A REVIEW ON THE FLUIDITY OF AL BASED ALLOYS

M. Di Sabatino, L. Arnberg
Norwegian University of Science and Technology,
Department of Materials Technology, A. Getz vei 2B, N-7491 Trondheim (Norway)

Abstract

Fluidity of molten metals is of significant importance in producing sound castings, particularly thin-walled castings. To meet the industrial demands of complex shaped castings, the knowledge of the parameters affecting fluidity is required in order to have a better control of the production processes. Since fluidity is one of the measures by which the castability of metals can be quantified, a definition and a description of castability are presented in this study. A definition of fluidity follows. Fluidity depends on many factors and this study reports the influence of the main factors: alloy composition, heat of fusion, superheat, grain refinement, modifying agents, mould material and temperature, melt cleanliness, coating and viscosity.

Riassunto

Lo studio della fluidità delle leghe di alluminio da fonderia sta diventando molto importante, soprattutto nella produzione di componenti a sezione sottile. La realizzazione di componenti dalle forme geometriche sempre più complesse richiede una maggiore conoscenza dei parametri che influenzano la fluidità e un maggiore controllo del processo di produzione. Poichè la misura della fluidità permette di valutare la colabilità delle leghe di alluminio da fonderia, una definizione e una descrizione della colabilità sono presentate in questo studio. La fluidità delle leghe di alluminio da fonderia dipende da molti parametri. Questo studio rivolge particolare interesse ai principali parametri che influenzano la fluidità: composizione chimica della lega, entalpia, temperatura di colata, raffinamento del grano, agenti modificanti, materiale e temperatura dello stampo, qualità del metallo fuso, rivestimento dello stampo e viscosità della lega.

1. INTRODUCTION

The industrial demand of thin-wall castings in aluminium alloys is of great importance in order to produce light components. The production of thin-wall castings is limited by the fluidity of the molten metal. The fluidity is influenced by many factors that can be divided into metallurgical and mould/casting variables. The metallurgical factors are the composition, superheat, latent heat, surface tension of the melt, including oxide film, and mode of solidification. The mould/casting factors are heat transfer coefficient at the interface, mould temperature and mould conductivity. Many researchers have investigated those factors and some of the main results are reviewed in this study.

2. CASTABILITY

The castability of a metal describes its ability to be cast without defects and to reproduce the mould pattern with the desired properties of the final casting [1]. It involves many different phenomena such as: mould-filling, feeding, porosity, macrosegregation, hot-tearing and fluidity. A sketch of those phenomena is shown in Figure 1.

2.1 MOULD-FILLING

A good mould-filling metal has the ability to fill out the mould pattern and reproduce fine details of the mould. Mould-filling is strongly dependent on the surface tension between the mould and the metal. Therefore it is affected by the mould characteristic, melt composition and melt cleanliness. The pressure in the metal will also have some effect on mould-filling [1,2].

2.2 FEEDING

Feeding is the process where material movement occurs to compensate the shrinkage during solidification. Feeding is one of the most important and critical phenomena to consider in order to achieve good quality castings. Incomplete feeding causes porosity in the poorly fed regions or in surface depressions. Campbell [1] has identified different mechanisms by which feeding can be achieved in a casting, depending on solidification conditions. There are principally five different ways by which material may be transported, although not all are expected to be operating in each casting [1]. The feeding processes operate in different ranges of fraction solid in the solidification interval. As the local fraction solid increases, feeding can occur due to liquid feeding, mass feeding, interdendritic feeding, burst feeding and solid feeding. Figure 2 shows a scheme of the five feeding mechanisms.

2.3 POROSITY

Porosity in a casting is attributed to both solidification shrinkage and high gas content. During solidification, pure aluminium and aluminium alloys contract. The inability of the molten metal to feed through the interdendritic regions causes porosity [1,2]. Moreover, even with perfect interdendritic feeding, porosity can form. When a liquid metal is trapped with completely solidified metal all around, hot spots form. When a hot spot solidifies and contracts, a macropore will form, unless extensive solid feeding occurs. Because most gases reduce their solubility with the temperature during solidification, gas rejection processes also causes porosity. Therefore porosity is strongly dependent on the internal pressure and on the gas content of the molten metal [1,2]. In order to decrease porosity and achieve good quality castings, the gas content, particularly the hydrogen content, has to be low.

