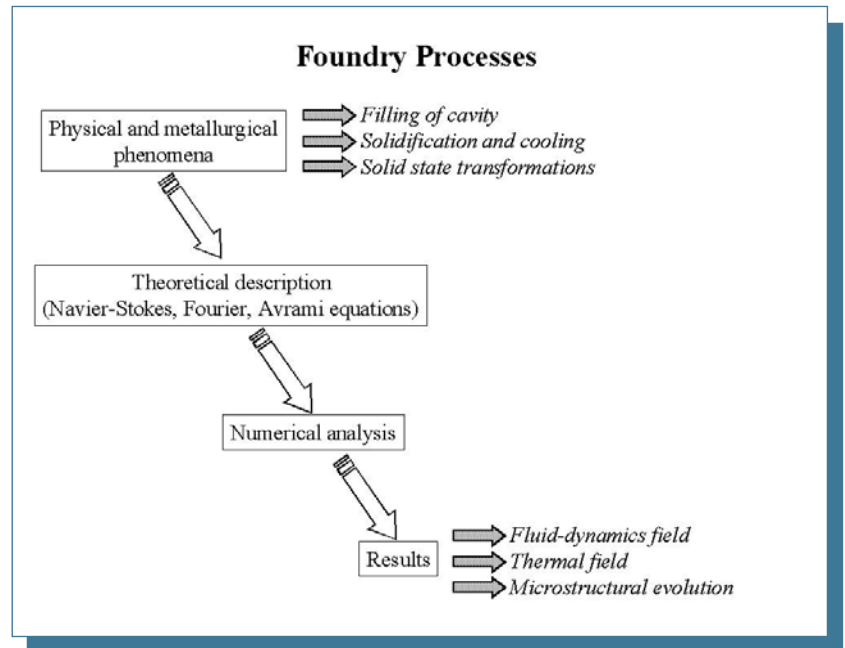


Fig. 1: Flow chart of the main steps in modeling foundry processes [1].

During simulation, for a given set of conditions, a higher number of elements in a simulation process may change the results. The effect of mesh generation on the simulation results was taken into account and, once the optimum mesh generation was established, the influence of important metallurgical parameters, such as heat transfer coefficient, casting temperature and coherency temperature, upon fluidity were 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 aluminum 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 upon 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, where the individual dendrites start to impinge upon their neighbors [12] which means that a solid network forms, and hence the fluid flow stops. The temperature at this point is called dendrite coherency temperature ( $T_c$ ) 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.

## NUMERICAL SIMULATIONS AND EXPERIMENTAL TESTS

The investigations carried out in the present work consisted of both numerical simulations and experimental fluidity tests. MAGMA soft commercial software package was used for numerically simulating the fluid flow of molten metal into spiral-shaped sand moulds. MAGMA soft 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 parameter 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 values and constants used in the experimental trials. 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

