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Aluminium And Its Alloys - Fluidity Evaluation Via Multi Strip Testing Moulds

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Contents

Page

European foreword

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Introduction

Thin wall castings are always considered as potential choice in range of applications because of their superior characteristics i.e., weight reduction, complex design flexibility, reduced machining, efficient production, effective heat dissipation, and cost effectiveness. These days, the demand for production of thin wall sections along with higher mechanical properties is receiving vast attention in automotive and aerospace sectors. Aluminium and its alloys are considered as promising candidates to meet these requirements due to their low density (2.7 g/cm^3), high strength to weight ratio, high specific stiffness, and good castability. Among available casting techniques, high pressure die casting (HPDC) is widely used these days for mass production of these thin wall aluminium components with near net shape configuration, high dimensional accuracy and excellent surface finish [1]. However, there are several challenges associated with these thin wall castings as thin sections undergo rapid cooling, which could affect the flow of molten metal while filling mould. It is greatly associated with the various casting problems such as mould cavity filling, feeding, cold shut, hot tearing and macro segregation [2]. Therefore, a proper understanding and thorough knowledge of molten metal flow in mould cavity are vital for achieving sound and defect free components.

In casting process, the pouring of molten metal and its ability to continuously flow in the designed mould cavity are considered critical steps, as the molten metal continuously losses its temperature while filling. It is the behaviour of the molten metal and its solidification mechanism that determine the quality and integrity of the final product. Poor filling of molten metal in the cavity leads to casting defects which not only result inevitably in rejection of components but also increases the manufacturing cost i.e., indirect economic loss in any production domain. Realising its vital importance, this topic has been investigated by many researchers, which ultimately results in pitching a quantitative concept of characterising metallic material in the liquid state called “fluidity”.

In foundry process, fluidity is defined as the empirical measurement of the maximum length covered by the molten metal or alloy in a specific channel of constant cross-sectional area before it fully solidifies [3, 4]. Thus, fluidity is simply a measure of distance in millimetres or centimetres. It is well known that the higher the fluidity of metal or alloys, the more complex and intricate thin wall castings can be produced. Regardless of its high significance, there are many attributes of this property on which very limited studies are present and, instead, more research efforts have been made on optimizing the casting process to achieve corrosion resistance and high mechanical properties [5-8]. Because of limited data that governs all possible attributes of fluidity, there is no widely accepted standardized method to measure the fluidity of metals and alloys.

Several testing methods have been adopted by different researchers to measure the fluidity of molten metals. Among them, two methods have gained widespread acceptance: the vacuum fluidity test (vertical and horizontal) and the spiral fluidity test:

The vacuum fluidity test consists of measuring the maximum length of the molten metal flow inside a narrow channel testing tube when drawn from a crucible by using a vacuum pump. The vertical vacuum test is preferred over the horizontal vacuum test because the experimental setup is considered simpler to assemble, as the testing tubes do not need an L shaped bend as in in horizontal testing.

In the spiral testing method, molten metal whose fluidity is to be determined is poured into a cylinder that terminates into a long, thin cavity shaped like a spiral. The walls of the cavity might be made of sand or coated metal, heated or unheated.

Common to both test is that molten metal is flown into narrow channel of constant cross-sectional area. Traditionally, vacuum testing moulds are considerably use less in foundry, and spiral testing has been widely used as it makes the fluidity test very compact and convenient by compressing mould into a small area and is very less sensitive towards levelling errors as well. Although widely used in foundry, spiral testing is still criticised as it shows no correlation to its application in real casting situations, as fluidity length measurement through spiral testing can only be obtained for channel section of constant cross-sectional area. This eventually raises many questions about how molten metal will behave in real castings where mould geometry has different thicknesses. Moreover, because of the lack of designed standard protocols for conducting these traditional tests, there exists poor repeatability of results under the same apparent conditions, which greatly affect the reliability of these testing methods. This is the reason why reliable fluidity data for aluminium and its alloys are not readily available in the literature.

To address these issues, multi-channel strip testing was proposed, in which multiple strips of identical length and different cross-sectional area are filled simultaneously from a common runner bar, and flow length for different cross sections can be measured simultaneously. The schematic representation for horizontal and vertical vacuum testing, spiral testing and strips testing are shown in Figure 1. Sabatino et al. [9] investigated fluidity evaluation for Al-Mg-Si alloys through spiral and strip testing methods. The results revealed that a higher relative repeatability (11 %) was achieved through strip testing as compared to the spiral testing method (5 %). Adefuye et al. [10] found that sand moulded multiple strips testing with thickness range from 4 mm to 1 mm could produce results with less than 10 % error by simple adjustments in design. Moreover, researchers have shown their interest in strip fluidity testing methods due to the higher repeatability in the results [11].

In the SALEMA project, the fluidity measurement for newly developed aluminium alloy with low criticality issues has been optimised and validated.

1 Scope

The aim of this document is to develop a testing method to evaluate fluidity of aluminium alloys for thin wall castings in a robust and reliable way to provide useful information for subsequent use in foundry. The adopted methodology is based on strip testing, and the primary objective of this work will be focused on defining standard protocols to achieve higher repeatability for fluidity of aluminium and its alloys. The present document describes the experimental procedure proposed for the fluidity testing method.

The fluidity for the AlSi10mnMg0.2 alloy via strip testing technique through permanent mould casting is included in Annex A.