2.4 MACROSEGREGATION

Macrosegregation is due to movement of liquid and solid within the mushy zone [2]. Highly segregated phases are present within the mushy zone during solidification. Physical displacement of these phases leads to macrosegregation. The displacement can occur by floating or settling of precipitated phases early in solidification. Equiaxed grains form early in solidification and, since they are not attached to other grains, they may float or settle. Inclusions may float or settle [1]. This is the macrosegregation due to gravity, but also shrinkage can cause macrosegregation. Due to contraction during solidification, movement of liquid and solid occurs to feed the solidification shrinkage. Pressure gradients can arise. 'V' segregates and 'inverse segregation' (segregation towards the ingot wall) may form [1]. Moreover, thermo-solutal and forced convection in the interdendritic liquid can cause macrosegregation. Macrosegregation reduces the quality of most castings.

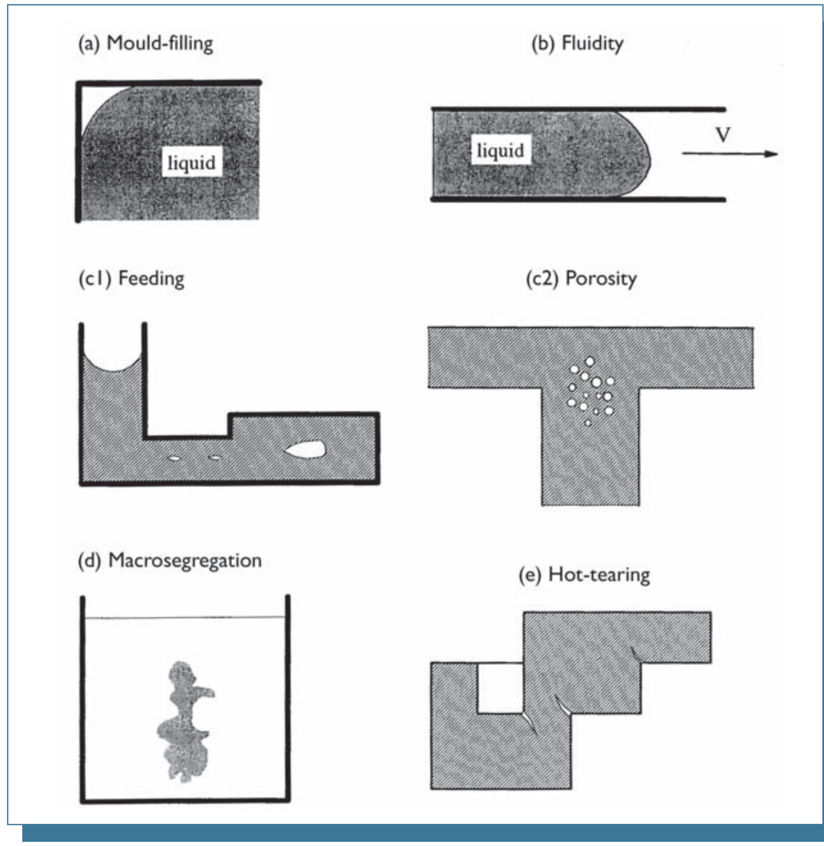

Fig. 1: Illustration of the phenomena related to the definition of castability [20]: (a) mould-filling, (b) fluidity, (c1) feeding, (c2) porosity, (d) macrosegregation, (e) hot-tearing

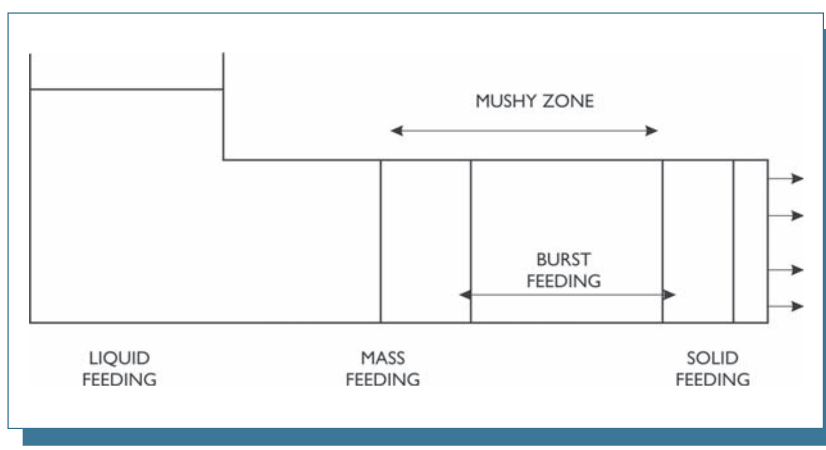

Fig. 2: Scheme of the five feeding mechanisms in a solidifying casting. As the local fraction solid increases, feeding can occur due to liquid feeding, mass feeding, interdendritic feeding, burst feeding and solid feeding [1]

2.5 HOT-TEARING

The solidification shrinkage and thermal contraction can cause significant stresses. The casting may tear in regions where the strength is still low. Those regions are not completely solidified and hot spots occur [2]. The formation of hot tears is due to a lack of feeding in the mushy zone. If the casting is well fed and the permeability in the mushy zone is high, the liquid can flow between the separating dendrites and heal the incipient tears.

