PROGRESS ON THE UNDERSTANDING OF FLUIDITY OF ALUMINIUM FOUNDRY ALLOYS

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Abstract

Fluidity of aluminium foundry alloys plays a key role for aerospace and automotive industries especially when producing thinner and hence lighter casting components. Fluidity is a complex property of the molten metal, which depends on many factors. This paper reports on recent results documenting the effect of important factors such as: casting temperature, grain refinement, alloy chemistry (particularly the presence of Sr, Ti, Mg and Fe), hydrogen and oxygen content, mould coating, etc. Over the years many test methods have been developed to assess fluidity; two specific and different methods were compared and analyzed. The results show that casting temperature, in the range investigated 700-730°C (1292-1346 F), plays the most important role in affecting fluidity. Alloy chemistry plays an important role as well. Neither the addition of a commercial 5:1 Ti:B master alloy, nor variation in the hydrogen level were observed to affect the fluidity of a standard A356 alloy significantly. Mould coating dramatically increases fluidity. The test methods compared give similar trends and can be used to rank alloys.

Keywords: *fluidity, aluminium alloys, casting.*

Introduction

Fluidity limits the castability of alloys and the final properties of castings, such as surface finish and wall thickness. Poor or insufficient fluidity affects the soundness of cast products and is detrimental to the final quality of the cast component, as well being critical to scrap reduction and increased profitability.[1] There is, therefore, a strong industrial demand for understanding the physical and process parameters governing the fluid flow of casting alloys in order to improve their fluidity. Moreover, many contradictory and uncertain results have been reported [2-7] on the influence of various parameters on fluidity, which to a large extent was one of the motivations of this work.

Much of the confusion in the literature stems from the fact that data reproducibility has not been a primary focus in past work. It is difficult to measure fluidity with a high degree of reproducibility, and that is the reason why reliable fluidity data for both pure and commercial aluminium foundry alloys are not readily available.

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.[8] Fluidity is a complex technological property and it depends upon many factors 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)
- Thermal conductivity
- Mass density
- Specific heat
- Surface tension

Other variables:

- Applied metallostatic head
- Channel diameter
- Casting temperature (superheat)
- Oxide/particle content

This investigation reports on the effect of casting temperature, alloy chemistry, grain refinement, hydrogen content, oxygen content, mould coating and test method used to assess fluidity.

Experimental

Fluidity was assessed using two different methods: (i) a spiral sand mould and (ii) a strip permanent mould. The spiral sand mould was designed and manufactured at SINTEF Materials and Chemistry (Norway) while the strip permanent mould is a commercially available test method for measuring fluidity of different types of alloys.

The main parts of the spiral 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). A full description of the test apparatus is given elsewhere.[9, 10] All alloys evaluated were melted in a 50kg induction furnace.

The main parts of the strip test apparatus are shown in Fig. 2 and are: drag consisting of five channels (*fingers*) of identical lengths and different cross sections; flat mould cope; gating system split into two semi-cylinders; an insulated pouring sleeve, held in place by a clamp ring on the top of the gating system. The total volume of the solidified alloy in the five channels was calculated and reported as a fluidity index. A full description of the test apparatus is given elsewhere.[11]

