CASTABILITY MEASURES FOR DIECASTING ALLOYS: FLUIDITY, HOT TEARING, AND DIE SOLDERING

B. Dewhirst, S. Li, P. Hogan, D. Apelian

Tautologically, castability is a critical requirement in any casting process. Traditionally, castability in sand and permanent mold applications is thought to depend heavily on fluidity and hot tearing. Given capital investments in dies, die soldering is a critical parameter to consider for diecasting. We discuss quantitative and robust methods to insure repeatable metal casting for diecasting applications by investigating these three areas. Weight reduction initiatives call for progressively thinner sections, which in turn are dependent on reliable fluidity. Quantitative investigation of hot tearing is revealing how stress develops and yields as alloys solidify, and this has implications on part distortion even when pressure-casting methodologies preclude hot tearing failures.
Understanding the underlying mechanism of die soldering presents opportunities to develop methods to avoid costly downtime and extend die life. Through an understanding of castability parameters, greater control over the diecasting process can be achieved.

KEYWORD: castability, die soldering, fluidity, hot tearing, part distortion, residual stress

INTRODUCTION

Over the years, castability has been addressed through various angles and perspectives. However no matter what has been accomplished, it is fair to state that at the present there is not a single method that the community can point to as a means of defining an alloy's castability in terms of measurable quantitative parameters. It is critical that means for controlling the casting process be developed. Without robust measures, one will not be able to control the casting process. It is the latter that is the motivating force behind this project. Hopefully, the investigative techniques being developed in this research will become standardized so that an accepted lexicon and methodology is practiced throughout the casting community.
This paper will focus on three parallel lines of research with applicability to light metals diecasting: fluidity, hot tearing (as it relates to stresses developing within solidifying metals as a function of chemistry and microstructure), and die soldering. Each of these three areas of research has the potential to positively benefit the HPDC industry, either directly or as an accompanying benefit to research conducted for other purposes.
Vacuum fluidity testing allows for the evaluation of various alloys and process modifications in a laboratory setting under rapid solidification conditions, but suffers from a poor reputation and, as a consequence, has principally been used for qualitative experimentation. Hot tearing, a consequence of stresses developing during feeding until the casting tears itself apart, is not found in alloys used in HPDC, but the investigative techniques being applied to understand hot tearing are providing a window into how these stresses develop. Die soldering is important because, in improperly designed castings, soldering can be a significant problem that can severely inhibit productivity.

B. Dewhirst, S. Li, P. Hogan, D. Apelian
Metal Processing Institute - WPI, 100 Institute Road - Worcester, MA 01609 USA

Paper presented at the International Conference High Tech DieCasting, Montichiari, 9-10 April 2008, organised by AIM

FLUIDITY

Fluidity is a material's ability to flow into and fill a given cavity, as measured by the dimensions of that cavity under specified experimental conditions, and fluidity is heavily dependent on heat flow during solidification.
Investigations into the impact of foundry variables such as mold coatings, alloying additions, head pressure, and especially superheat have been investigated and correlated with mechanisms. For sand and permanent mold castings, it is abundantly clear that increasing solidification range results in decreasing fluidity (all other factors being equal). Specific investigations are often alloy or metal/mold/coating specific in scope, but very subtle influences of minor varia-

tions in alloy purity can be detected. There is some question as to whether these trends transfer over to die casting, and that question will be the focus of our discussion.
Thanks in large part to the work of Ragone in developing his vacuum testing apparatus, which Flemings et al. built upon, fluidity has seen great advances since Ragone's 1956 doctoral thesis [1-6]. Over a period of 8 years, Flemings and collaborators produced the fluidity equations and solidification mechanisms which are at work in linear castings during standard fluidity tests.
Ragone demonstrated that the influence of viscosity or a change in viscosity on (casting) fluidity was minimal, and while the equations he presented did include a viscosity term, subsequent formulations correctly dropped it as insignificant as compared with other sources of experimental error [1].
The fluidity equation from Flemings [3], for metal with some superheat ΔT and a mold which conducts heat rapidly is given below as Equations 1 and 2.