Casting temperatures, freezing range and grain size are important variables affecting hot tearing [2]. A low casting temperature is often beneficial for reducing hot-tearing. Narrow freezing range alloys show better resistance to hot-tearing. Grain refinement reduces the hot-tearing susceptibility [1,2].

3. DEFINITION OF FLUIDITY

Fluidity, in the foundry science, is defined as the ability of molten metal to flow before stopped by solidification [2]. Fluidity is quantified by measuring the length a molten metal will flow when it is poured into a small cross section channel. The small cross section channel provides conditions for rapid cooling and large temperature gradient, which give good fluid flow [2, 3].

A mathematical model for estimating fluidity length was proposed by Flemings et al. [2,3]. The model provides the following equation for calculating the flow length L_f:

$$Lf = \frac{A\rho V_0(f_{scr}DH + c_pDT)}{hS(T - T_0)}\,(1+K/2) \qquad (1)$$

where:

A is the mould cross sectional area;

ρ is the liquid density;

V_0 is the flow velocity;

f_{scr} is the critical fraction solid for flow stoppage;

DH is the heat of fusion;

c_p is the specific heat of the metal;

DT is the melt superheat;

h is the heat transfer coefficient between mould and metal;

S is the circumference of the mould channel;

T is the temperature of the liquid;

T_0 is the room temperature;

K is a constant depending on h, the heat transfer coefficient and, hence, the resistance to heat flow (metal-mould interface).

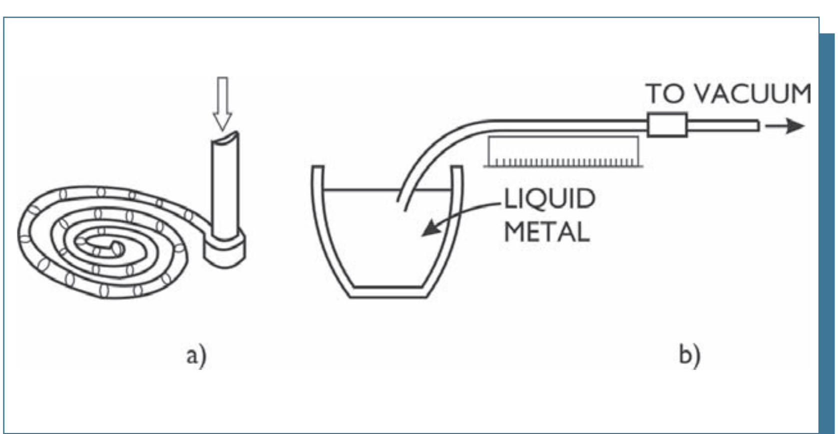

Fig. 3: Scheme of two fluidity tests: a) spirals test: the molten metal is poured in a spiral-shaped mould; b) vacuum test: the molten metal is sucked through a tube by a vacuum pump [2]

In the development of the model represented by Equation (1), it is assumed that [3]:

- solid particles form at the tip during flow in a fluidity channel and travel downstream with the liquid;
- flow stops when the mean solid concentration near the flow tip reaches a certain value (critical solid fraction f_{scr});
- flow velocity is constant until flow stops.

Equation (1) shows:

a) fluidity increases linearly with the increase of superheat DT;
b) fluidity is not zero at zero superheat;
c) fluidity increases with increasing heat of fusion DH;
d) fluidity increases with velocity of flow;
e) fluidity is proportional to the ratio of the cross sectional area, A, and the circumference of the channel, S.

The equation by Flemings quantitatively is in reasonable agreement for the Al-4.5%Cu alloy with the experimental data obtained with a vacuum fluidity test [3]. However, the assumptions make the formula difficult to apply to the different Al based alloys. Reliable fluidity data for aluminium casting alloys are not presently available, even though those data are very important in the optimisation of the casting properties of the alloys [4], and there is a need for improved fluidity test methods.

4. FLUIDITY TESTS

The most used tests for measuring fluidity are the vacuum fluidity test and the spiral test. The first method measures the length the metal flows inside a narrow channel when sucked from a crucible by using a vacuum pump. The second method measures the length the metal flows inside a spiral shaped mould. Those tests are shown schematically in Figure 3.

5. SOLIDIFICATION MODES

In the solute rich alloys with a wide solidification range, fluidity is limited by choking. The flow is choked by precipitation of equiaxed grains at the leading tip of the flowing stream and by the accumulation of solid crystallites [3].