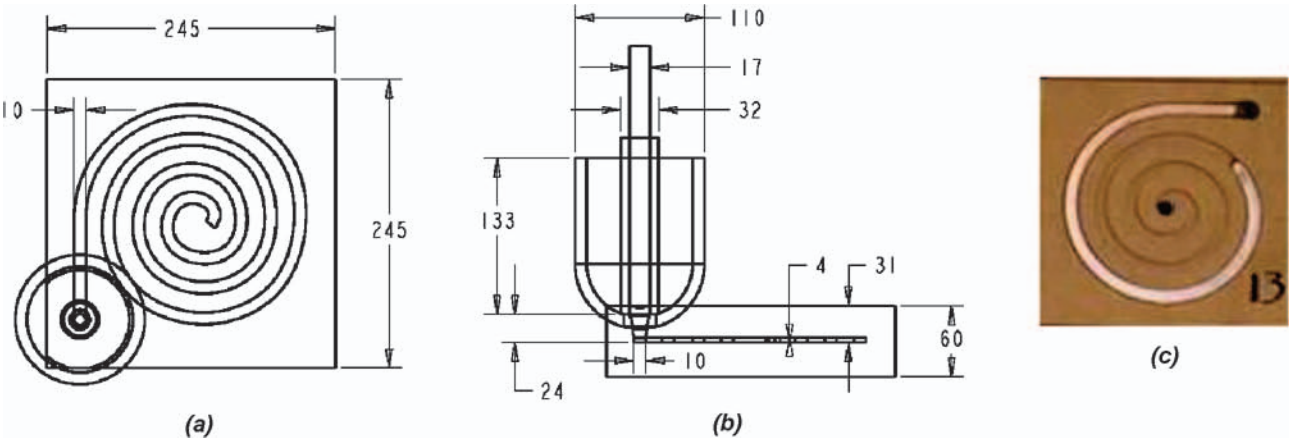


Figure 1. Drawing of the spiral mould showing a) top view and b) side view of stopper rod, pouring cup and sand mould (all dimensions are in mm); c) open mould and casting specimen.

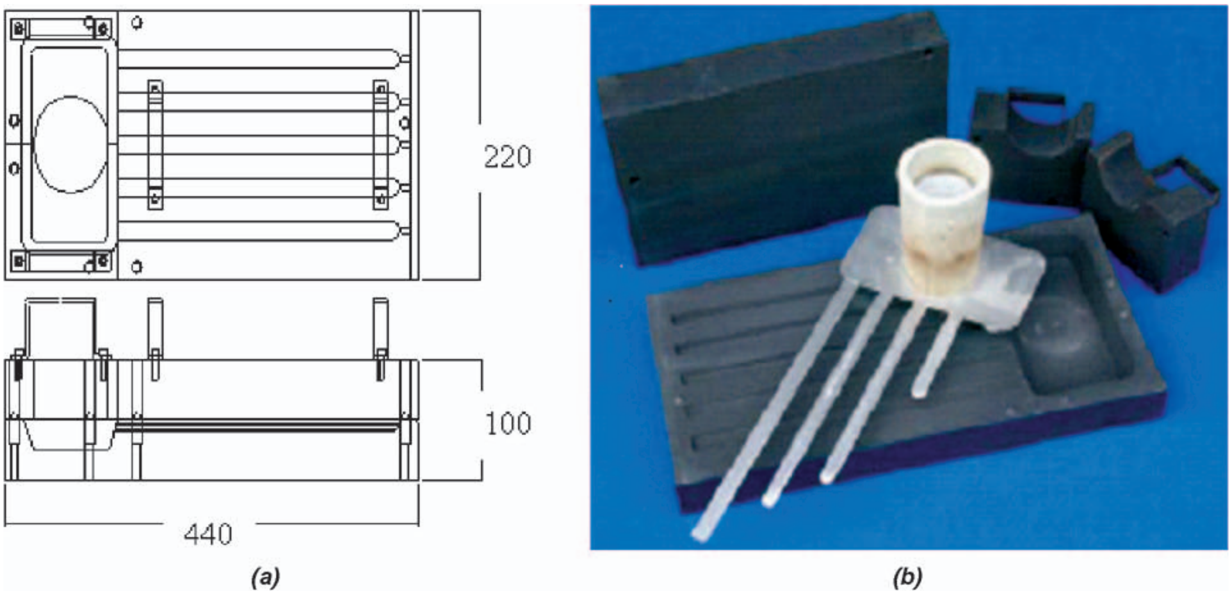


Figure 2. a) Top and side views (all dimensions are in mm) of the strip mould (11); open mould and casting specimen.

Table 1. Chemical composition (wt. %) of the alloy used to study the effect of casting temperature and grain refinement on fluidity.

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

Table 2. Chemical composition (wt. %) of the alloys investigated as supplied.

ALLOY*	Si	Mg	Fe	Cu	Ti	Sr	Mn	Ni	Cr
520	0.25	10	0.09	0.15	0.13	0	0.04	0.002	0.001
390	18	0.58	0.8	4.73	0.04	0	0.21	0.05	0.06
Al-17Si**	17	0.01	0.11	0.01	0	0.001	-	-	-
356	6.95	0.43	0.12	0.02	0.2	0	-	-	-

** AA designation* ***This alloy was made in the laboratory at WPI*

Table 1 shows the chemical composition of a standard A356 alloy, which was used to study the effect of casting temperature and grain refinement. Al-5wt%Ti-1wt%B rod type master alloy was added to the melt in order to increase the Ti content by 0.01, 0.02 and 0.04wt%, respectively, which are typical levels for grain refining Al foundry alloys.

