Fluidity of Aluminium Foundry Alloys: Development of a Testing Procedure

D. Caliari, G. Timelli, F. Bonollo, P. Amalberto, P. Giordano

The aim of this work is the study and the development of a specific testing methodology for evaluating the fluidity of aluminium foundry alloys. This method, based on the Archimedean spiral, is intended to be easily and practically used in foundry. The necessary device to perform the tests is made by sand moulds and it reproduces the Archimedean spiral cavity where the molten alloy is poured. An A356 alloy has been used and a series of tests has been carried out with the purpose to make the methodology operative according to a standardized operating sequence. The focus has been the maximum repeatability of the results. Fluidity tests, carried out at different molten metal temperature, have been performed both on the laboratory scale and within a foundry plant, and they have concerned either the EN standard alloy and the grain refined and Sr-modified one. Finally, a specific experimental test has been numerically studied by means of a commercial process simulation software. The obtained results suggest to increase appropriately the initial temperature of the bath to improve the repeatability of the experiments. Furthermore, thin section of the spiral cavity induces high cooling rates able to prevail over the effects of preliminary treatments of the molten bath.

Keywords: Aluminium alloy - Fluidity - A356 - Foundry - Archimedean spiral - Methodology

INTRODUCTION

Among the physical properties characterizing a metallic material at the liquid state there is definitely the *fluidity*, which indicates the capability of a molten metal to flow into a mould cavity during its cooling. This property significantly affects the different foundry processes because it directly influences the mould filling stage, and consequently the integrity and the final quality of castings. Poor fluidity induces a difficult filling and increases casting defects. An incomplete casting is rejected and this corresponds always to an economic loss in any production context. These considerations evidence how the fluidity could greatly impact on a production reality, and, consequently, this gives an idea about the importance of a thorough study on this topic. Despite the importance of this property, the knowledge on the fluidity and the presence of experimental data are still limited; in particular, many aspects of the testing procedure are still poorly understood and detailed information are available only for few families of materials. Among the reasons that may explain this deficiency, there is currently a lack of an universally accepted and standardized method to measure the fluidity of an alloy [1]. This lack of knowledge affects not only the research laboratories but also the industrial world, and it makes difficult a reliable and objective comparison between different materials and castings, thus hindering the development of strategies to improve the fluidity.

Most of the historically developed testing methods shows poor repeatability of the results due to "*interferences*" occurring during trials; this implies an excessive variability of the results among tests carried out under the same *apparent* conditions. Therefore, the traditional methods are affected by poor reliability and this can explain the reasons of contradictory data in literature [2].

This work is aimed at developing a specific fluidity testing method for Al foundry alloys, which is based on an easy and practical procedure to be used in foundry. The implemented procedure is based on the Archimedean spiral testing. The experimental results obtained and discussed

Daniele Caliari*, Giulio Timelli, Franco Bonollo
University of Padova,
Department of Management and Engineering,
Stradella S. Nicola, 3 I-36100 Vicenza, Italy.
(Daniele Caliari: caliari@gest.unipd.it
Giulio Timelli: timelli@gest.unipd.it
Franco Bonollo: bonollo@gest.unipd.i

Paolo Amalberto, Paola Giordano
GE-Avio Aero – Getti Speciali Srl
Via Rondò Bernardo, 15 I
10092 Borgaretto di Beinasco (TO), Italy.
Paolo Amalberto: paolo.amalberto@avioaero.com
Paola Giordano: paola.giordano@avioaero.com

Corresponding author: **D. Caliari*
Tel.: 00 39 0444 998769; fax. 00 39 0444 998889.
E-mail address: caliari@gest.unipd.it

in the present work do not have the purpose to evaluate the fluidity of a specific alloy, but to study the repeatability of the results under different operating conditions and to determine how the result of a single test may represent the real physical property of the analysed alloy.

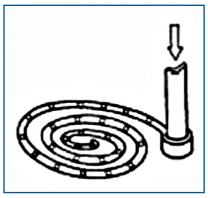
THEORETICAL ASPECTS: DEFINITION AND MEASUREMENT OF FLUIDITY

The *fluidity* of an alloy is a complex physical and technological property that depends on many factors. In physics, the fluidity is defined as the inverse of the viscosity [2,3], but it is expressed with measures not easily intuitive and practically usable. This feature showed the need to formulate an alternative definition of the fluidity in order to make it more easily measurable in foundry. Therefore, the fluidity has been empirically reformulated as "*the maximum distance (L_f) that a metal treads before solidifying in a standard cavity of constant section formed in a mould*" [2-4].

Most of the testing methods developed to measure the fluidity of an alloy is based on the relationship between the fluidity and the L_f value, so this property can be quantitatively evaluated by simply measuring a distance [2-5]. Several devices have been historically developed to reproduce mould cavities with different geometry, such as the Archimedean spiral shape and the straight one. Among the disadvantages limiting the use of these traditional tests, there exists a poor repeatability affecting the reliability of the methods.