Pure aluminium, dilute alloys and eutectics stop by pinching because solidification proceeds smoothly from the channel wall. Those different mechanisms of flow stoppage are shown in Figure 4.

The hypoeutectic Al-Si alloys, that precipitate dendrites with complex shapes, show lower fluidity than hypereutectic alloys that precipitate simple plate-like crystals [5,6]. In a fluidity spiral test, solid particles form during flow and travel downstream with the liquid. The flow stops when the mean solid fraction reaches a so-called "critical solid fraction" [7]. Flow velocity is essentially constant until the flow stops. In most fluidity spiral tests the effective metal head is low and a small amount of solidification near the flowing stream is sufficient to stop the flow. With Al-4.5%Cu alloy and an effective metal head less than 5cm, about 5% of the solid is sufficient [7]. At higher pressures more solidification can occur before flow ceases. In the fluidity tests usually employed, and for most sand castings, factors such as surface tension, surface films or melt viscosity may be neglected [7].

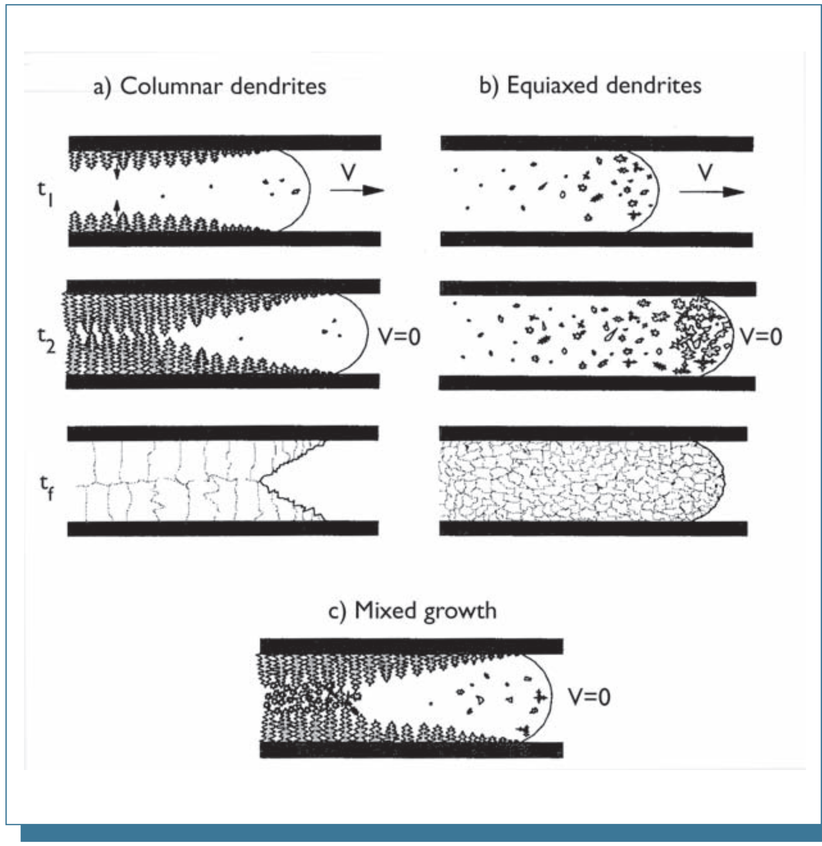

Fig. 4: Three types of solidification modes in the fluidity tests [20]: a) pure metals, dilute alloys and eutectics stop by pinching because solidification proceeds smoothly from the channel wall; b) solute rich alloys with a wide solidification range, stop by choking and the flow is choked by precipitation of equiaxed grains and by the accumulation of solid crystallites; c) third type of solidification mode with mixed growth for the other cases