Table 2 shows the chemical composition of the alloys investigated as supplied. All alloys follow the Aluminum Association designation with the exception of Al-17wt.%Si which was made in the laboratory at WPI. In order to investigate the effect of alloy chemistry, the fluidity lengths of these four alloys and pure Al (99.999%) were evaluated and compared.

The Taguchi design of experiment (DOE)[12,13] methodology enables one to reduce the number of experiments needed to investigate a process or a feature that depends on many variables. Taguchi/DOE was used to evaluate the effect of different alloying elements on fluidity of a standard A356 alloy; namely, the concentration of Sr, Ti, Fe and Mg. Also the effect of casting temperature was evaluated and analyzed. Each variable was investigated at two different levels. Table 3 shows the list of variables and the levels used in the experiments. These levels were selected based on:

- For the temperature: two levels which give low and high superheat
- For Sr, Fe, Mg, Ti: two values within the variation range of a standard A 356

All casting experiments were performed with the strip mould. Details of the statistical methodology can be found in.[11].

For each variable investigated, the percentage contribution to fluidity and the trend (positive, i.e. increased fluidity, or negative, i.e. decreased fluidity) were calculated from:

- Mean Squared Deviation (MSD):
  $$MSD = \frac{(1/Y^2_1 + 1/Y^2_2 + ... + 1/Y^2_n)}{n}$$ and
- Signal to Noise (S/N) ratio:
  $$S/N = -\ 10\times\log_{10}(MSD)$$

PoDFA (Porous Disc Filtration Analysis) tests[14, 15] were performed to analyse the level of inclusions. The molten metal is poured in a pre-heated crucible, placed on top of a vacuum chamber, and forced to flow through the porous filter disc via vacuum. Inclusions and oxides are retained on the surface of the disc, which is subsequently analyzed metallographically. 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" in the as-received condition.

In order to study the effect of hydrogen on fluidity, two levels of hydrogen were selected. The first level was the hydrogen level in the melted alloy after degassing with pure argon (99.99 wt.% Ar) with a rotating impeller for 45 minutes. The second hydrogen level was measured after plunging pieces of wood beneath the surface of the molten metal. The hydrogen levels obtained were 0.13 and 0.43 ml/100g for the argon degassed (D), and hydrogen gassed (G) melts, respectively. For each hydrogen level, ten spirals were cast at 700°C (1292 F). Porosity formation was qualitatively evaluated with a reduced pressure test (RPT)[15] during the cast trials, and quantitatively from density measurements.[15]

Table 3. List of variables, constants and their respective levels considered in the Taguchi design of experiments.

Independent Variable			Constant		Dependent Variable
Variable	Level		Constant	Level	
	Level 1	Level 2			
T	70ºC Superheat (126F)	130ºC Superheat (234F)	Mold	Steel die (H-13)	Total volume of metal filled in five channels
Sr	0 wt.%	0.023 wt.%	Mold Coating	Commercial coating	
Ti	0 wt.%	0.2 wt.%	Mold Pre-heat	295ºC (563F)	
Fe	0.006 wt.%	0.24 wt.%	Pouring Velocity	Maintained by the sleeve	
Mg	0.003 wt.%	0.45 wt.%			

Table 4. Chemical composition (wt. %) of the alloy (and scrap addition) used to study the effect of oxygen level on fluidity.

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.

In order to study the effect of oxides on fluidity, three alloys were investigated: a standard A356, and the same alloy with 20% and 50% scrap additions. The chemical composition is shown in Table 4. The scrap additions consisted of turning chips recycled from Al-7wt.%Si and Al-11wt.%Si alloys for wheel production. 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 chemistry, *i.e.* Al-7wt.%Si alloys.

In order to study the effect of coating on fluidity, a standard A356 alloy was cast in the strip permanent mould. Two series were compared: the first series of experiments used an uncoated mould; whereas in the second series a 0.2mm-thick commercially available coating was used. The mould was pre-heated to 295˚C (563 F) for all experiments. Two casting temperatures were used for both series, namely 684 and 744˚C (1263.2 and 1371.2 F) which gave approximately 70 and 130˚C (126 and 234 F) superheat, respectively.

Finally, the last part of this work compared the fluidity measurements from the two different methods, the spiral and strip moulds, in order to determine whether the test methodology chosen influences the results.

Results and Discussion

Effect of Casting Temperature

Figure 3 shows the results of the study on the effect of casting temperature on fluidity using the spiral sand mould test. Fluidity increases linearly with casting temperature following: $L_f = 5.633t - 3480$

where L_f is the length on the spiral (mm) and t is the casting temperature (°C).