(1) $$L_f = \frac{(p' * a * V_o)(\lambda H + c' * \Delta T)}{2 * h * (\overline{T} - T_o)}$$

(2) $$\lambda = \left(\frac{c'}{H}\right) * \frac{L_f}{dL_f / dT} \quad \text{evaluated at Tm}$$

Where:

Lf	final length, fluidity
a	channel radius
k	critical solid concentration
c'	specific heat of liquid metal
To	ambient environmental temperature (room temperature)
ΔT	superheat
ρ'	density of metal
Vo	velocity of metal flow
H	heat of fusion of metal
h	heat transfer coefficient at mold-metal interface
T	the time average melt temp in the fluidity test
Tm	metal melting temperature
T'	temperature of superheated metal entering flow channel
λ	critical solid concentration required to stop flow in 'mushy' alloys

Flemings reports that the critical solid concentration is between 0.2 and 0.3 fraction solid, and Campbell gives 0.5-0.6 using slightly different criteria [4,7,8]. This is the fraction solid where, as will be discussed under flow stoppage mechanisms, the flow is choked off. Attempts to tie this choking off to dendrite coherency by Dahle, as explored by Backerud, were inconclusive. He did not find an unambiguous impact of dendrite coherency measurements on fluidity [9-11]. The specific fraction solid at which this takes place varies with alloy composition and solidifying phase morphology. This critical fraction solid is likely to be higher for die casting due to the increased pressure involved, but the extent of increase is likely to depend on alloy-specific morphology characteristics. Much work on the relevant solid fractions where flow is possible has been carried out in the area of SSM, both in terms of alloy rheology and thermodynamics, and this may have much to contribute in understanding how this factor changes according to the specific casting and alloy conditions [12].
Past work in the field has focused on maximizing fluidity, however we believe that decreasing the variations in fluidity is as important as determining under which conditions fluidity is maximized. There are two main aspects to variation in fluidity:
→ One is the standard deviation of test methods used in the lab to determine fluidity.
→ The other is the range over which fluidity values will vary in a real casting environment where alloy chemistry, temperature controls, etc. vary within some range.
Given the high part numbers involved in die casting, questions of repeatability are especially important. Thin sections are desirable for a variety of reasons, and can be achieved with increased mean fluidity, but if that increase is coming at the expense of increased fluidity variation, this will have the undesirable effect of increasing scrap rates.
Often, the factors which can be adjusted to improve fluidity have other impacts on the casting process, and so a careful tradeoff must be achieved between insuring there is enough fluidity (and a margin of safety) without causing deleterious side-effects. Greater fluidity is often achieved by increasing melt superheat, but as will be discussed below, this has negative implications for die soldering. Mold coatings can decrease the heat transfer coefficient, and thus increase fluidity, but this may have a small negative impact on cycle time. While minor alloy additions often have little impact on fluidity, the secondary alloy components (specifically, their heat of fusion and morphology) do contribute to fluidity.
Our work to improve the laboratory testing of vacuum fluidity measurements is largely focused on improving the repeatability of measurements by controlling the various experimental parameters. After a controlled volume of melt is collected, a thermocouple is inserted into it. When the metal cools to a preset temperature, it is elevated such that the end of a borosilicate tube is immersed in the melt, and vacuum is applied. The measurement of that length is then made before the pyrex tube is removed from the experimental setup, as the rapid fracturing of the glass and other factors otherwise make it difficult to determine the 'zero point.' Through repeated measurements under controlled experimental conditions we are establishing the reliability of the test.
A continuing trend in all of engineering, including metal casting, is the application of modeling software to problems of interest. These codes, in the case of casting intended to predict filling, hot spots, etc. are no more reliable than the data upon which they are built. It is hoped that increased precision of fluidity testing will have a positive impact on these modeling codes by allowing direct comparison of simple geometries in both simulation and the laboratory. Since these codes do not include direct fluidity calculations, accurate experimental tests of fluidity would seem to be a good independent check.

HOT TEARING AND INTERNAL STRAIN

Though hot tearing is a casting phenomenon that occurs in sand castings and processes where the solidification rate is slower than in die-castings, the mechanism of stress distribution during solidification is appropriate for discussion in high integrity castings.
This is true more so now than ever now that we can measure and quantify stresses during solidification. Material behavior during solidification is what matters.
Campbell [7] defines a hot tear as a uniaxial tensile failure, which results in cracks on the surface or inside the casting. Alloys having a wide freezing range have a higher tendency to hot tear. Variables that influence hot tearing include alloy composition and processing variables [13,14].