Repeatability of results means the ability of a method to provide the same fluidity value performing different tests under the same conditions. This attitude depends not only on the intrinsic accuracy of the method, but also on the precision, i.e. the ability to accurately reproduce the defined testing conditions. The traditional procedures are very sensitive to the casting variables that are difficult or impossible to control rapidly and practically. Moreover, the lack of standard protocols designed to define the operating procedures generates a great variability of the boundary conditions during the experiments, with negative consequences in terms of reliability and repeatability. These problems afflict also the Archimedean method, even if several developments and arrangements have been recently achieved in order to improve the repeatability of the test [2]. The Archimedean method is based on a compact system, which, compared to other testing types, can be easily used inside a foundry environment. The spiral-like cavity could be obtained in a sand mould or shell. Figure 1 shows a draft and an example of an Archimedean spiral.

The fluidity of an alloy is a property particularly sensitive to the temperature, which is one of the most critical variable to be controlled and monitored during testing due to the rapid cooling of the liquid metal during the manual operations of tapping and pouring. In order to compare the fluidity of different alloys, it is essential to test the material at the same melt superheat.



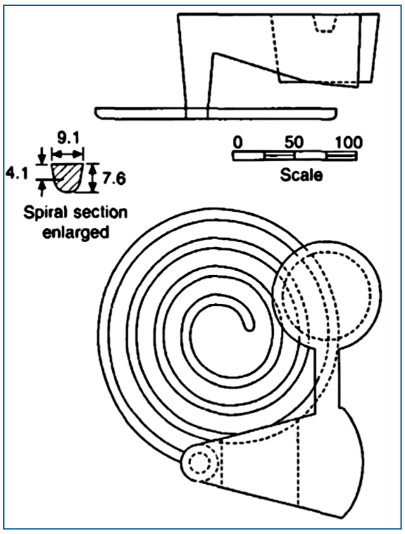


Fig. 1 - (a) Schematic representation of a spiral fluidity test [2]; (b) example of a spiral test configuration [4].

DESCRIPTION OF THE IMPLEMENTED METHODOLOGY

In this section, an operative sequence based on a specific experimental device and aimed to minimize the interferences influencing the fluidity is described. Thus, the final result will be a complete methodology able to ensure good repeatability and significance of the results, conciliating these objectives with a practical and functional execution.

In Figure 2 the different components of the equipment used in the present work are shown:

- quartz sand *cope* and *drag* (Figures 3 and 4), where the cavity reproducing the spiral geometry was obtained;
- quartz sand *pouring basin* (Figure 4), which is placed over the *cope*;
- *stopper*, made by steel, is used to interrupt the connection between the pouring basin and the spiral cavity; when the metal reaches a defined temperature, the stopper is removed, allowing the outflow of the metal through the ingate.

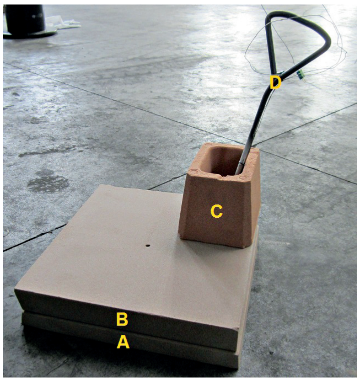


Fig. 2 - Main components of the test equipment: (A) drag, (B) cope, (C) pouring basin and (D) stopper.

The operator decides when removing the stopper by observing the molten temperature detected near the spiral ingate. The temperature monitoring is essential to keep the testing temperature as constant as possible between

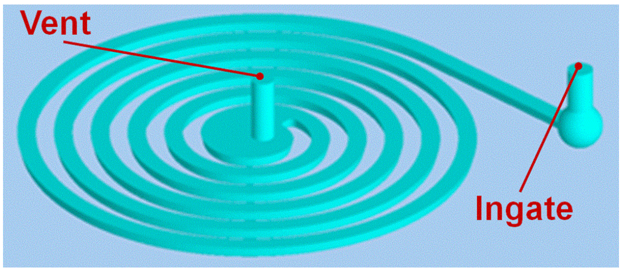


Fig. 3 - Archimedean spiral geometry obtained in the drag.

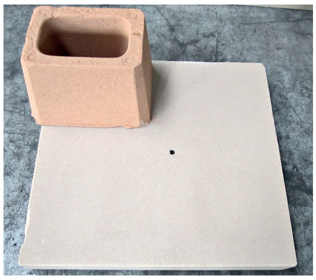


Fig. 4 - Pouring basin located over the cope at the spiral ingate.