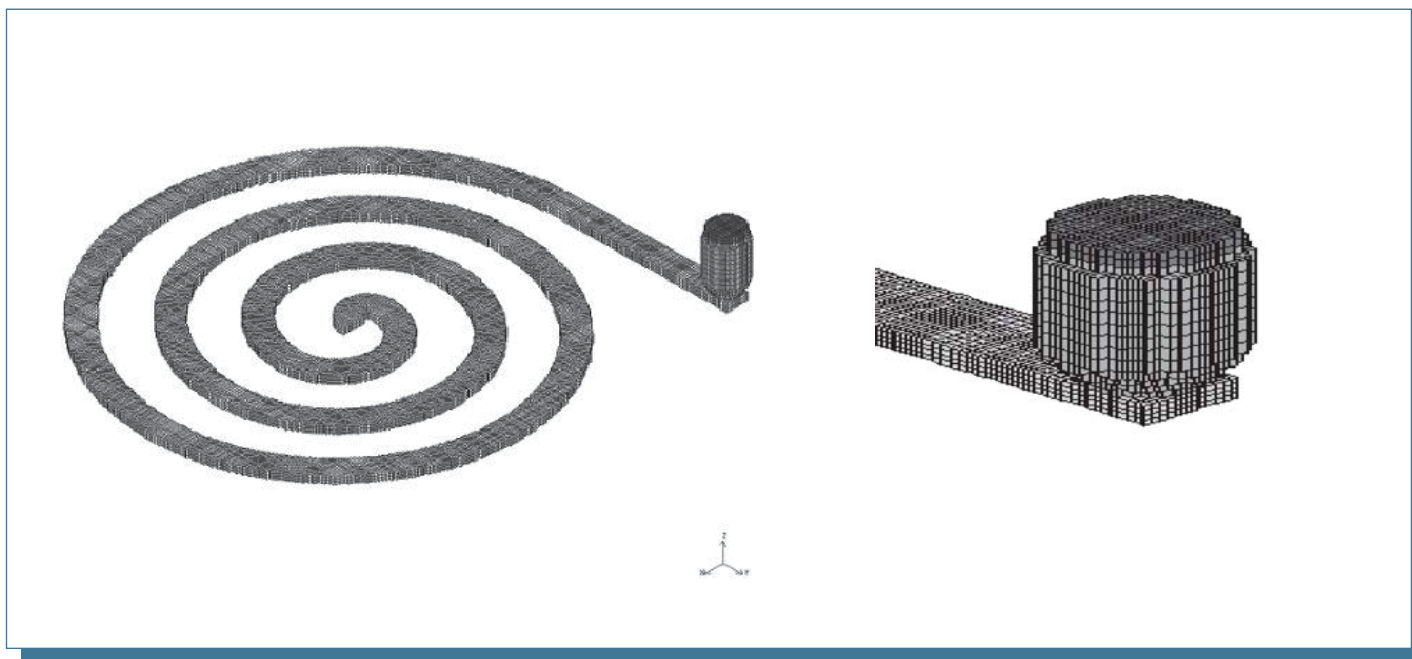


Fig. 2: Geometry and mesh: a) inlet, pouring cup and spiral; b) higher magnification to show the mesh quality.

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 <sup>2</sup> K Casting Temperature: 700°C T <sub>c</sub> : 600°C (f <sub>c</sub> =30%)
	1000000	1500000	3000000	3500000	
2	Heat Transfer Coefficient, HTC, W/m <sup>2</sup> K				Alloy: A356 Casting Temperature: 700°C Mesh: 3 *10 <sup>6</sup> elements T <sub>c</sub> : 600°C (f <sub>c</sub> =30%)
	3500	2000	1000		
3	Casting temperature, °C				Alloy: A356 HTC: 3500 W/m <sup>2</sup> K Mesh: 3 *10 <sup>6</sup> elements T <sub>c</sub> : 600°C (f <sub>c</sub> =30%)
	650	700	750		
4	Coherency Temperature, T <sub>c</sub> , °C				Alloy: A356 HTC: 3500 W/m <sup>2</sup> K Casting Temperature: 700°C Mesh: 3 *10 <sup>6</sup> elements
	560	580	600		

alloy. Table 2 shows the physical constants and properties of the A356 alloy [15] for the experimental trials. Coldbox at 20 °C was chosen as sand mould material in the MAGMA soft'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 upon the metallostatic pressure, which was calculated from the geometry of the equipment and experimental conditions; the stop criteria was based on the coherency temperature,  $T_c$ . 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  $T_c$  of 600°C [17].

In detail, the simulations consisted of a 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 °C. 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.

The molten metal was poured into a pouring cup and when its temperature, measured by a thermocouple placed in the cup, reached a pre-set 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.

TABLE 2. PHYSICAL CONSTANTS AND PROPERTIES OF THE A356 ALLOY FOR THE EXPERIMENTAL TRIALS [14].

Density of liquid (kg/m <sup>3</sup> )	2340
Density of solid (kg/m <sup>3</sup> )	2520
Liquidus (°C)	614
Solidus (°C)	542
Viscosity of liquid metal (Pa s)	1.3×10 <sup>-3</sup>

TABLE 3. MESH GENERATION FOR THE SIMULATION RUNS.

Mesh generation		
Method	Automatic	
Mesh size	Control Volumes, CVs	2984618
	Metal cells	112539

TABLE 4. COMPARISON BETWEEN THE RESULTS FROM THE SIMULATION RUNS AND SPIRAL TESTS. THE RESULTS FROM THREE CASTING TEMPERATURE ARE COMPARED: THE LENGTH OF SIMULATED SPIRALS, AND THE AVERAGE LENGTH OF THE EXPERIMENTAL SPIRALS WITH THEIR STANDARD DEVIATION IN THE MEAN VALUE,  $\bar{\sigma}_m$ , ARE MEASURED.