6. FACTORS INFLUENCING FLUIDITY: LITERATURE REVIEW

Composition is one of the main factors influencing fluidity. Small alloying additions to pure metals reduce fluidity [1, 2], and the fluidity of unalloyed aluminium is reduced with decreasing purity [8]. Among elements which decrease the casting fluidity of pure aluminium, Ti, Fe and Zr exert an intermediate effect, while Cr, Mn and Cu have a smaller effect [9]. Gowri and Samuel [10] studied the A380 die casting alloy and observed that an increase in the Fe content decreases the fluidity of the alloy. The additions of 1.5 and 1.7%wt Fe to the A380 alloy caused a decrease in fluidity of 4% and 6%, respectively. The additions of 1.3%wt Zn to the 380 alloy caused a decrease in fluidity of 5%. However, the additions of 1%wt Cu to the 380 alloy caused a increase in fluidity of 4%. No significant change in the fluidity of the A380 alloy was observed when 0.23 and 0.5wt% Mg were added. Rooy [11, 12] reported similar reductions in the fluidity of the Al-Si based foundry alloys with the increase in Fe content. Wang et al. [13] reported a decrease in the fluidity of molten aluminium with increase of Fe without any appreciable change in the surface tension, due to an increase in the amount of insoluble Fe-bearing phases that form in the alloy [13, 14]. However, Pfeiffer and Sabath [15] observed that fluidity increased as the total combined concentration of Fe, Mn and Zn was increased in an Al-8%Si-3%Cu alloy. The variation of fluidity with composition in Al-Si alloys has been reported by Lang [16] and is shown in Figure 5. The fluidity of pure Al decreases with increasing Si content to the maximum solubility limit, at 1.65 wt%, beyond which it remains relatively constant by further additions. At Si content higher than 7-8 wt%, however, there is a remarkable increase in running length towards a maximum at about 18 wt% Si (well above the eutectic composition of 12 wt% Si). The fluidity of hypereutectic Al-Si alloys is better than that of hypoeutectic and even eutectic compositions. One of the reasons is the high heat of fusion of primary silicon [17]. The heat of fusion of primary silicon is 4.5 times higher than the heat of fusion of pure aluminium[18]. Moreover, in the Al-Si alloys, even at eutectic composition, aluminium dendrites are present due to a skewed coupled zone [19]. The dendrites disappear at a higher Si content than eutectic. Alloying elements can have beneficial effects on fluidity [3,9,20] since:

- increase in superheat due to lowering of the liquidus temperature;
- change in temperature range over which solidification occurs;
- change in the nature of the primary crystals which are formed;

- change in the nature of the oxide films.

Superheat, i.e. the difference between the melt temperature and the liquidus temperature, is also a very important factor influencing fluidity. The fluidity increases with increasing the melt temperature for a given alloy composition. Kolsgaard [21] has reported that the fluidity length, measured with a spiral test in sand mould, increases linearly by increasing superheat. The increase by 1°C in the melt temperature gives an increase of 1% in the fluidity length, in the temperature interval 700-760°C [21]. Sahoo and Sivaramakrishnan [22] measured the fluidity of an Al-8.3%Fe-0.8%V-0.9%Si with a standard spiral test in sand mould. They reported an increase of 0.4% in the fluidity length when the melt temperature increased by 1°C, in the interval 860-900°C [22]. Deviating results on the effect of grain refinement on fluidity have been reported in the literature. Mollard et al. [8] showed a reduction in fluidity when 0.15% Ti was added to an Al-4.5%Cu alloy, tested with a vacuum fluidity apparatus. Tiryakioglu et al. [23] found no effect on grain refinement in A356 Al-Si alloy tested in a sand spiral test, adding 0.04 wt% Ti as AlTi5B1 master alloy. Lang [16] found a significant increase in fluidity with boron additions in the range of 0.04-0.07 wt% B to Al-Si alloys, tested with a bar die casting. Dahle et al. [24, 25] observed a more complex variation in fluidity with successive additions of AlTi5B1 in AlSi7Mg and AlSi11Mg alloys tested with sand spirals. Fluidity was reduced with grain refinement below 0.12% Ti, while it increased with additions above 0.12% Ti. The fluidity length decreased 5% with 0.01% Ti and up to 9% with a further addition of 0.12% Ti [25]. Alloys only grain refined by boron showed the smallest grain size (the largest fraction solid at dendrite coherency) and the best fluidity. Chai [26] investigated the effect of grain refinement of an Al-4%Cu alloy with a vacuum fluidity apparatus, observing that increased grain refinement correlated with increased fluidity and increased solid fraction at coherency. The effect of grain refinement on the fluidity of Al based alloys depends on many factors: type and amount of grain refiner, alloy composition, holding time and temperature in the furnace. The complex behaviour of grain refinement has been recently explained by Greer et al. [27, 28, 29]. The studies by Greer et al. give an explanation of the controversial previous results.