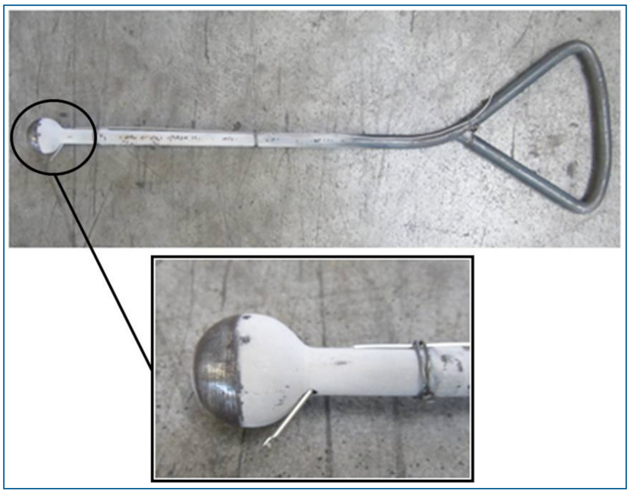


Fig. 5 - Thermocouple located close to the stopper.

different trials performed under the same conditions. A K-type thermocouple was fastened to the stopper as shown in Figure 5. This configuration ensures that the thermocouple is always located 5 mm far from the bottom of the basin and 5 mm from the spherical seat; further, it allows to easily place the stopper in the same position, thus avoiding influences due to the different positioning of the thermocouple.
The cope, drag and pouring basin were made by coldbox sand, which is compacted through mechanical force and catalyzed with sulfur dioxide. The stopper was coated with a refractory paste in order to reduce the heat loss and to facilitate the cleaning operations after each pouring.
An ideal testing method should carefully monitor all the variables that can affect the fluidity, especially temperature, with the aim to limit undefined fluctuations of the variables: these fluctuations would have deleterious consequences in terms of results' comparability. However, during an experimental campaign this objective is not easy to be achieved, especially if the testing method is thought to be practical and easy to be used in an industrial context.
The variety of variables influencing the alloy's fluidity makes the control of this property very complex [1,2,4,6-11]: pouring and mould temperatures, geometry and cross section of the mould cavity, surface tension, thermal conductivities of both metal and mould, metal-mould heat transfer coefficient, chemical composition and solidification interval, cleanliness of the bath (inclusions, oxides), flow rate, metallostatic pressure, environmental conditions (temperature, humidity).
In the present work, the control of the variables affecting the fluidity were performed by using both direct monitoring, such as the temperature measurement by means of thermocouples, and a proper protocol that consisted on standardized operations to homogenize disorders due to not-controlled variables. A standardized preheat of the pouring ladle, performed in the same way and for the same time in all the tests, is an example of such protocol. All not-controlled variables (room temperature, humidity, etc ...) constitute inevitably "noise" acting on the system and adversely affecting the repeatability of the results.
The specific operative protocol is hereafter described, including in the discussion the components used:

- the environmental temperature ranged between 6 and 12°C;
- the alloy was melted in an electric resistance furnace with a 12 kg graphite crucible;
- a steel ladle with a capacity of 2 kg was used for pouring;
- the temperature monitoring was performed by using K-thermocouples (□1 mm) protected with Inconel 625 tube;
- the bath level in the crucible was maintained constant: this attention was paid to limit the temperature oscillations of the bath due to the immersion of the ladle;
- the mould temperature was indirectly controlled by performing the experimental campaign in the same environment and period;
- the filling operation of the pouring basing was standardized;
- the thermocouple located close to the stopper was placed in the same direction with respect to the pouring direction;
- the slag was periodically removed from the bath surface and before each casting operation.

The operative sequence can be divided into the following stages:

1) *preheating the stopper*, the stopper is previously preheated over the furnace for 10 minutes; this operation allows to reduce the temperature difference

between the molten metal and the stopper, with the aim to limit the heat loss of the metal into the pouring basin; this solution allows to improve the temperature homogeneity in the basin and to reduce the cooling rate;

2) *preheating the ladle*, the ladle is previously preheated with a flame for 3 minutes;
3) *drawing the metal from the bath*, the casting ladle is submerged into the bath for 10 seconds in order to reduce the metal cooling inside the ladle during the transfer from the crucible to the pouring basin; the ladle is always filled at the maximum level to standardize the interferences on the metal temperature and to get a constant metallostatic pressure in the basin;
4) *pouring into the basin*, the metal is always poured into the basin in the same region and from the same side in order to reduce different filling dynamics;
5) *temperature monitoring with a thermocouple fastened to the stopper*, an operator controls the temperature of the metal detected by a thermocouple with a digital equipment;
6) *stopper removal at the desired temperature*, when the temperature of the metal reaches the desired value, the operator removes the stopper to allow the flow through the ingate;
7) *cleaning of the stopper*;
8) *moulds opening and casting removal*.

In the present work, a key function is to obtain a homogeneous temperature distribution of the molten metal inside the pouring basin because this will allow a metal outflow through the ingate at constant temperature (except for the progressive and inevitable cooling of the bath), and consequently better repeatability of the data. About this, the advantage of a preheated stopper than a cold one is visible in Figure 6, where the monitoring of two preliminary pouring operations with and without stopper preheating is shown.