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

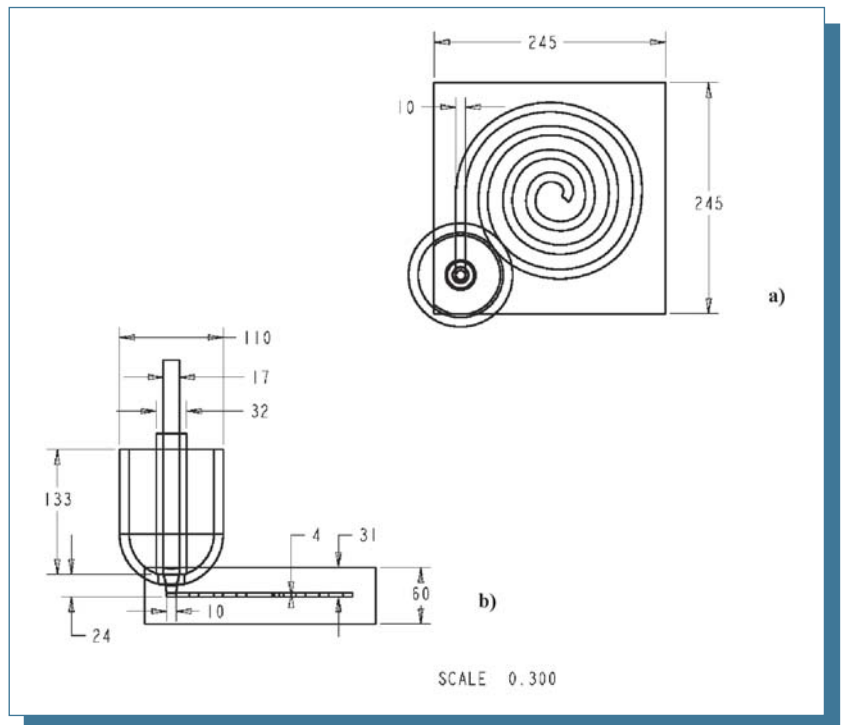


Fig. 3: Drawing of the equipment for the fluidity tests: a) plan view of the pouring cup and sand mould, and b) side section through the stopper rod and the sand mould. (All dimensions are in mm).

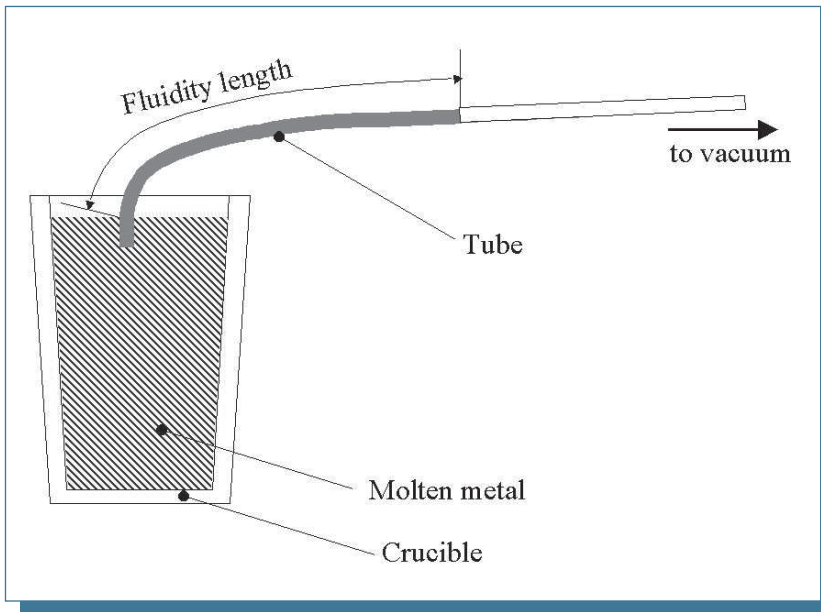


Fig. 4: Schematic representation of the device for the evaluation of vacuum fluidity length.

Furthermore, the results of the fluidity tests were compared to those recently achieved by Bonollo *et al.* [19], using a 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.