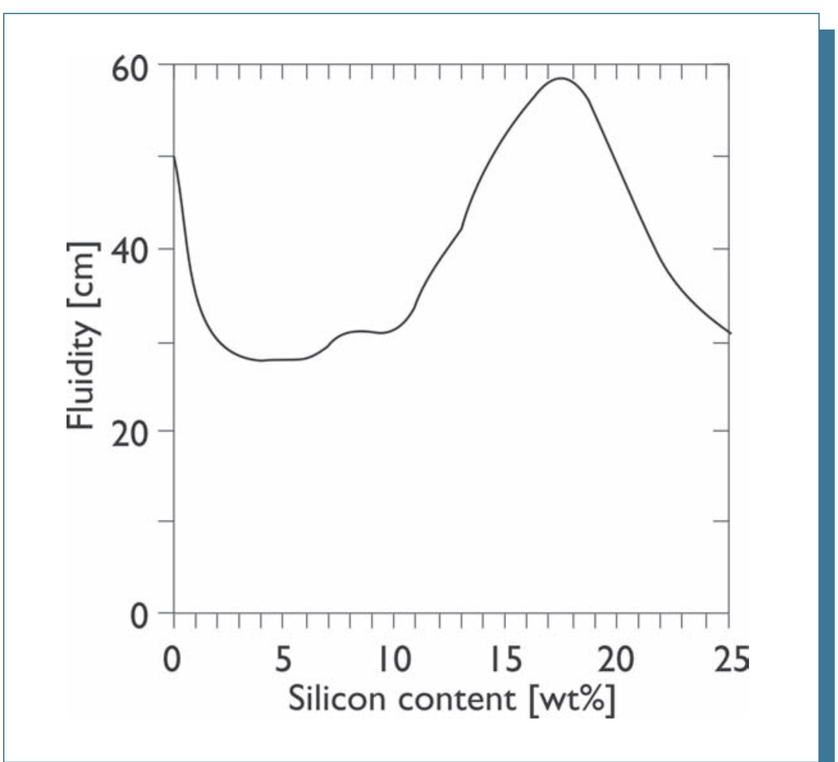

Fig. 5: Fluidity of binary Al-Si alloys, poured at a constant pouring temperature of 800 °C [16]. First, the fluidity length decreases as the silicon contet increases; afterwards the fluidity lenght increases to a maximum value corresponding to about 18% Si content.

Since fluidity is determined by phenomena occurring at the initial stage of solidification, the effect of eutectic modifying agents in Al-Si alloys would not be expected to give any large effect [20], unless the Si content is close to the eutectic composition. The effect of additions on the constitution and properties of the oxide skin may, however, be more significant. Reported data [21,30] show a slightly decreased fluidity with addition of modifiers. Modification of Al-Si hypoeutectic alloys, by adding Na or Sr, gives strength and ductility to the casting. Plate-like coarse silicon particles are converted into fibrous particles. Kotte [31] found that both Na and Sr reduce fluidity to some extent, but with Sr the reduction in fluidity was less than with Na. Venkateswaran et al. [32] have studied the effect of trace elements on the fluidity of eutectic Al-Si alloys. Fluidity decreases with the additions of Na, Na plus Sr, Ti, Na plus Ti, Na plus Sr plus Ti, while it increases with the additions of S, Sb, Sb plus Ti, S plus Ti. Modification of Al-Si alloys reduces fluidity up to 10% [8]. Sheshradri et al. [9] found that the modification of AlSi12 reduced the fluidity by 5% to 7% in a sand mould and by 2% to 3% in a cast iron mould. Lang [16] found that B increases fluidity, while Na has the opposite effect. Sahoo and Sivaramakrishnan [22] studied the effect of modification by Mg in Al-8.3%Fe-0.8%V-0.9%Si alloy on the fluidity. The found that the modified alloys posses better fluidity than the unmodified alloys. High purity magnesium was added to the melt at 880°C temperature. The addition of 1% pure Mg gave 15% better fluidity than the unmodified alloy [22].

The influence of mould materials was studied by Niyama et al. [17]. It has been shown that in vacuum test, the fluidity in stainless steel tubes is higher than in quartz tubes. Flemings at al. [7] found that fluidity in fine grain sand was lower than in coarse sand. Significant metal penetration was obtained in the coarse sand spirals, which resulted in an increase of the length of the spiral [21]. Fluidity in green sand moulds was unaffected by change in grain size, moisture content or by small addition of sand additives such as cereal or sawdust [33].

Groteke [34] measured a very strong effect of the melt cleanliness on fluidity. Up to 20% improvement in fluidity was observed when the melt was cleaned by purging with halogen gases in