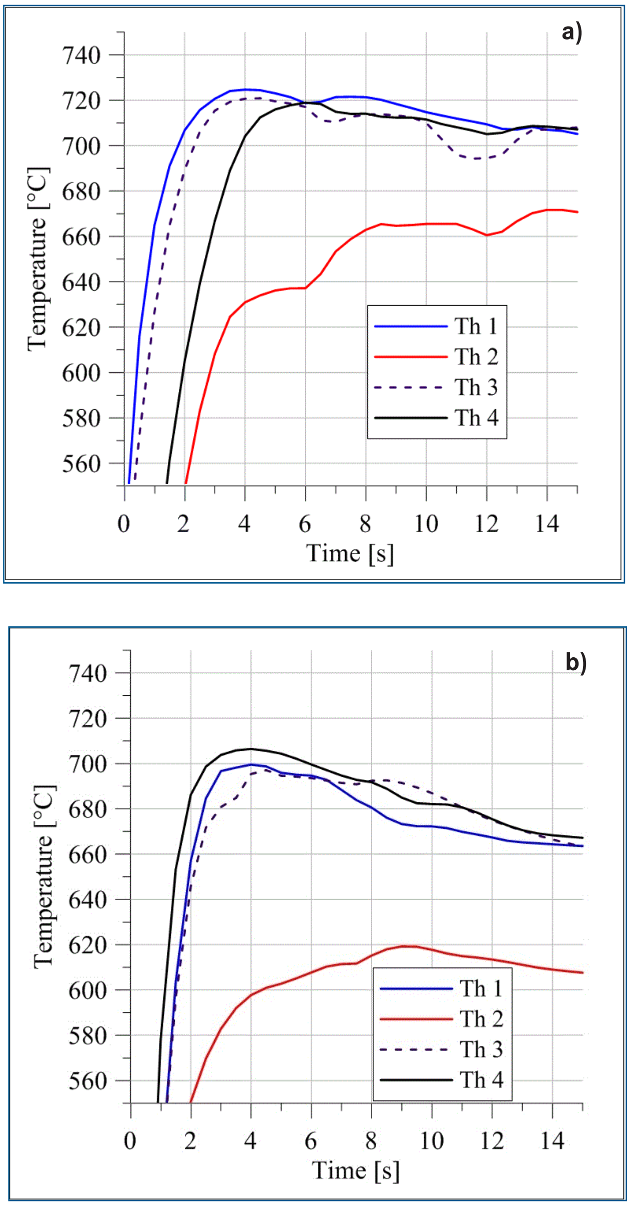


Fig. 6 - Temperature profiles detected during two different operations of pouring into the basin, respectively (a) with and (b) without stopper preheating; thermocouples are numbered as indicated in Figure 7.

Assessment of repeatability

This work was completed by a series of experimental tests designed to evaluate the repeatability of the results under various experimental conditions, which were carried out with the aim to identify the variables' combination that allowed the best accuracy. Some variables, affecting significantly the fluidity such as the bath temperature or the holding time in the pouring basin before the stopper removal, were systematically varied during the application of the aforementioned procedure. On the other hand, the variation of other variables, such as the filling of the basin, were ignored and therefore considered as constant.

The fluidity tests were performed by using an A356 foundry alloy (equivalent to the designation EN AB-42100), whose chemical composition is shown in Table 1.
Several tests were performed with different molten metal temperature to asses the impact on the repeatability of the results. Regarding the holding time of the metal into the pouring basin before the stopper removal, two diffe-

Si	Fe	Cu	Mn	Mg	Zn	Ti	Ca	Sr	Na	B	Al
6.797	0.0645	0.0007	0.0002	0.288	0.0078	0.129	0.0009	0.0003	0.0006	0.0001	bal.

Table 1 - Chemical composition of the A356 alloy used in the present work (wt.%).