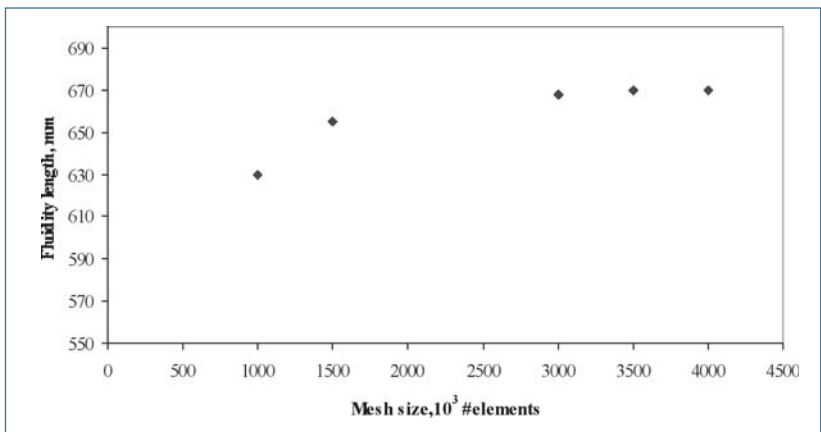


Fig. 5: Results of the simulations of the fluidity test with the mesh size as a variable.

## 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 million control volumes must be used as the mesh size because from this value the fluidity length vs mesh curve shows a plateau, i.e. further increase on the mesh will not significantly affect the results. Figure 6 shows the influence of the heat transfer coefficient (HTC) upon fluidity. Increasing 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 upon the 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:

$$L_f = 3.3T - 1660 \quad (1)$$

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 1°C, in the interval 700 – 730 °C, gives an increase in the fluidity length equal to approximately 0.6%.

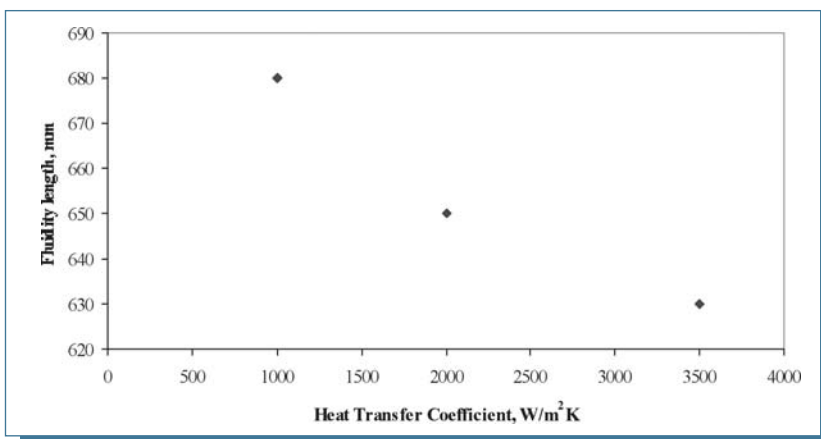


Fig. 6: Results of the simulations of the fluidity test when the heat transfer coefficient at the casting/mould interface is a variable.

**EXPERIMENTAL FLUIDITY TESTS  
(SPIRAL CAVITY)**

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

$$L_f = 5.6T - 3480 \quad (2)$$

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

**SPIRAL CAVITY VS VACUUM FLUIDITY TESTS**

The results of vacuum fluidity tests on the A356 alloy are shown in Figure 9. With respect to 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, can 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 of fluidity of about 0.9%.

**SIMULATION VS SPIRAL CAVITY FLUIDITY TEST**

Table 4 compares the results from the simulation runs and those from the spiral tests. The length of simulated spirals, the average length of the experimental spirals with their standard deviation in the mean values,  $\sigma_m$ , were measured. Clearly, the simulation predictions fit well with the experimental results as it is shown in Figure 10. The results from the simulation runs at 700°C and 730°C are consistent with the experimental results from the spiral tests at the same casting temperature. Figure 11 shows the influence of the coherency temperature ( $T_c$ ) upon fluidity. Three values of  $T_c$  have been investigated, namely 560, 580 and 600°C. These temperatures for the A356 alloy investigated correspond to a fraction solid ( $f_c$ ) of 90%, 46% and 30%, respectively. Increasing the coherency temperature causes the dendrites to impinge earlier during solidification, and hence solid skeleton, which stops the metal flow, forms earlier. Accordingly, increasing the value of  $T_c$  decreases fluidity.