319 and Almag alloys. However, Tiryakioglu et al. [23] reported that fluidity of A356 was unaffected by fluxing and it was within the experimental scatter. The presence of inclusions showed no significant effect. Moreover, degassing resulted in a slight reduction in fluidity of 356 alloy. Flemings et al. [3] reported an insignificant effect of small contents of dissolved gas on fluidity of Al-4.5%Cu. Kim and Loper [35] also reported insignificant effect for Al-Si based foundry alloys. Recent studies by Young-Dong Kwon et al. [36] have shown that oxide inclusions in the melt decrease the fluidity especially at a low pouring temperature.
An important function of mould coatings is to reduce the heat transfer rate between the flowing metal and the mould. The greater the resistance to heat flow at the metal-mould interface, the longer the metal will retain its heat and remain fluid. The coating affects the heat transfer condition only during the first small fraction of a second. Afterwards, almost throughout the solidification process, their effect on heat transfer is negligible [21]. Niyama et al. [17] showed that fluidity increases drastically when simultaneously casting in an argon atmosphere and using an organic mould surface coating. Argon showed no appreciable influence when used alone. Studies have revealed that a zirconia coating, as well as hexachloroethane and carbon black, enhances fluidity [7, 23].
Since the measurement of fluidity involves both a high cooling rate as well as a large flow rate, a refinement in structure that will change the rheology during solidification is expected. Large undercoolings, established during cooling, and dendrite fragmentation, will postpone the dendrite coherency point [20]. Therefore it is not straightforward to compare the measurements of dendrite coherency, measured under stagnant condition, and fluidity since there is a large difference in solidification conditions.
The viscosity of molten metals is quite low, for instance below 0.003 Pa◊s for Al-7%Si-Mg alloy [37]. Therefore the effects of viscosity on fluidity in a casting mould can be neglected as long as the metal maintains the liquid state during pouring [21, 37]. Bastien et al. [38] found that the fluidity of a molten metal, measured by a spiral test, does not depend on its viscosity. In general, it is of little value to measure the viscosity in order to determine alloy properties if importance in a foundry. The viscosity and surface tension may become important only in extremely thin section castings [17, 38].

7. CONCLUSIONS

A definition and description of castability have been presented in this study. The definition of castability involves many phenomena. A description of those phenomena has been given.
A definition of fluidity and a literature review of the main factors influencing fluidity have been presented.
The review of the factors influencing fluidity has shown that:

- Composition: fluidity of pure metal and eutectics is higher than for alloys. Between the alloying elements, Fe significantly decreases fluidity of Al based alloys.
- Superheat: fluidity increases linearly with increasing melt superheat.
- Grain refinement: researchers have found controversial results on the effect of grain refinement on fluidity. The complex behaviour of grain refinement has been recently explained.
- Melt quality: the oxide inclusions decrease fluidity, particularly at low pouring temperature.
- Coating: the Zr coating plays an important role in the enhancement of fluidity.

8. ACKNOWLEDGEMENTS

The present work was funded by the project NorLight Shaped Castings of Light Metals, with the following partners: Alcoa Automotive Castings, Scandinavian Casting Center ANS; Elkem Aluminium NS: Fundamus AS; Hydro Aluminium Metal Products; Hydro SA, Hydro Magnesium; Netherlands Institute for Metals Research; Norwegian University of Science and Technology (NTNU); and SINTEF. The authors thank the industrial partners and the Norwegian Research Council for financial support.

REFERENCES

[1] Campbell J., Castings, Butterworth-Heimann Ltd., Oxford, (1991)
[2] Flemings M.C., Solidification Processing, McGraw-Hill Inc. London, (1974)
[3] Flemings M. C., Niyama E. and Taylor H.F., Fluidity of Aluminium alloys. An experimental and qualitative evaluation, AFS Trans., (1961), vol. 69, pp. 566-576
[4] C.R. Loper, Jr. Fluidity of aluminum-silicon casting alloys, AFS Trans., 1992, pp.533-538
[5] Kayama N., Murai K., Kiguchi S. and Satoh H., Effect of formation of primary crystals on fluidity and viscosity in nearly stages of solidification, Report of the casting research laboratory, Waseda Univ., n. 27, (1976), pp. 1-8
[6] Kayama N., Viscosity and fluidity in the early stages of the solidification of metals, Quality control of engineering alloys and role of metals

science, Delft Univ. of Tech., (1978), pp.103-119

[7] Flemings M.C., Mollard F.R. and Taylor H.F., Mould variables influence on fluidity of aluminium- Doubling casting ductility by fluidity control, Modern Casting, (1961), pp.100-110

[8] Mollard F.R., Flemings M.C. and Nyama E.F., Understanding aluminium fluidity: the key to advanced cast products, AFS Trans., (1987), vol. 95, pp.647-652

[9] Sheshradri M.R. and Ramachandran A., Casting fluidity and fluidity of aluminium and its alloys, Modern Casting, (1965), vol.21, pp.110-122

[10] Gowri S. and Samuel F.H., Effect of alloying elements on the solidification characteristics and microstructure of Al-Si-Cu-Mg-Fe 380 alloy, Metall. Trans. A, (1994), vol.25, pp.437-448

[11] Rooy E.L., Recycling and its impact on the metal castings industry, AFS Trans., (1985), vol. 93, pp.935-938