Thus increasing the pouring temperature by 1˚C, in the interval 700-730°C (1292-1346 F), gives an increase in the fluidity length by 1%. It is important to note that at zero superheat, fluidity is not zero (L_f= 42 mm), which means that even if an alloy is cast at its melting temperature, the alloy can still flow for a short distance.

Effect of Alloy Chemistry

Figure 4 shows the fluidity values of pure Al and four Al alloys measured with the strip permanent mould. Alloy A520 (Al-Mg alloy system) possesses the least fluidity. This is consistent with the results of the Taguchi/DOE investigation (Mg decreases fluidity). Al-17wt.%Si alloy has no Mg as compared to the 0.58wt.% Mg in the A390 alloy (Table II). A390 alloy has less fluidity that Al-17wt.%Si alloy. This indicates that at constant Si levels increasing Mg decreases fluidity. Al-17wt.%Si alloy shows the best fluidity; higher than, for example, pure Al. It has been stated that in general, pure element and alloys at eutectic composition have the best fluidity.[1, 2, 5]. However, the Al-Si system deviates from this rule and has the highest fluidity in the hypereutectic region (at around 17-18wt.%Si). This is also consistent with previous reported observations.[16] .The positive influence of high Si content is attributed to the high latent heat of fusion of Si.[5, 17]

Effect of Grain Refinement

Table 5 shows the average fluidity lengths and standard error in the mean values for ten spirals cast with and without grain refiner additions. The average grain size for each grain refiner addition can be noted. The average grain size decreases by increasing grain refiner, as one may expect. However, it is evident that there is no significant effect of grain refinement on fluidity. One may notice that the alloy already contained Ti (0.059 wt. %). Therefore, the addition of grain refiner to an already somewhat refined alloy, as a standard A356 alloy, does not improve its fluidity.

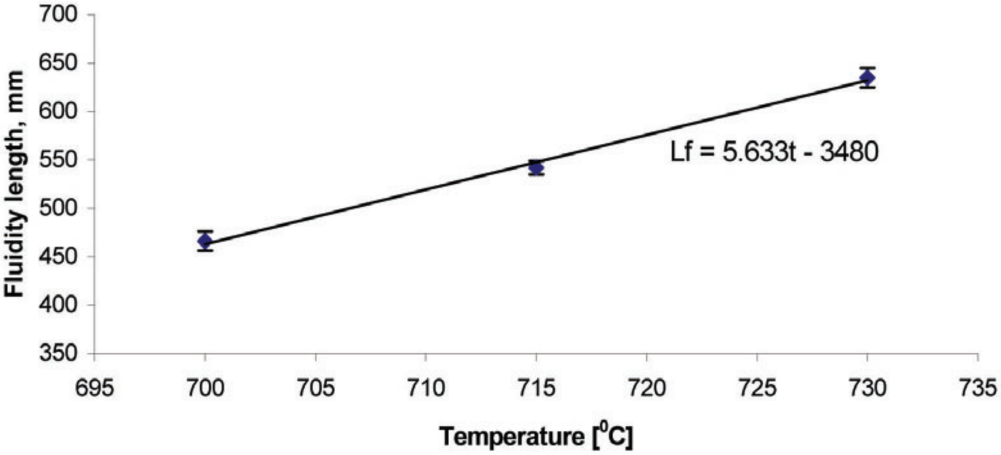


Figure 3. Average fluidity length of spirals versus pouring temperature (equation of best fit line is shown).