In foundry processes, the filling behaviour of die and mould cavities is controlled by the viscosity of the liquid metal/alloy employed i.e., the technological relevance is very high. However, experimental data on the viscosity of liquid metals and alloys are lacking due to the difficulty in carrying out high temperature viscosity tests. The evaluation of fluidity, intended as a technological property of metals and alloys representing the inverse of viscosity, can supply fundamental information to be used in foundry processes. This document describes the testing procedure for evaluating the fluidity with specific reference to aluminium and its alloys for thin wall casting applications by means of multi strips testing methodology. The document provides detailed guidelines for designing and experimental testing followed by data processing.

NOTE 1 The testing method described here will refer to evaluate L_f for aluminium and its alloys for various thicknesses. It is noteworthy to mention that the evaluation of fluidity (L_f) is highly dependent upon multiple variables (as discussed in clause 4), so optimization in those variables will lead to different L_f values for the same alloys. Therefore, L_f cannot not be considered as an intrinsic property of the material, but rather a material and mould based characteristic property.

NOTE 2 There are multiple studies available in the literature regarding the effect of variable factors on the fluidity of aluminium alloys. However, this document will focus on mould geometry and defining an operational standard protocol to achieve higher reproducibility of data, making this technique more reliable and easier to use in foundry.

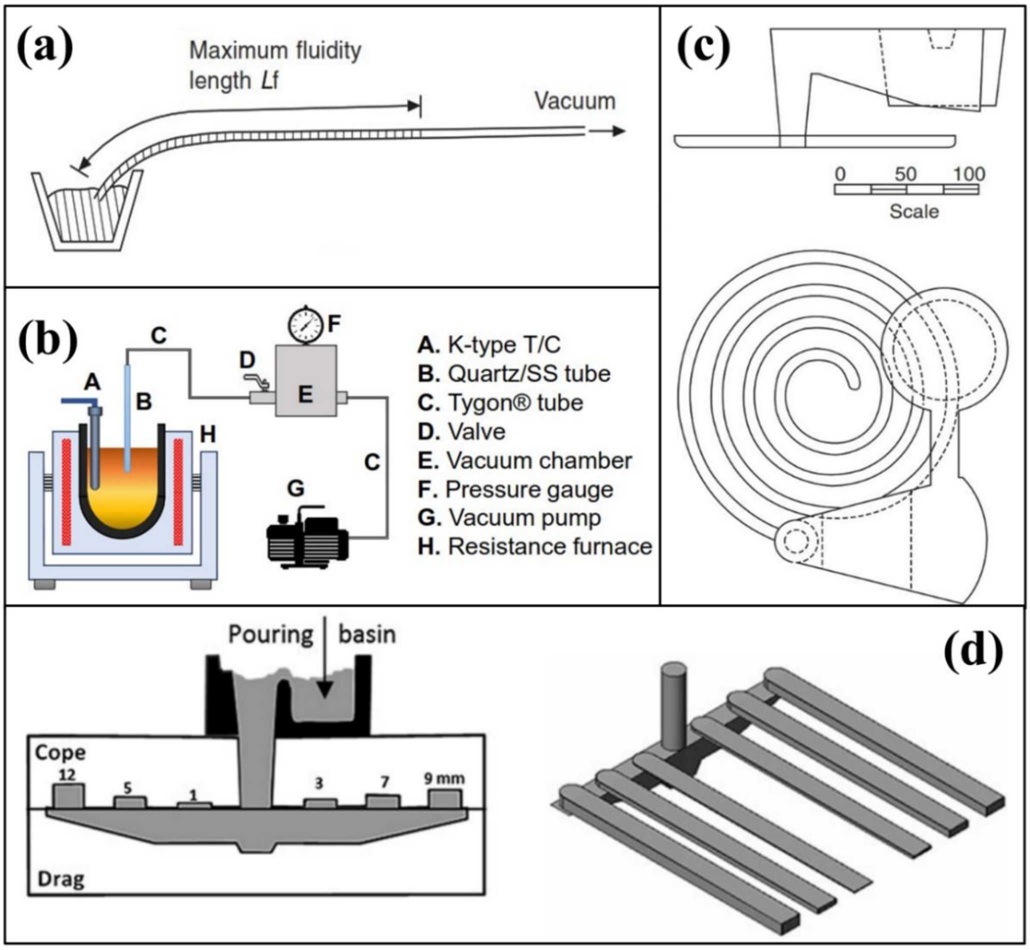

Figure 1 — Schematic representation of (a) horizontal vacuum testing [4] (b) vertical vacuum testing [12] (c) spiral testing [4] and (d) strip testing [13]

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 12258-1:2012, *Aluminium and aluminium alloys - Terms and definitions - Part 1: General terms*

EN 1706:2020+A1:2021, *Aluminium and aluminium alloys - Castings - Chemical composition and mechanical properties*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in EN 12258-1:2012 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at https://www.electropedia.org

— ISO Online browsing platform: available at https://www.iso.org/obp/ui

3.1
fluidity, L_f
the empirical measurement of the maximum length covered by the molten metal or alloy in a specific channel of constant cross-sectional area after it has fully solidified [3, 4, 14]

4 Theoretical background

Fluidity cannot be attributed as a simple physical property as it is a complex technological property. In physics, fluidity is defined as the reciprocal of viscosity; however, this definition doesn't apply in foundry terms as there are multiple factors on which its measurement will depend upon. Therefore, a thorough knowledge of all factors affecting the overall fluidity of metals or alloys is necessary before its measurement. All factors influencing the fluidity can be divided into two main categories.