[12] Rooy E.L., Metals Handbook 9th Ed., Castings, ASM, (1988), vol.15, pp.743-770

[13] Wang L., Makhlouf M. and Apelian D., Aluminium die casting alloys: alloy composition, microstructure, and properties-performnce relationships, Inter. Mater. Rev., (1995), vol.40, pp.225-252

[14] Mbuya T.O., Odera B.O. and Ng'ang'a, Influence of iron on castability and properties of aluminium silicon alloys: literature review, Int. Jour. of Cast Met. Res., (2003), vol.16, n.5, pp.451-465

[15] Pfeiffer W.D. and Sabath G., Banyasz. Kahsz. Lapok, (1986), vol.37, pp.39-43 (MITS Translation NF 168)

[16] Lang G., Aluminium, (1972), vol.48, No.10, pp.664-672

[17] Niyama E., Anzai K., Funakubo T. and Hiratsuka S., Some basic reasearch for thin-wall casting technology, J. of Mat. Proc. Tech., (1997), vol.63, pp.779-783

[18] Metals Handbook 9th Ed., Properties and selection: non-ferrous alloys and pure metals, ASM, (1979), vol.2, pp.164-165

[19] Fisher K., Fundamentals of solidificaiton, 3th ed., Trans Tech Pub., (1989)

[20] Dahle A.K., Bæckerund L. and Arnberg L., Castability of Aluminim foundry alloys, Final report for AFS, (1997)

[21] Kolsgaard A., Casting characteristics of SiC particulate reinforced AlSi7Mg aluminium matrix composites, PhD thesis, NTNU Univ. of Science and Tech., (1993)

[22] Sahoo K.L. and Sivaramakrishnan C.S., Come studies on Al-8.3Fe-0.8V-0.9Si alloy for near net shape casting, J. of Mat. Proc.Tech., (2003), vol.135, pp.253-257

[23] Tiryakioglu M., Askeland D.R. and Ramsay C.W., AFS Trans., (1994), vol. 102, pp.17-25

[24] Dahle A.K., T¿ndel P.A., Paradies C.J. and Arnberg L., Met. Mat. Trans. A, (1996), vol. 27A, pp.2305-2313

[25] Dahle A.K., Karlsen S. and Arnberg L., Int. J. of Cast Metals Res., (1996), vol.9, pp.103-112

[26] Chai G., PhD thesis, Stockholm University, Chem. Com., (1994), No.1

[27] Greer A.L., Grain refinement, Manufacturing high integrity aluminium and magnesium castings, Int. Summer School, Worcester Polytechnic Institute, 14-18 July (2003)

[28] Schumacher P., Greer A.L., Worth J., Evans P.V., Keams M.A., Fisher P. and Green A.H., New studies of nucleation mechanism in Al alloys: implications for grain refinement practice, Mat. Sc. Tech., (1998), vol.14, pp.394-404

[29] Greer A.L., Bunn A.M., Tronche A., Evans P.V. and Bristow D.J., Modelling of inoculation of metallic melts: application to grain refinement of aluminium by Al-Ti-B, Acta Mat., (2000), vol. 48, p.2823-2835

[30] Dahle A.K. and Arnberg L., Proc. 4th Int. Conf. on Aluminum Alloys, Eds. Sanders Jr. T.H. and Starke Jr. E.A., Atlanta (GA), (1994), pp.91-98

[31] Kotte B., Strontium modification gives critical melt control, Modern Casting, (1985) pp.33-35

[32] Venkateswaran S., Mallya R.M. and Sheshadri M.R., Effect of trace elements on the fluidity of eutectic Al-Si alloy using the vacuum suction technique, AFS Trans., (1986), vol.94, pp.701-708

[33] Mollard F.R., Flemings M.C., Nyama E.F. and Taylor H.F., Fluidity of Aluminium, surface tension, vibration and heat losses in runner systems effect, AFS Trans., (1962), vol. 70, pp.1029-1039

[34] Groteke D.E., AFS Trans., (1985), vol.93, pp.953-960

[35] Kim J.M. and Loper Jr. C.R., AFS Trans., (1985), vol. 103, pp.521-529

[36] Young-Dong Kwon and Zin-Hyoung Lee, The effect of grain refining and oxide inclusion on he fluidity of Al-4.5Cu-0.6Mn and A356 alloys, Mat. Sc. And Eng. A, (2003), vol. 60, pp.372-376

[37] Kayama N., Viscosity and fluidity in the early stages of solidification of metals, Quality control of engineering alloys and the role of metals science, Delft University of Technology, (1978), pp.103-119

[38] Bastien P., Armbruster J.C. and Azov P., Flowability and viscosity, AFS Trans., (1962), vol.70, pp.400-409