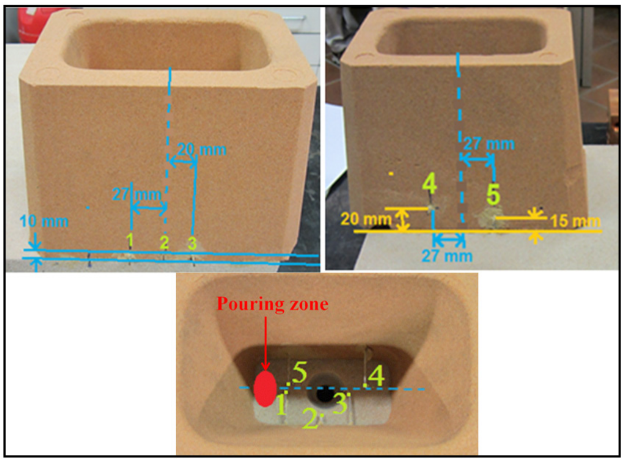


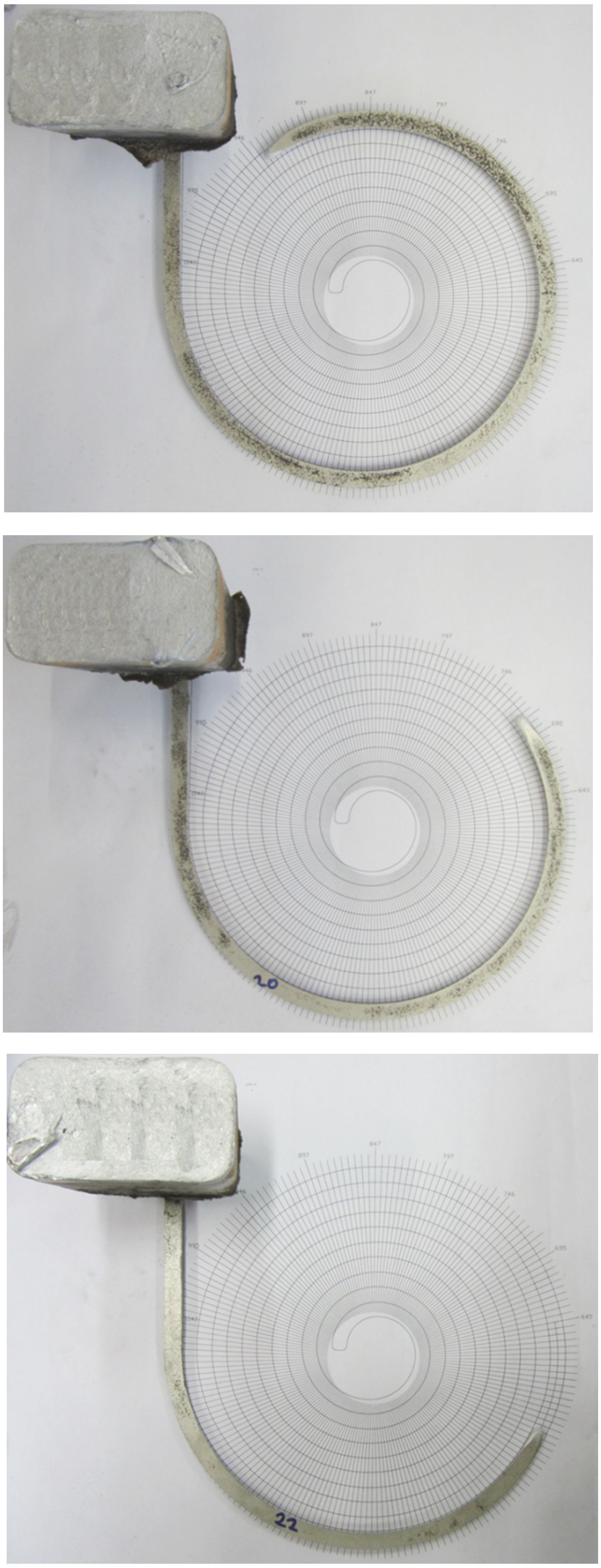
Fig. 7 - Location and notation of the thermocouples inside the pouring basin; the pouring zone is also indicated.

rent levels were chosen in the design of the experiments (10 and 17 s). These levels were selected because feasible at industrial scale. The holding time into the basin strictly depends both on the molten temperature in the furnace and on the preset execution temperature of the test; therefore, greater the difference between these values, higher the holding time will be. The temperature of the molten metal in the furnace was then selected taking into account this feature. The design of experimental matrix (DoE) is shown in Table 2. All the tests considered in this DoE were carried out with a preheated stopper.

T_{bath} (°C)	$T_{stopper\ removal}$ (°C)	$t_{holding}$ (s)
760	712	10
750	695	10
740	680	10
760	680	17

Table 2 - DoE performed to assess the impact on the repeatability due to the variation of stopper removal temperature and to the holding time of the metal into the pouring basin.

Figure 8 shows the most representative castings obtained for each set of tested temperature. It can be observed how lower the stopper removal's temperature, lower the fluidity length, in accordance with Refs. [2,4,6]. Figure 9 shows a comparison between different series of tests carried out at different temperature levels (712, 695, 680°C) but with the same holding time into the pouring basin (10 ± 2 s). It can be observed how the dispersion of the results increases as the temperature decreases with the same holding time. The experimental results suggest to increase the temperature in order to improve the repeatability of the results.
Table 3 shows a comparison between the series of tests performed at different holding times (10 ± 2 and 17 ± 1



a)

b)

c)

Fig. 8 - Representative castings from the tests carried out at (a) 712, (b) 695 and (c) 680°C, respectively, and with the same holding time of liquid into the pouring basin (10 ± 2 s).