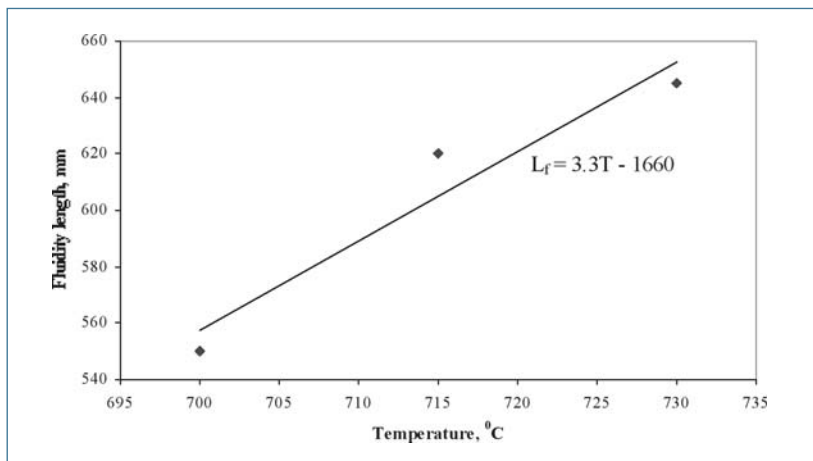


Fig. 7: Results of the simulations of the fluidity test with the casting temperature as a variable.

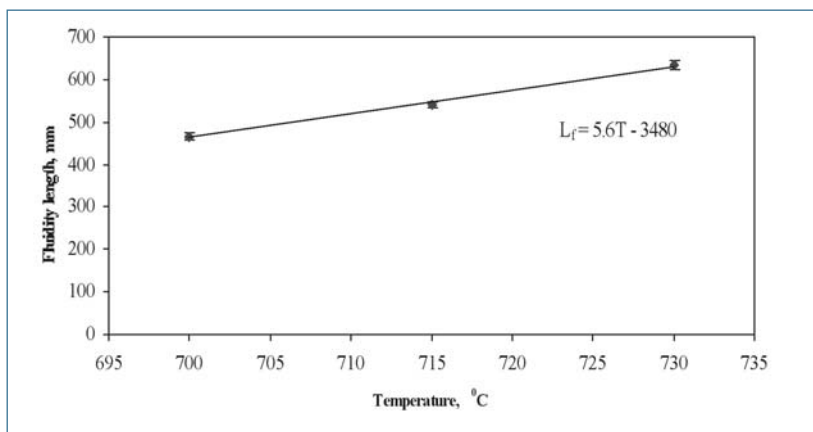


Fig. 8: Experimental results of the fluidity measurements with the spiral moulds showing the fluidity length vs temperature curve. The statistical error bar and the equation of the line of best fit (trend line) are also shown.

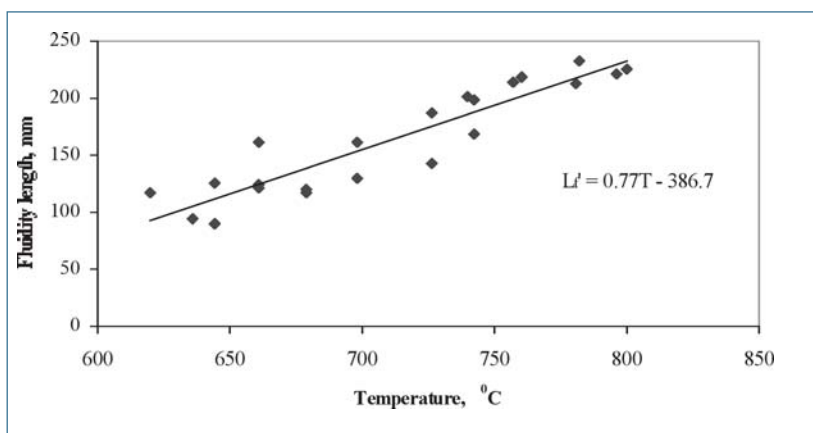


Fig. 9: Experimental results of the fluidity measurements with the vacuum method, showing the fluidity length vs temperature curve and its trend line for the A356 alloy investigated.