— Melt based factors.

— Mould based factors.

4.1 Melt based factors

4.1.1 Material composition

Pure metal and alloys behave differently in term of fluidity because alloying elements play a major role in influencing viscosity, solidification mode, superheat, terminal freezing range, and surface tension of the alloys. Pure metals, along with eutectic alloys, show the highest fluidity. The alloying elements present in pure metals can significantly reduce the fluidity, while in alloys, these elements can increase eutectic fraction, resulting in achieving maximum fluidity at eutectic composition.

4.1.2 Viscosity

Viscosity is considered as one of the important thermophysical properties that influence the flow characteristics of molten metal. For every newly developed alloy, it is essential to understand viscosity and its influence on castability. The viscosity of alloys is affected by multiple factors including alloy composition, metal temperature and inclusions present. To achieve higher fluidity, the viscosity of alloys must be low.

4.1.3 Melt superheat

Melt superheat is the difference between the temperature at which molten metal is cast and the liquidus temperature of metal. Higher casting temperatures, and therefore higher melt superheat, slow the nucleation and growth of fine grains at the flowing metal tip in the testing channel, which enhances molten fluid life, and molten metal can flow for longer time. However, chemical reactions may also occur at high temperatures, which can increase viscosity, thereby reducing the fluidity of the molten metal.

4.1.4 Surface tension

Surface tension is the property that arises from cohesive forces between the mould and molten metal interaction at the interface, often known as capillary repulsion. It affects how well molten metal spreads and wets on a mould surface. Lower surface tension typically promotes molten metal flow, which greatly aids in filling intricate shapes, while higher surface tension causes more fractional forces at the molten metal-mould interface, resulting in lower fluidity.

4.1.5 Metallostatic pressure

It refers to the pressure exerted by molten metal within the channel due to its weight. Higher metallostatic pressure creates more driving force for molten metal to flow in the channel, thus increasing fluidity.

4.1.6 Specific weight

Specific weight, often referred as material density, can impact the fluidity of molten metal during casting. The molten metal with higher specific weight tends to increase the metallostatic pressure at the bottom of the casting, which reduces the resistance of the liquid metal in the mould and thus enhances fluidity. On other hand, molten materials with lower specific weight cannot exert as much pressure, resulting in lower fluidity.

4.1.7 Melt cleanliness

The cleanliness of molten metal i.e., the presence of inclusions, gas entrapment, and oxide formation, greatly influences the fluidity and overall quality of casted components. Non-metallic inclusions in the molten melt act as nucleation sites for pore formations, which affects the flow of molten metal. Similarly, entrapped gasses, i.e. hydrogen bubbles hinder the melt flow, while oxide formation on the molten melt surface tends to have poor wettability, ultimately resulting in decreasing fluidity.

4.1.8 Solidification mechanism

The mechanism of solidification greatly influences fluidity. In pure metals and alloys with short freezing range, solidification takes place through the advancement of planar crystal formation from the outside mould walls towards the molten metal, without affecting flow until the liquid metal is fully solidified. While alloys with long freezing range produce independent crystallization, such as dendritic and other irregular fragments, at the solidification tip in moving liquid metal, which greatly hinders the molten metal flow. This is why fluidity values generally show an inverse relation to the solidification range.

4.2 Mould based factors

4.2.1 Mould material

The mould extracts heat from molten metal when it flows. If the thermal conductivity of the mould material is higher, the rate of heat dissipation by the mould material from the molten metal will be high, i.e. the molten metal will have less time to flow inside the mould and hence lower fluidity. Conversely, a mould with a lower thermal conductivity will retain heat for longer time in the molten metal, thus promoting fluid flow i.e., higher fluidity.

4.2.2 Mould temperature

When molten metal is poured into a mould at room or lower temperatures, the cooling rate i.e., chilling effect, will be higher , causing the molten metal to solidify at a faster rate and thus reducing fluidity. Conversely, a mould at higher temperatures can keep the molten metal in a liquid state for longer time, thereby increasing fluidity. This is why, for thin wall casting, the mould is always preheated to a high temperature to reduce the chilling effect.

4.2.3 Mould permeability

Permeability in the mould refers to the ability of the mould to allow gases, such as air and other volatile gases, to escape from the mould while molten metal is poured into the mould cavity. These entrapped gases can create hurdles in molten metal flow. Molten metals poured into a mould with high permeability result in higher fluidity.

4.2.4 Mould coating

Coatings are often applied to the mould inner surface to suppress heat dissipation between the flowing molten metal and the mould. These coatings cause less heat transfer at metal-mould interface, so that the molten metal can retain a higher temperature for longer time, increasing fluid life and thus achieving higher fluidity.

4.2.5 Mould surface characteristics

The surface finish of the mould greatly affects the fluidity of molten metal. A mould with a poor surface finish causes more hindrance and friction for the molten metal to flow, adversely affecting fluidity. Conversely, molten metal in a mould with smooth finish does not face any hindrance while filling, leading to higher fluidity.

5 Test material, equipment and fixture

5.1 Test apparatus

The main components used in strip testing equipment are shown in Figure 2, which are:

— electric resistance furnace (a);

— heating oil unit (b);

— experimental mould (c).