T_{bath} (°C)	$T_{stopper\ removal}$ (°C)	ΔT (°C)	$t_{holding}$ (s)	σ (mm)
740	680	60	10 ± 2	84
760	680	80	17 ± 1	32

Table 3 - Dispersion of the results as a function of holding time of the metal into the basin at the same execution temperature (680°C); the difference between the molten metal temperature and the stopper removal temperature ΔT is shown.

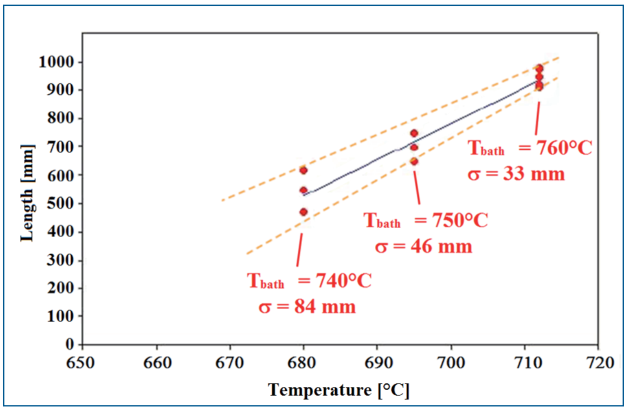


Fig. 9 - Fluidity of A356 alloy as a function of the temperature, with a constant holding time into the basin (10 s); standard deviations are also indicated. For each molten metal temperature (740, 750 and 760°C) the minimum, the maximum and the average length values are indicated. The average lengths are interpolated by the central trend line.

a)

b)

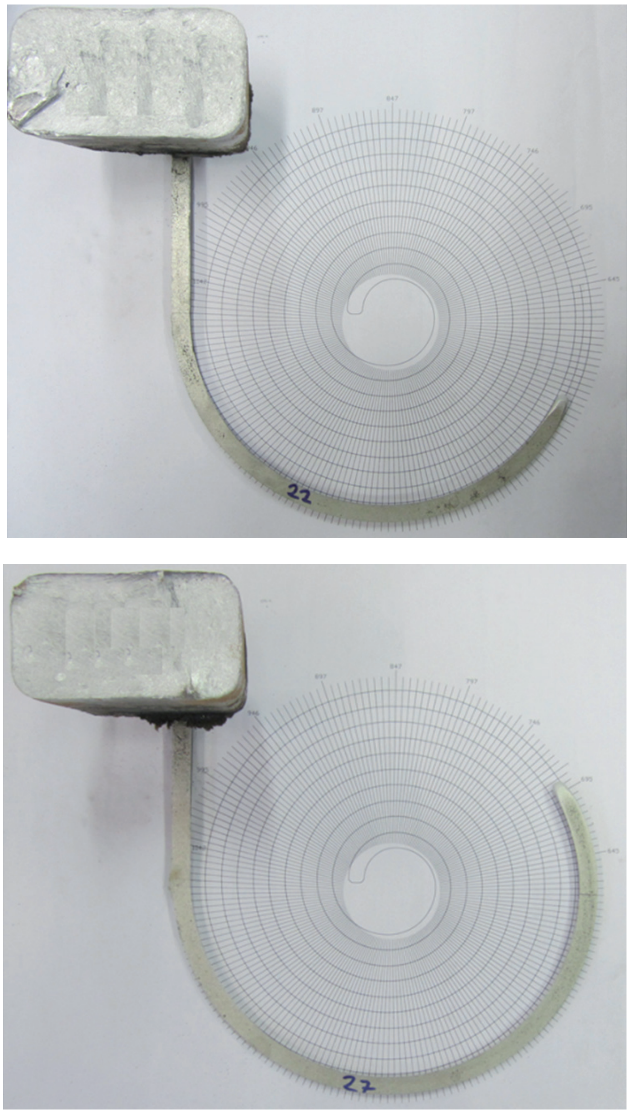


Fig. 10 - Representative castings from the tests carried out with a bath temperature of (a) 760 and (b) 740°C, respectively, and at the same stopper removal temperature (680°C).

s), but at the same experimental temperature (680°C). The repeatability of the data increases with the increase of the holding time. It can be observed that, at the same temperature of the stopper removal, greater the difference between the molten temperature and the stopper removal temperature, lower the dispersion of the results will be; this difference strictly depends on the holding time, and it is related to the progressive homogenization of the liquid bath into the basin. The different pouring temperature affects also the final fluidity length, as shown in Figure 10 where the most representative castings are displayed.
The obtained results suggest to increase the holding time of the molten metal into the pouring basin in order to obtain the maximum repeatability. This aspect is also evidenced in Figure 6, where a progressive homogenization of the temperatures among different points in the basin is observed.