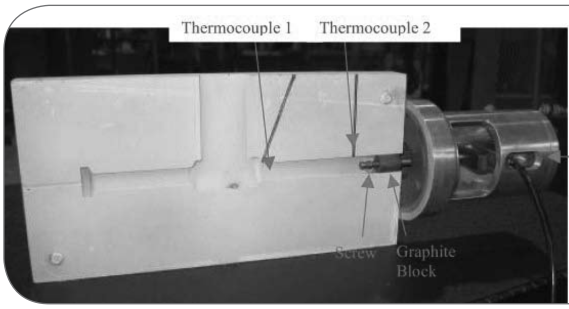

Fig. 1

Cast Iron Mold designed to detect the onset of the hot tearing. Commercial cast alloy 713 and 518 were evaluated; the former is known to be sensitive to hot tearing, and the latter has good resistance to hot tearing. The pouring temperature was set at 60°C above the melting point of the alloy during this effort. The mold temperature was maintained around 200°C.

Stampo in ghisa progettato per rilevare l'insorgenza di cricche a caldo. Sono state valutate le leghe commerciali 713 e 518; la prima è risaputa essere sensibile alla criccatura a caldo, mentre la seconda ha una buona resistenza verso tale fenomeno. In questa prova la colata è stata eseguita a una temperatura di 60°C al di sopra del punto di fusione della lega. La temperatura dello stampo è stata mantenuta intorno ai 200°C.

Hot tearing susceptibility of alloys is greatly influenced by solidification behavior of molten metal in the mushy zone. Solidification can be divided into four stages [15]: (i) Mass feeding where the liquid and solid are free to move; (ii) Interdendrtic feeding when the dendrites begin to contact each other, and a coherent solid network forms; (iii) Interdendritic separation. With increasing fraction solid, the liquid network becomes fragmented. If liquid feeding is not adequate, a cavity may form. As thermal contraction occurs, strains are developed and if the strain imposed on the network is greater than a critical value, a hot tear will form and propagate. Lastly, in stage (iv), Interdendritic bridging or solid feeding occurs. Simply stated, hot tearing occurs if the solidification shrinkage and thermal deformation of the solid cannot be compensated by liquid flow.

Measuring the development of strains and the evolution of hot tearing during solidification is not trivial. The Metal Processing Institute is a member of the Light Metals Alliance, and we have teamed up with our alliance partner CANMET to address hot tearing in aluminum alloys. The constrained bar mold used in this study was developed at CANMET Materials Technology Laboratory (MTL) and designed to measure load and temperature during solidification. Fig. 1 shows one of the mold plates and testing setup. The mold is made of cast iron and coated with insulating mold wash. The test piece has two arms. One test arm (12.5mm) is constrained at one end with heavy section (22.5mm) to keep the bar from contraction, so the tension will be developed and hence cracking could be induced during solidification. The other arm is for load and temperature measurement with one end connected to a load cell. This opened end of the mold is closed with a graphite cylinder block which can move freely in horizontal direction. The block is connected to the solidifying material on inner side with a screw and on external side with a load cell. Two K-type thermocouples are used for the temperature measurement. One is positioned at the riser end and the other at the end of the bar as shown in Fig. 1. After pouring the melt into the mold, the temperature and load were recorded with a computer data acquisition system.

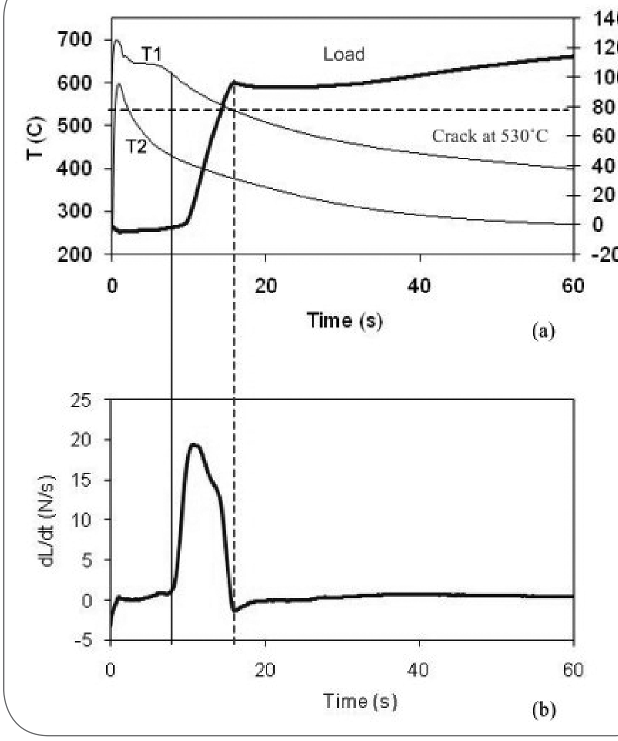

Fig. 2

(a) Temperature-load-time curves of alloy 713; (b) Derivative of Load vs. time curve.