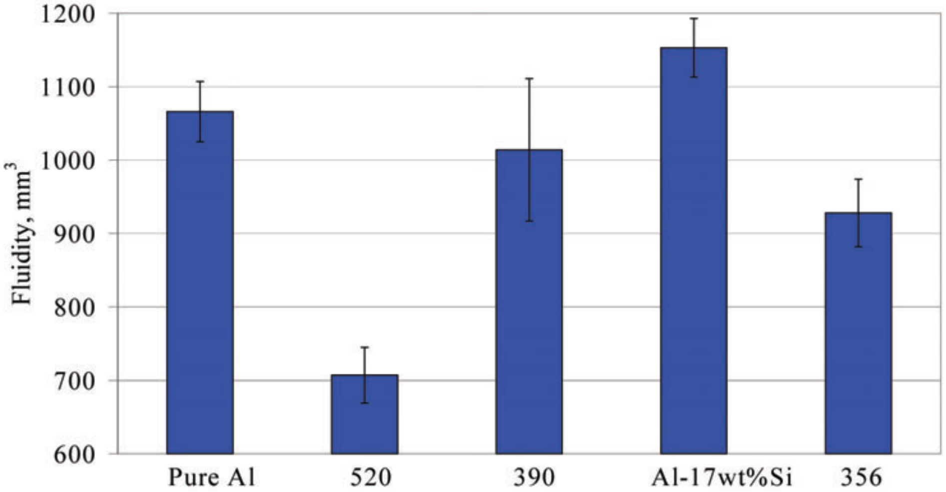


Figure 4. Fluidity of five alloy systems: pure Al (99.999%), A520, A390, Al-17wt%Si and A356. The fluidity was measured with a commercial strip mould test at a constant melt superheat (70°C, 126F).

Table 5. Average fluidity length and standard error, σ_m, for each level of grain refinement.

Grain refinement level wt.% Ti	Average fluidity length ± σ_m mm	Average grain size ± σ_m µm
0	540± 10	300± 30
0.01	550± 10	270± 30
0.02	560± 10	215± 30
0.04	550± 20	180± 25

Table 6. Quantitative and qualitative analysis of selected independent variables on fluidity from the Taguchi/DOE investigation.

Parameters	Contribution (%)	Trend
Sr	1.1	+
Ti	<1	
T	65.4	+
Fe	<1	
Mg	13	-
Error	16	

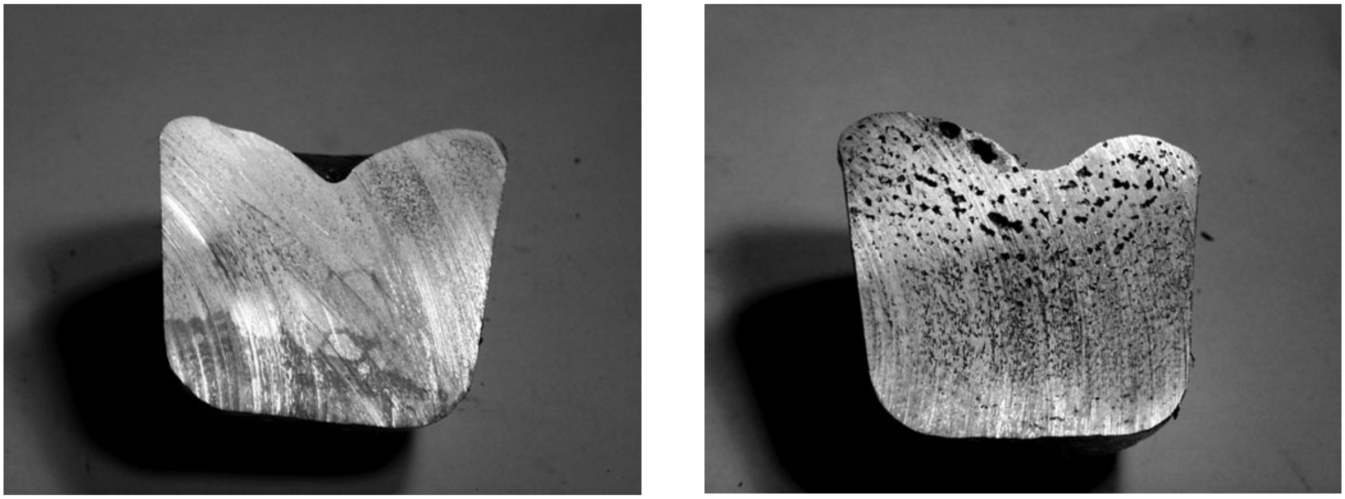
Some influence on fluidity by the grain refinement process might be expected, since it has been shown[2] that fine particles are more effective in stopping a flowing stream than an equivalent percentage by weight of coarse particles. In this case, fluidity might be expected to decrease with grain refinement. Conversely, however, it has also been shown[18] that grain refinement postpones the dendrite coherency point which studies[5, 8] have demonstrated to be related to fluidity. 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 in this work, the coherency point varies between 24% and 25% [10, 18], which is likely to give no significant effect on fluidity.

Taguchi/DOE Investigation

Table 6 summarizes the results of the Taguchi analysis. The study suggests that the variation of casting temperature gives the most pronounced change in fluidity of the melt (65.4% relative effect on fluidity). Higher casting temperature results in higher fluidity. Moreover, the analysis shows that within a family of Al-Si alloy such as A356, 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. The Fe content, within the limits of composition tested, does not have any effect on fluidity.