TESTS PERFORMED ON GRAIN REFINED AND MODIFIED A356 ALLOY

This work was extended to the same A356 alloy, previously analysed, after a preliminary treatment with grain refiner and modifier. This operation was performed by adding commercial AlTi5B1 grain refiner and AlSr10 modifier in the form rods into the molten base alloy to ensure that the Ti and Sr levels in the melt reached the desired content. The amount of grain refiner addition will be hereinafter referred to as Ti content. The contact time of the grain refiner was 15 min and the melt was stirred for ~10 s before pouring. The final Ti and Sr contents were about 0.2 wt.% and 150 ppm.
Table 4 shows the mean values and the standard deviations of the fluidity tests carried out under the same operating conditions, with and without preliminary treatment of AlTi5B1 grain refinement and Sr modification.

No substantial differences in the fluidity are observed between the base A356 alloy and the treated one, for what concerns both the scattering of the results and the absolute values. The metallographic characterization of the spirals shows a very fine microstructure, with a microstructural scale, evaluated by means of the secondary dendrite arm spacing, of about 25 µm, regardless of the preliminary treatment of the bath (Figure 11).
Figure 12 shows the macrostructure of the tips drawn from two different spirals, one casted with base alloy and the other casted with refined and modified alloy: this comparison highlights the same macrostructural scale for both the specimens. This indicates a high cooling rate and is referred to the reduced wall thickness of the spiral cavity; this feature may hide the possible effects of these treatments on the fluidity of the metal.

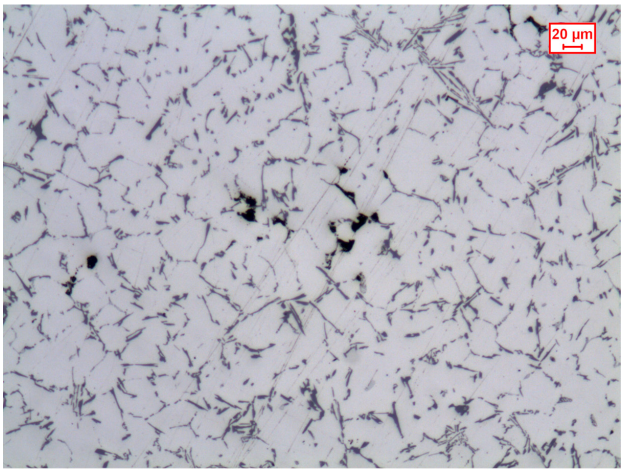
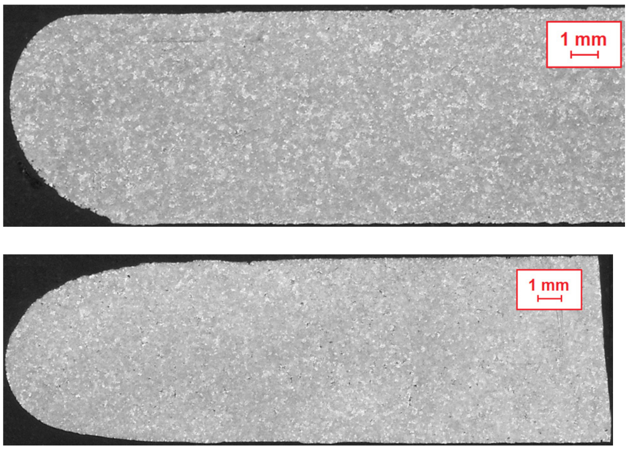


Fig. 11 - Typical microstructure of the tested A356 alloy and obtained from the tip of a spiral.



a)

b)

Fig. 12 - Macrostructures of the tips drawn from (a) a spiral casted in A356 base alloy and (b) a spiral casted in refined and modified alloy.

NUMERICAL FLUIDITY SIMULATIONS

A specific experimental fluidity test was numerically studied by using a commercial numerical simulation software, NovaFlow&Solid, with its module for gravity casting [12]. The experimental test taken as a reference for the software calibration was performed without stopper preheating, and the pouring operation was monitored through 5 thermocouples placed as indicated in Figure 7. Virtual thermocouples were also introduced into the numerical model in order to control the temperature profiles and to compare these values with the experimental ones. The stopper removal occurred at the reference temperature of 692°C.
The numerical process simulation was split into two sequences: the first refers to filling of the pouring basin, while the second step reproduces the filling of the spiral cavity. The stopper removal was neglected in order to simplify the set up of the numerical simulation. Thus, the simulated results of the first step were used to set up the boundary conditions of the second stage. The average temperature measured by the thermocouples at the instant of stopper removal was selected as the molten temperature at the ingate of the spiral. The metallostatic pressure at the ingate was considered constant during the spiral filling as well as the temperature of the metal at the ingate during the stopper removal.
The initial conditions for the numerical simulation of the basin filling were defined to reproduce the gravity casting parameters. Therefore, A356 alloy and gravity manual pouring process were initially selected from the software database. The pouring temperature of the alloy was set at 730°C, while, for the cold-box sand mould and the carbon steel stopper, the temperature was assumed to be at a uniform room temperature. The physical constants and properties of the mould and the alloy, and their evolution with temperature, were chosen among those present in the software database. The conductivity at the mould-alloy interface was defined as 0.22 W/mK. The pouring process with a ladle was simulated by selecting a metallostatic head height of 95 mm, i.e. the distance between the bottom of the pouring basin and the nozzle of the ladle; the pouring angle with respect to the vertical axis was set at 15°, the filling time at 3 s and the flow rate was 0.3 kg/s, respectively.
For the spiral cavity filling, the boundary conditions remained almost the same with exclusion of the pouring temperature now set at 662°C and the metallostatic head defined at 75 mm, i.e. the distance between the surface of the bath in the pouring basin and the ingate of the spiral.
Figure 13 shows a good agreement between the numerical simulation results and the experimental spiral.