Relevant aspects:

— The experimental die made of H-13 steel has two main parts: an upper half top part (cope) that consists of 6 channels (strips/fingers) of identical length and different cross-sections, and a lower half part (drag).

— The pouring basin made of H-13 steel, which is placed on the cope.

— An electric resistance furnace in which ingots of alloys can be melted.

— A ladle to pour molten metal from furnace to mould.

— Heating oil pumping unit for uniform hot oil circulation in the mould.

— Calibrated *K*-type thermocouples to monitor molten metal and mould temperature.

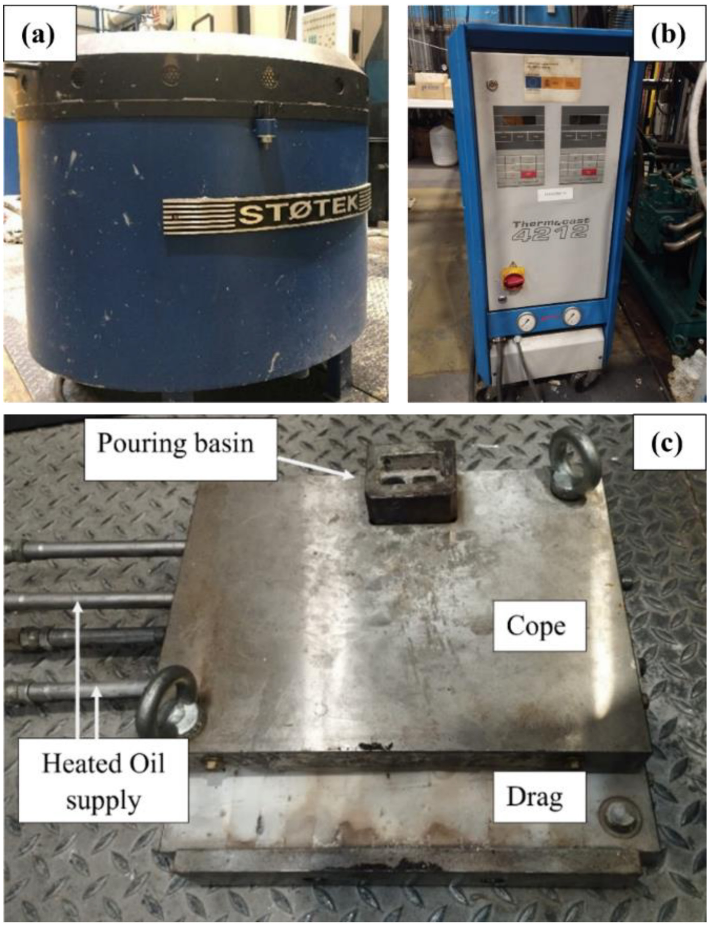

Figure 2 — Main components for fluidity evaluation (a) electric resistance furnace (b) heating oil unit (c) experimental mould

5.2 Mould and pouring basin geometry

The 2D and 3D drawings for the cope mould geometry are illustrated in Figure 3 (a) and (b, c) respectively. The pattern consists of six strips with identical lengths of 228 mm and widths of 20 mm. The thicknesses of cross section are 1, 3, 5, 7, 9 and 11 mm. The 2D and 3D drawings for the drag mould geometry are shown in Figure 4 (a) and (b, c) respectively. The pouring basin geometry is shown in Figure 5 (a) and (b) respectively. The complete fixture for fluidity testing is shown in Figure 6.