Effect of Hydrogen Level

Figure 5 shows two samples from the reduced pressure test (RPT) that were taken for the argon degassed (D), and hydrogen gassed (G) melts. It is evident that the hydrogen gassing has increased porosity, but no significant effect on the inclusion level is noticed. In fact the inclusion levels were 2.2 and 1.5 ppm (volume) for the low (D) and high (G) hydrogen levels, respectively. Figure 6 shows the average length of the fluidity measurements for the low (D) and high (G) hydrogen levels as well as the standard error. This result suggests that the hydrogen level does not affect the fluidity of an alloy.



(a) *(b)*

Figure 5. Results of the reduced pressure test: a) low hydrogen level; b) high hydrogen level.

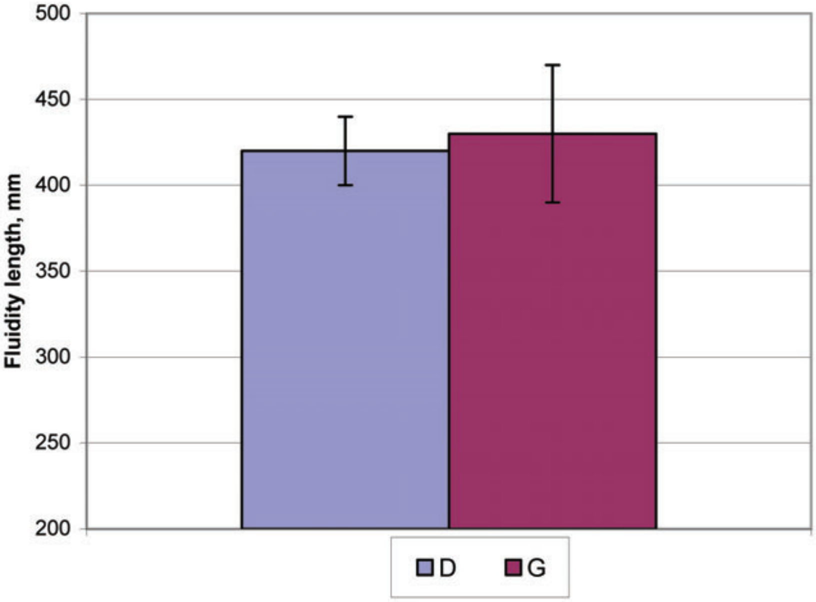


Figure 6. Fluidity for the two alloys with low (D) and high (G) level of hydrogen, respectively. The standard error bar is shown.

Effect of Oxide Level

Figure 7 shows the spiral fluidity lengths for three alloys: standard A356, A356+20% and A356+50% recycled alloys. The standard error is also shown. Clearly, A356 alloy has a 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.

The results of PoDFA analysis giving a measure of the total content of inclusions and oxides are shown in Table 7. Inclusions and oxides are measured in mm^2/kg and N/kg, respectively; the area of inclusions trapped (mm^2) and the total number of oxide particles (N) is evaluated per the amount of metal passed through the filter (kg). The A356 alloy is very clean: both total amount of inclusions and oxides are small, while the additions of 20% and 50% scrap significantly increase both inclusions and oxides. 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%

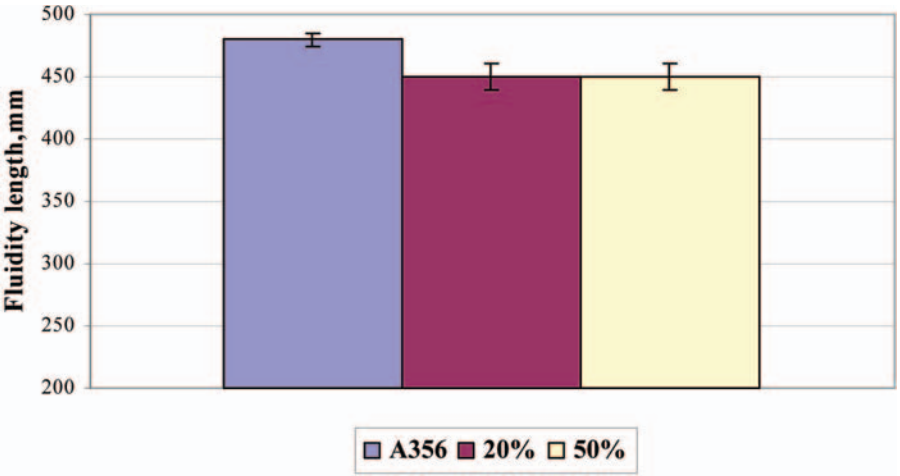


Figure 7. Fluidity for three alloys: standard A356, A356 + 20% scrap additions and A356 + 50% scrap additions. The standard error bar is shown.