(a) Curve temperatura-carico-tempo per la lega 713; (b) andamento della derivata del carico vs. tempo.

Fig. 2 and 3 show the measured temperatures and load recorded during casting as a function of time for alloy 713 and 518 respectively. The load represents the tension force developed in the casting during solidification. The cooling curve T1 was recorded with thermocouple tip positioned at the riser end and T2 with thermocouple tip at the end of the bar as shown in Fig. 1. A rapid rise in temperature (both curves) was observed immediately after pouring and the temperature started falling shortly. It's noticed that negative loads (compressive forces) were developed shortly after pouring for the tests, probably due to the pressure head of the melt [16]. When the rod begins to solidify but cannot contract freely, the tension force increases. Fig. 2(b) and 3(b) are derivatives of load vs. time curve to determine onset of hot tearing. An obvious change in the rate suggests that cracking might occur there.

From Fig. 2b, load began developing at proximately 9 seconds and the solidification temperature was around 617°C (Fig.2a), then increased rapidly. It is shown that the rate changed abruptly to zero at 16.5 seconds, suggesting a severe tear occurred there.

Hot tearing occurred at around 530°C, corresponding to 94% solid, according to Pandat Scheil solidification calculation.

The technique developed to measure hot tearing tendency is a valuable tool to differentiate between alloys and to use it to optimize alloys for high integrity castings.

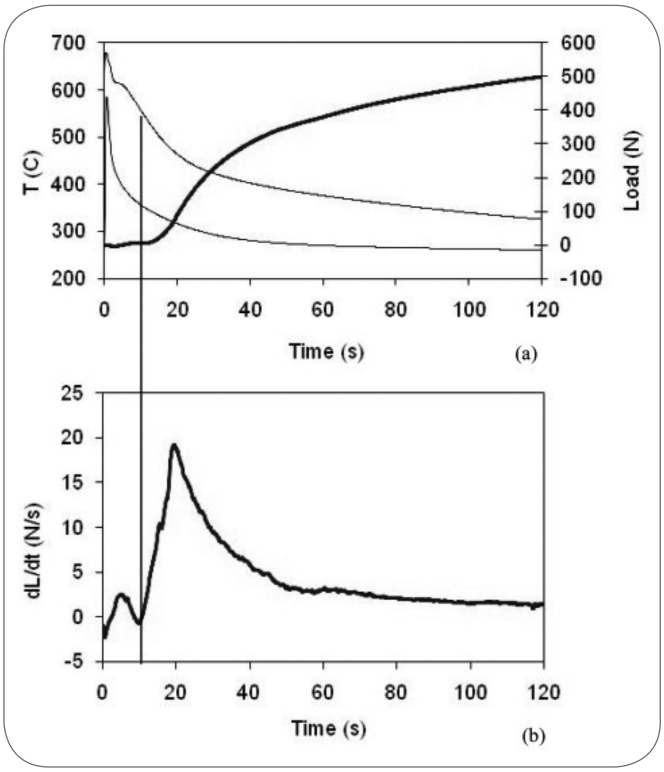

Fig. 3

(a) Temperature-load-time curves of alloy 518; (b) Derivative of Load vs. time curve.

(a) Curve temperatura-carico-tempo per la lega 518; (b) andamento della derivata del carico vs. tempo.

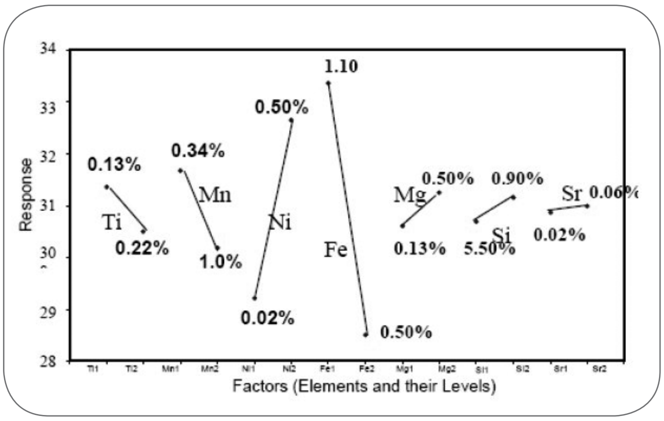

Fig. 4

Main effects plot of the effect various alloying elements on die soldering. Iron, Manganese and Titanium show strong positive effects on reducing soldering, while Nickel promotes soldering [17].