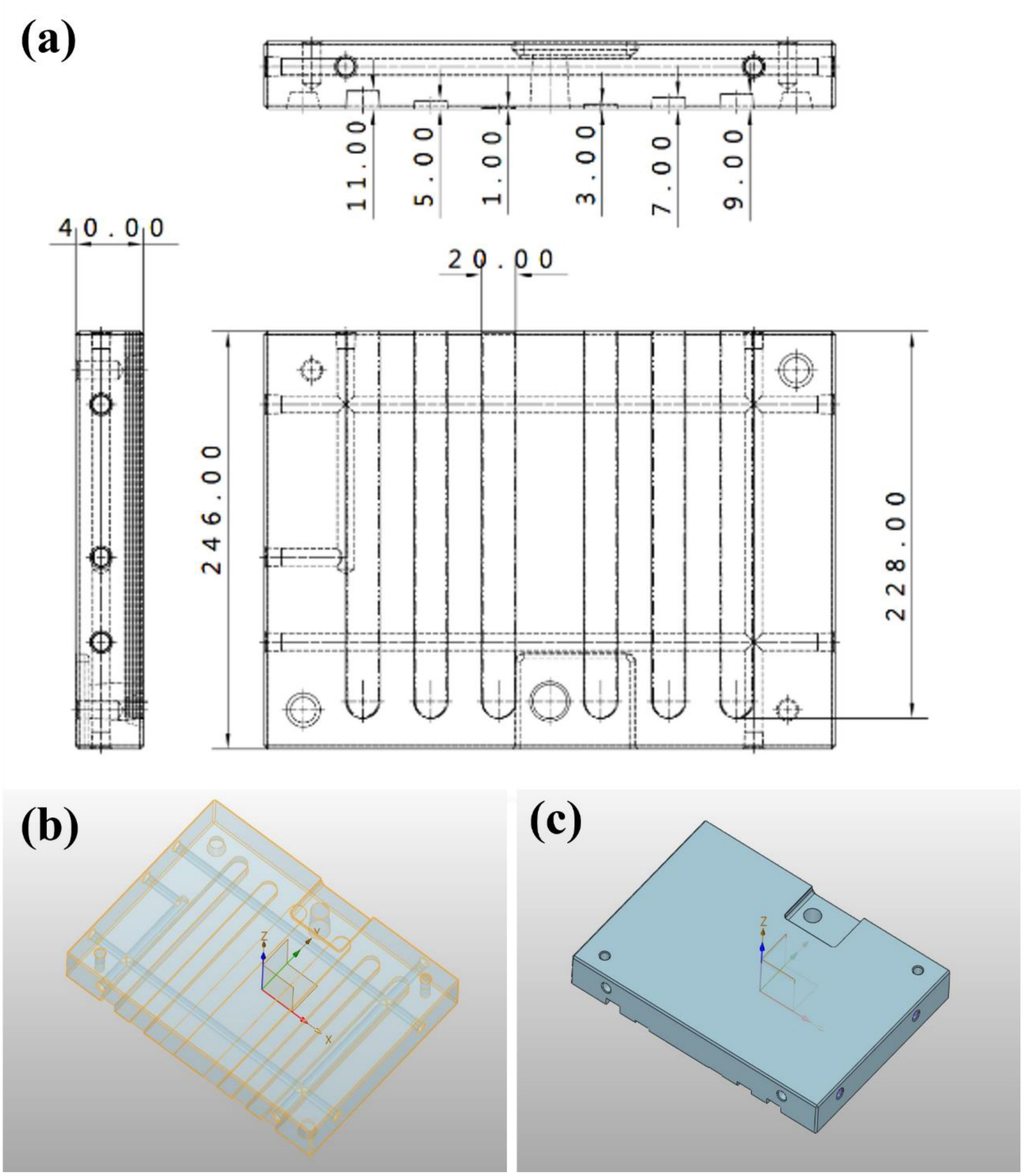

Figure 3 — (a) 2D and (b) and (c) 3D drawings of the cope

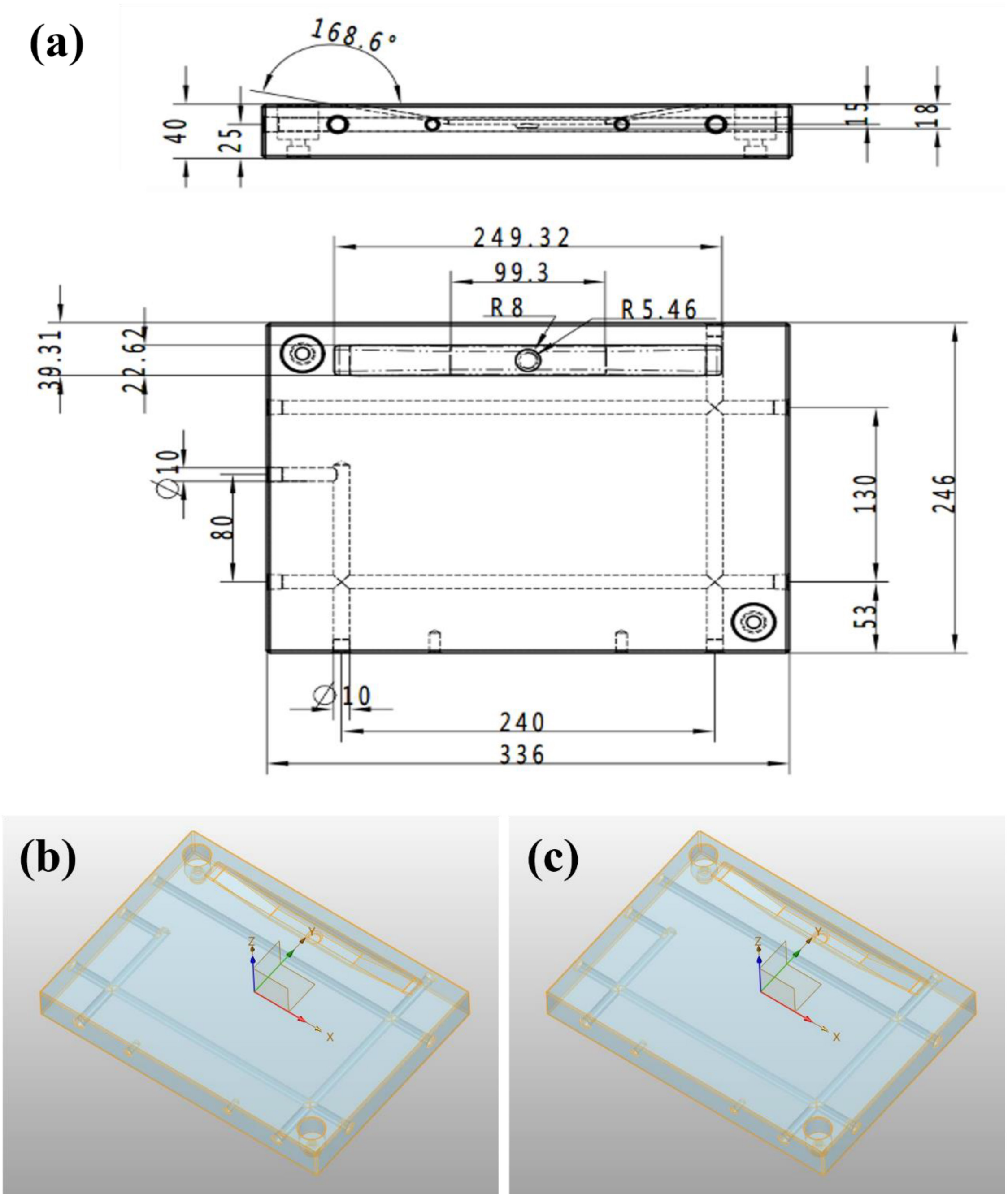

Figure 4 — (a) 2D and (b) and (c) 3D drawings of the drag

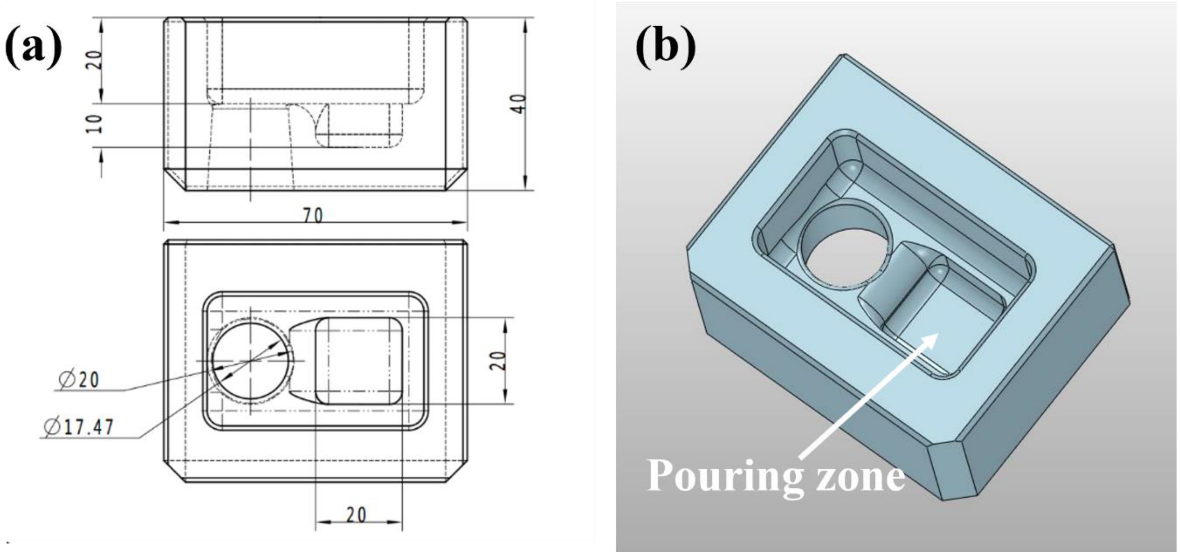

Figure 5 — (a) 2D and (b) 3D drawings of the pouring basin

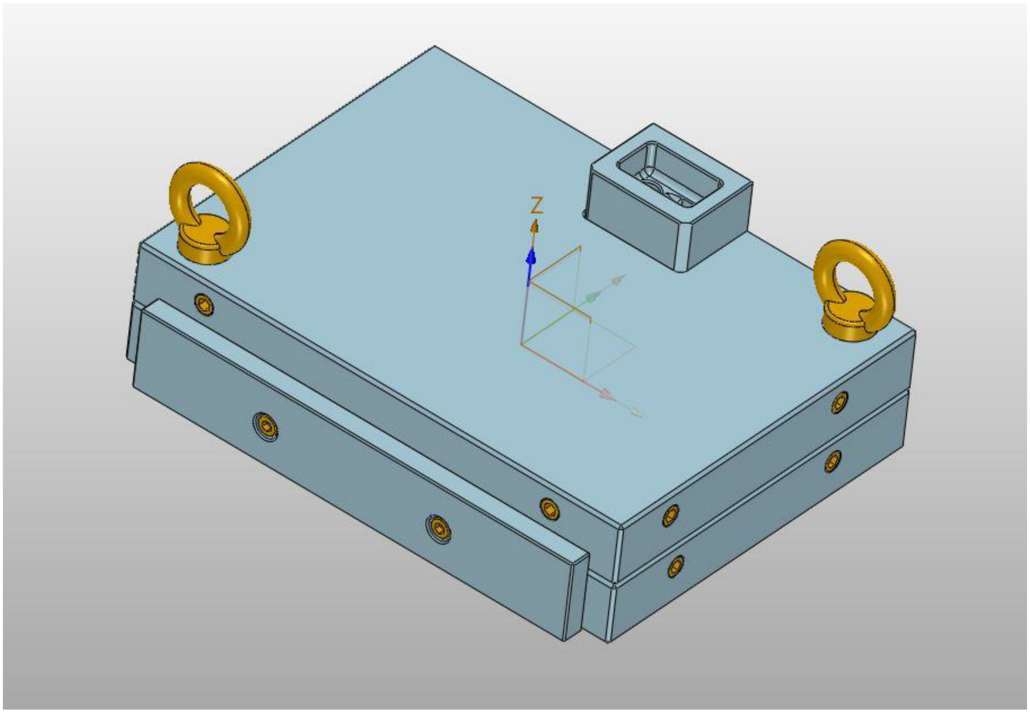

Figure 6 — Complete fixture for the fluidity strip testing

6 Operational procedure

6.1 Standardisation of operative protocols

As reported in clause 4, there are a number of factors that influence the fluidity of alloys. Therefore, ideal testing for evaluating fluidity of alloys must consist of careful monitoring and control of all those factors in a very tight manner to avoid any fluctuations in repeatability of the results. For this reason, it is necessary to follow a standardised operating protocol:

- All L_f experiments must be conducted in an open environment.
- The ingots of aluminium alloy whose fluidity is to be measured shall be cleaned thoroughly with acetone to remove all dust and greasy particles present on them before inserting them into the furnace for melting to avoid any possible foreign contamination.
- Ingots shall be melted in an electric resistance furnace equipped with a graphite crucible.
- A reinforced fibre glass material (RFG) ladle coated with boron nitride shall be used to pour molten metal from furnace to the mould because of its non-wetting nature for molten aluminium.
- The ladle shall be filled with molten metal at the same level in order to keep the metallostatic pressure constant for all sets of experiments.
- Mould temperature must be monitored using *K*-types thermocouples placed at the centre of the drag before each test to avoid any fluctuation caused by differences in mould temperature.
- The pouring temperature must be measured with another *K*-types thermocouple exactly before pouring.
- An identical pouring zone (as indicated in Figure 5 (b)) in the pouring basin shall be identified where molten metal shall be poured.
- Molten material shall be poured into the mould with a constant pouring velocity and at the same time pouring angles for all sets of experiments.
- Dross must be removed from the melt surface shortly before pouring into the mould.

6.2 Experimental procedure

In order to obtain reliable and robust results, it is crucial to closely monitor all the process variables for each test. Temperature monitoring is key to keep testing temperature as constant as possible across different trials conducted under the same conditions. The proposed steps below outline how the fluidity tests must be conducted:

- Aluminium ingots of ~ 40Kg shall be melted in an electric resistance furnace equipped with a graphite crucible having a maximum capacity of 50 kg to perform a series of experiments.
- To suppress heat transfer from the melt to the mould, the mould coating shall be sprayed on mould surfaces (cope and drag) with a spraying gun.
- The drag shall be placed on a perfectly horizontal surface to avoid any levelling error. The cope should then be placed over the drag by aligning side holes with those on the drag until the bolts can pass through each other. After alignment, nuts shall be screwed tightly to firmly tighten both halves together.
- To reduce chilling effect, heated oil (~ 120^0 C) shall be flown through the mould cope and drag via a heating oil pumping unit before pouring molten metal into the mould cavity to achieve a homogeneous and stable temperature in the mould cavity.
- The ladle must be preheated in the same manner for all performed tests, for 5 minutes, and should be immersed into the molten metal bath for 15 sec for all tests before pouring molten metal into the mould.

— The pouring of the metal shall be done in the pouring basin at the identified pouring zone for all sets of experiments, ensuring a more stable and homogeneous filling pattern and avoiding any differences in the filling dynamics of the molten material.

— The mould shall be opened after ~ 30 seconds to remove the casting.

6.3 Reproducibility

To ensure the representativeness of the results achieved, each alloy must be tested n number of times under similar conditions to avoid any deleterious consequences in terms of results comparability.

7 Analysis of results

To conduct analysis and assess the impact on reproducibility of results, L_f for each strip must be analysed periodically using the same approach for all n number of experiments. The following statistical approach must be used:

— Average value (x_{avg}) of L_f for n number of experiments:

$$x_{avg}\,(\text{mm}) = \frac{\sum_i^n x_i}{n} \tag{7-1}$$

Where x_i is the L_f (mm) in strip for *i*-th experiment.

— Standard deviation (σ) for n number of experiments:

$$\sigma\,(\text{mm}) = \sqrt{\frac{\sum_i^n (x_i - x_{avg})}{n-1}} \tag{7-2}$$

Where x_i is the L_f (mm) in strip for *i*-th experiment and x_{avg} is average of x_i for n number of experiments.

— Relative reproducibility (RR):

$$\text{RR}\,(\%) = \left(\frac{\sigma}{x_{avg}}\right) * 100 \tag{7-3}$$

Where x_{avg}, σ are the recorded average L_f and the standard deviation values from Equations (7-1) and (7-2) respectively.

After measuring L_f for all strips, the total fluidity volume of solidified alloy in all six strips must be calculated for every experiment using the following formula:

$$V_f\,(total) = \sum_{i=1}^{6} (A_i * L_{f_i}) \qquad (7\text{-}4)$$

Where $V_f\,(total)$ is the total volume (mm^3), A_i (mm^2), and L_{f_i} (mm) are the cross-sectional area and the measured fluidity length for each strip, respectively.

Annex A
(Informative)

Fluidity via strip testing technique through permanent mould casting

A.1 Material of reference

Fluidity was investigated for the AlSi10MnMg0.2 alloy using the strip testing technique through permanent mould casting in the context of the SALEMA project. The chemical composition of the investigated alloy is provided in Table 1.

Table 1 — Chemical composition (wt%) of AlSi10MnMg0.2 alloy used in present investigation for fluidity testing

Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Pb	Sn	Ti
9-11,5	0-0,2	0-0,03	0,45-0,65	0,15-0,25	0-0,03	0-0,03	0-0,07	0-0,03	0-0,03	0,05-0,15

A pouring temperature of 680 ºC was selected for conducting the fluidity test. Boron nitride (BN) coating was applied to the inside surfaces of the cope and drag before each experiment. Figure 7 displays the most representative multi-strip fluidity test casting of AlSi10MnMg0.2 obtained by following the described procedure.