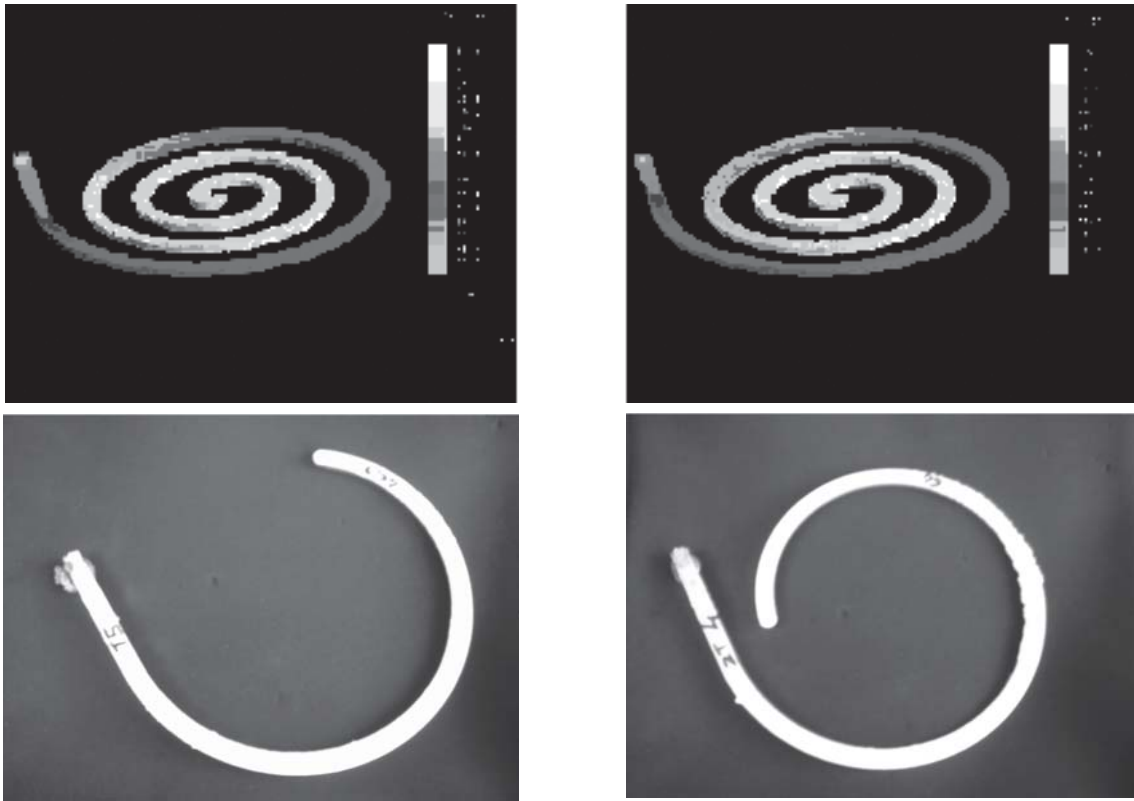


Fig. 10: Simulation results of fluidity at a) 700°C fluidity length 550 mm, and b) 730°C fluidity length 645mm; and experimental results from the spiral tests at c) 700°C fluidity length 460 mm, and d) 730°C fluidity length 630 mm.

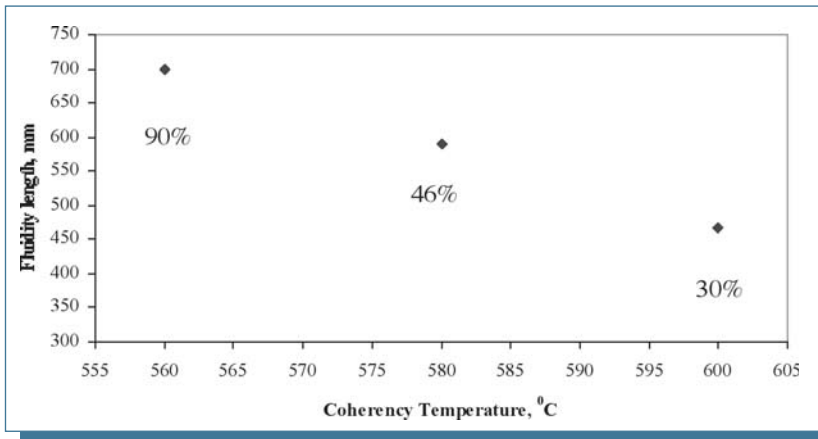


Fig. 11: Results of the simulations of the fluidity test with coherency temperature as a variable. Three coherency temperatures are used and the corresponding coherency fractions,  $f_c$ , are shown.

## 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 in heat transfer coefficient and coherency temperature causes a decrease in the fluidity length of the A356 alloy.

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