Table 7. Results of the PoDFA analysis on the level of inclusions and oxides for each tested alloy.

	A356	A356+20%	A356+50%
Inclusions,mm^2/kg	0.438	0.967	1.305
Oxides, N/kg	2	46	25

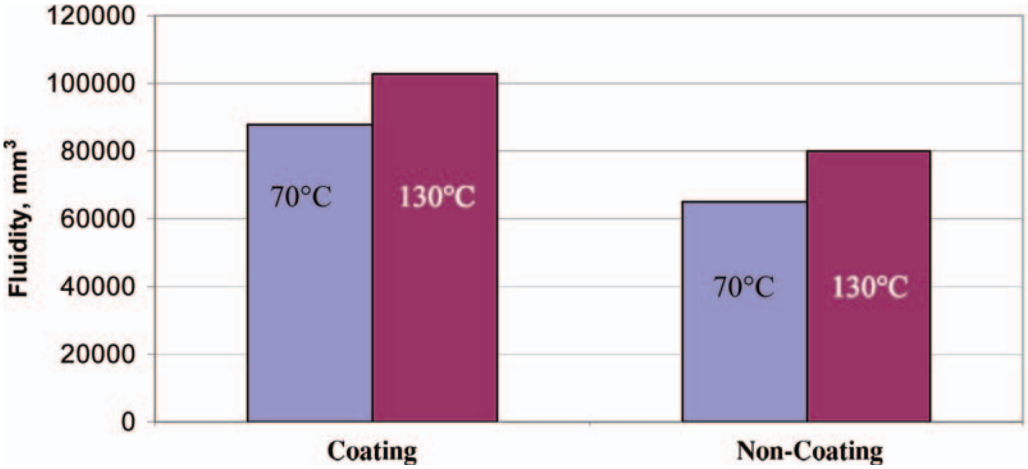


Figure 8. Fluidity of coated and uncoated moulds at two different superheats (70 and 130°C, 126 and 234 F).

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 due to the tendency of oxides to float to the surface.[19] No significant difference in oxide content may be the reason for no significant difference in the fluidity measurement for these alloys (Figure 7). Recycling aluminium alloys is possible at an industrial level and does not deteriorate fluidity, once operators manage to keep the inclusions and oxide contents at a low level. These findings are consistent with some industrial observations,[15, 20] which report that the addition of about 40% of recycled material to their alloys results in no difference in product strength, porosity level and scrap rate.

Effect of Mould Coating

Mould coating reduces the heat transfer from the melt to the mould.[21] Figure 8 shows fluidity measurements of the above alloys cast in a strip permanent mould with and without a coating. Clearly, the coating has a dramatic effect on fluidity. In this investigation, mould coating increased fluidity by approximately 20 to 40%.

The use of two different casting temperatures (superheats of 70 and 130°C, 126 and 234 F) confirms the strong effect of temperature in increasing fluidity.

Comparison of Fluidity Test Methods

The fluidity measurements obtained with the spiral sand mould and the strip permanent mould are shown in Fig. 9. The fluidity assessments were performed for alloy A356 at the same casting temperatures. The equations of the best fit line are reported and show that, although the two test methods give different absolute values of fluidity measurements, they have a similar trend. Thus, even though the two test methods are intrinsically different (one measures the length of a spiral cast in a sand mould, whereas the other measures the total length of five fingers cast in a steel mould, they can be used for ranking alloys. The two fluidity test methods provide a good means of assessing castability of alloys from the perspective of fluidity, and it is worth to underline that the ease of use of these methods is an advantage for the practitioner.

Conclusions

This study has reported some of the latest results on the parameters affecting the fluidity of aluminium foundry alloys. The following conclusions were 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.
- Fe content, within the limits of alloy composition evaluated, does not have any effect on fluidity.
- There is no statistically significant effect of grain refiner addition to a standard A356 alloy.
- High hydrogen content does not significantly affect the fluidity of A356 alloy, although, as to be expected, porosity increases.
- Inclusions play an important role on fluidity. Increasing inclusions and oxide content decreases fluidity.
- The addition of recycled alloys may increase inclusions and oxide content. However, the percentage of recycled aluminium alloys does not significantly affect fluidity for the same content of inclusions and oxides.
- Coating the mould is a useful practice to increase fluidity, particularly at low casting temperatures.