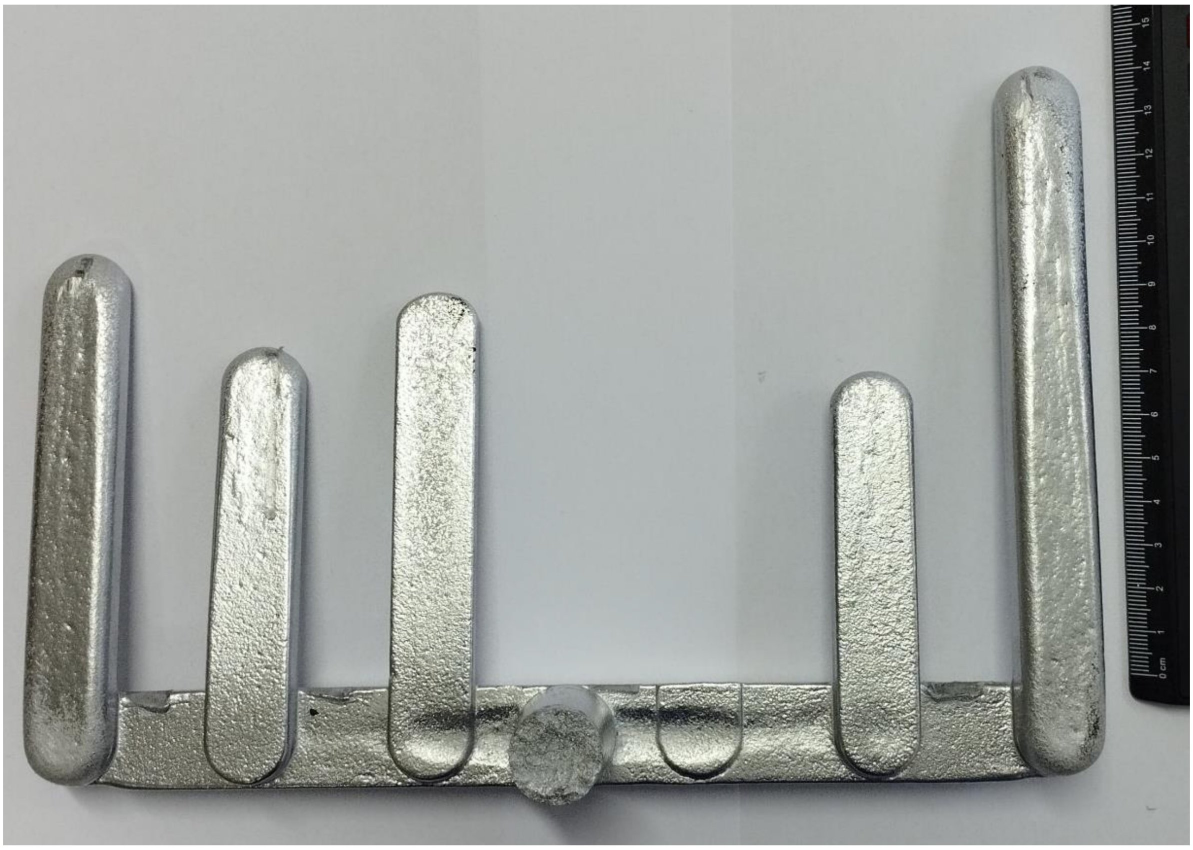

Figure 7 — Representative multi-strip fluidity test casting of AlSi10MnMg0.2

Figure 8 (a) shows the average fluidity length measured for each strip recorded along with their standard deviations and Figure 8(b) shows the average total fluidity volume obtained along with its standard deviation.

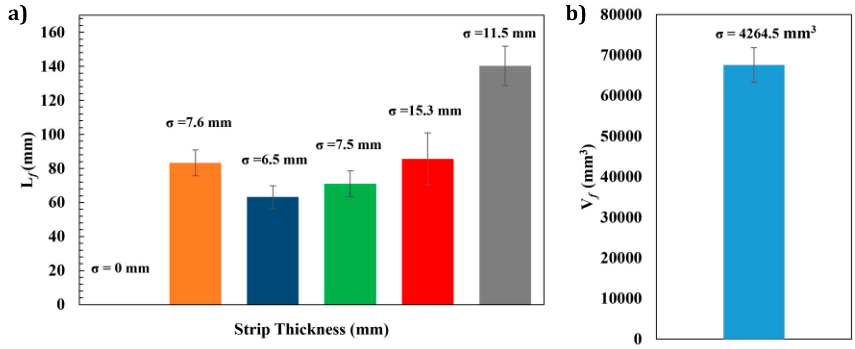

Figure 8 — (a) Fluidity length measurement (L_f) for each strip along with their standard deviations (b) Average total fluidity volume along with standard deviation

The fluidity length for AlSi10MnMg0.2 alloy was investigated using the multi-channel strip testing method. The test results demonstrate that the fluidity results are internally consistent and exhibit the same trends for all sets of performed experiments, with a very narrow range of standard deviation. The designed standard protocols and operational procedures also prove highly reliable in achieving higher reproducibility. Moreover, the testing method described here will be used to evaluate L_f for aluminium and its alloys for various thicknesses.

More results obtained with the mould and experimental procedure described here, that prove the test repeatability and ability to discriminate between different fluidity levels, will be published in conferences and/or scientific publications in the near future.

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