CONCLUSIONS

In this work, a specific testing method for the fluidity evaluation has been developed and it has been studied in terms of repeatability of the results under different experimental conditions. Based on the results obtained

a) b)

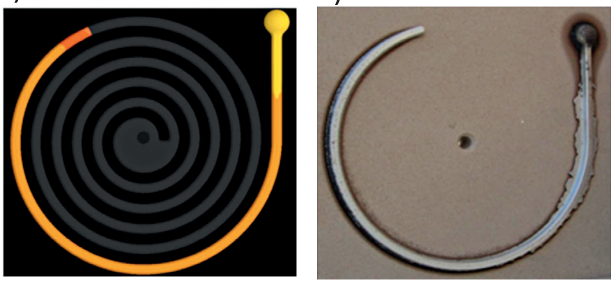


Fig. 13 - Comparison between (a) numerical simulation result of fluidity and (b) the experimental result from the spiral test.

in the present study, the greatest repeatability has been obtained with stopper and casting ladle preliminary preheated. It is necessary a standardization of pouring operations, particularly for what concerns the preheating of the stopper and of the casting ladle besides the maintaining of the same metal quantity poured. The lowest dispersion of the results has been obtained holding the metal into the basin of about 17 seconds before the stopper removal, with a temperature of the bath in the crucible of 760°C and a stopper removal temperature of the metal of 680°C.

The difference between the holding temperature in the furnace and the temperature measured in the pouring basin before the stopper removal affects the holding time of the metal into the basin and the repeatability of the experiments. In order to study the fluidity of an alloy at various temperatures, it is suggested to change appropriately the initial temperature of the bath.

The experimental tests carried out on the grain refined and Sr modified A356 alloy, no appreciable variations of the fluidity are detected with respect to the base alloy. Thin sections of the spiral cavity induces high cooling rates and this feature can prevail over the effects due to preliminary treatments of the molten bath.

ACKNOWLEDGEMENTS

The author would like to acknowledge Mr. G. Mazzacavallo (DTG, Italy) and Dr. F. Grosselle (QMC srl, Italy) for the experimental support to the research.

REFERENCES

[1] D. Apelian, M.M. Makhlouf, Casting characteristics of aluminum die casting alloys, DOE/ID—13716, 2002.

[2] M. Di Sabatino, Fluidity of aluminium foundry alloys, PhD thesis, Norwegian University of Science and Technology (NTNU), 2005.

[3] M.C. Flemings, Solidification Processing, McGraw-Hill Inc., London, 1974, pp. 80-84.

[4] J. Campbell, Castings, Oxford, Butterworth-Heinemann, 2003, pp. 74-96.

[5] F. Bonollo, E. Faltracco, F. Danieli, B. Molinas, Evaluation of fluidity in aluminum alloys, Proc. Conf. "EUROMAT 2001", Rimini (2001), paper 910; Associazione Italiana di Metallurgia – Milano.

[6] M. Di Sabatino, S. Shankar, D. Apelian, L. Arnberg, in "Shape Casting: The John Campbell Symposium", Ed. M. Tiryakioglu and P.N. Crepeau, TMS 2005, p. 193.

[7] M. Di Sabatino, F. Syvertsen, L. Arnberg, A. Nordmark, Int. J. Cast Met. Res., vol. 18 (2005), p. 59.

[8] G. Timelli, F. Bonollo, Int. J. Cast Met. Res., vol. 20 (2007), p. 304.

[9] M. Di Sabatino, L. Arnberg, S. Brusethaug, D. Apelian, Int. J. Cast Met. Res., vol. 19 (2006), p. 94.

[10] M. Di Sabatino, L. Arnberg, S. Rorvik, A. Prestmo, Mat. Sci. Eng. A, vol. 413-414, (2005), p. 272.

[11] M. Di Sabatino, L. Arnberg, Int. J. Cast Met. Res., vol. 18, (2005) p. 181.

[12] Novacast, NovaFlow & Solid CV Gravity Casting, available at http://novacast.se/wp-content/uploads/2013/10/PRODUKTBLAD-NovaFlow-Solid-CV.pdf ; accessed 18 december