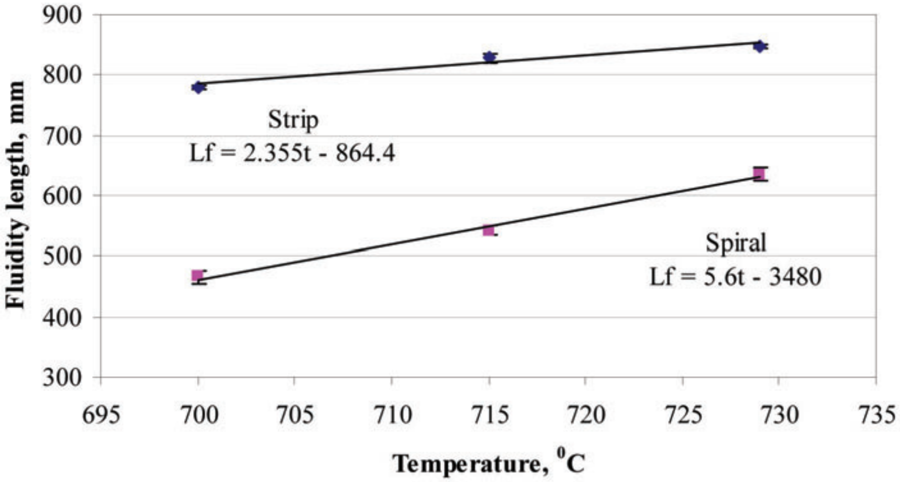


Figure 9. Comparison of fluidity measurements obtained with two different test methods: spiral sand mould and strip permanent mould.

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Dr. Øyvind Nielsen (SINTEF) is acknowledged for interesting discussions. NTNU, SINTEF and the Norwegian Research Council (NFR) are gratefully acknowledged for the financial support. Dr.s Libo Wang, Freddy Syvertsen and Arne Nordmark are acknowledged for their help with the casting experiments. The authors thank N-Tec for providing the fluidity strip mould.

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Technical Review and Discussion

Progress on the Understanding of Fluidity of Aluminium Foundry Alloys

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Reviewer: Suggestion for future work: If grain refiner wasn't added to the melts used for this study, either directly or inadvertently via the chips, then it might be a good idea to produce a truly clean melt by floating a cleaning flux on the top of the metal during degassing. PoDFA numbers of 0.01 have been obtained this way in commercial casting operations.

Authors: *A good suggestion, however, work on this project is completed. If future work is to be carried out, we can incorporate this suggestion.*

Reviewer: It would be interesting, under similar experimental conditions, to study the mold filling / fluidity of a metal in a real casting. In a cast part changes in porosity (shrinkage,gas) locations and occurence could be related to the different testing parameters: composition, metal cleanliness, metal temperature, mould temperature , H2 content, etc...

Authors: *The results of this work certainly apply to real castings. The data obtained is commercially applicable.*

Reviewer: It is not clear whether the DOE was carried out for both spiral and strip mould test results, or just on one mould. If the latter, please indicate justification for it. Sand mould vs. permanent mould?

Authors: *The experiments with the strip mould were intended to evaluate the influence of alloying elements on fluidity and consequently several parameters were studied in a series of experiments. Therefore, DOE was an appropriate tool for these experiments. In the spiral mould experiments, however, only one variable was evaluated in each experimental series and thus a DOE was not utilized.*

Reviewer: Was the fluidity length for the strip mould measured by the total length of all the fingers filled? As the two methods (spiral and strip moulds) as pointed out by the authors are intrinsically different, it may be confusing to propose formulas for absolute fluidity length and plotted on the same graph for both methods. It is also confusing to use volume as well as length measures for the strip mould method at different places.

Authors: *This has been commented on in the paper. For comparisons, fluid length is most appropriate. A few sentences have been added in the manuscript to clarify.*

Reviewer: The conclusions seem to imply that fluidity results from both the sand mould and permanent mould are equivalent in all respects. As this was not discussed in the paper, for example the results are presented for one mould under some parameters and the other mould for other parameters, perhaps the authors should clarify this point to avoid possible confusion?

Authors: *The conclusions do not mention anything about similarities and/or differences between the two methods. This has been elaborated in the discussion in the final paper.*