Mappatura dei principali effetti dei vari elementi di lega sull'incollaggio allo stampo. Ferro, manganese e titanio mostrano forti effetti positivi sulla riduzione della adesione, mentre il nichel promuove tale fenomeno [17].

Fig. 3 shows the temperature-load-time curves of alloy 518. The load started to develop at 10 seconds, and then increased smoothly with time. No abrupt change of rate was observed, suggesting no crack would occur during solidification. The difference between the load curves of alloy 713 and 518 reveals different hot tearing susceptibility between the two alloys.

DIE SOLDERING

Die soldering occurs when the cast aluminum alloy comes into contact with die steel.
Due to the natural affinity of iron and aluminum, a reaction occurs at the surface which results in the formation of intermetallic phases. Over a series of shots, a significant amount of aluminum becomes stuck to these phases at the die surface, and the resulting cast part can begin to miss critical tolerances or to lose integrity. At this point, the die must be shut down and cleaned, which is an expensive process when it occurs too frequently. It is estimated that 1 to 1.5% of variable overhead is directly attributed to die soldering in casting plants.
With such a large economic effect on the casting process, it is clear why die soldering needs to be controlled. There are several ways in which this can be achieved. These can be broken down into three groups, which will be discussed further below: melt chemistry, process conditions and the die surface condition.
The chemical composition of an alloy can have a dramatic effect on soldering behavior.
The importance of alloy chemistry was shown at WPI's Metals Processing Institute by Sumanth Shankar [17]. In his experiments, he dipped H13 steel pins in 380 alloy and rotated them to simulate the drag force experienced at the surface of the die during injection of the metal. After dipping, the thickness of the intermetallic layers that had formed on each sample was analyzed as a measure of soldering tendency. His results showed that small additions of Sr and Ti (0.004% and 0.125%, respectively) had a much greater effect on soldering tendency than the time of dipping (30 to 75 seconds) or the temperature of the melt (1150 to1250F).
To further expand on this discovery, Shankar performed another set of experiments to test the effects of a much wider range of alloying elements. The main effects are shown in Figure .
Not surprisingly, iron had the greatest effect of any alloying element in the study on reducing die soldering. Iron has long been added to die casting alloys in order to reduce the die soldering tendency of alloys. It is well known that alloys with insufficient iron content (<0.8-0.9%) will solder readily to the die under the right conditions. A look at the phase diagram in Fig. 5 shows that the solubility of iron in aluminum with 10% silicon at typical casting temperatures is quite low, around 2-3%. At temperatures where the melt is likely to be in contact with the die, this solubility drops even lower. Therefore, even at low concentrations the presence of iron in the melt reduces the chemical potential gradient of iron from the steel to the melt significantly and slows the reactions that occur at the surface.
Of the other alloying elements, strontium also has the potential to help control die soldering, in addition to its common use as a eutectic modifier. In industrial trials a small strontium addition was shown to reduce die soldering by more than 20%. The effect is not apparent in the main effects plot above because both of the levels selected were at or above the critical concentration.
The mechanism behind this reduction has to do with the effect strontium has on the viscosity and surface tension of the alloy. As Fig. 6 shows, the addition of strontium changes the apparent viscosity and subsequently the surface energy of the alloy. This causes a reduction in the ability of the alloy to wet

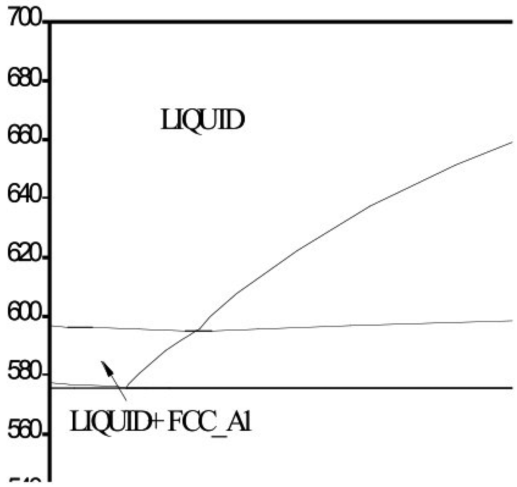

Fig. 5 ***Phase diagram of Aluminum-10% Silicon and low solubility of Fe.***
Diagramma di stato dell' alluminio-10% silicio con bassa solubilità del ferro.

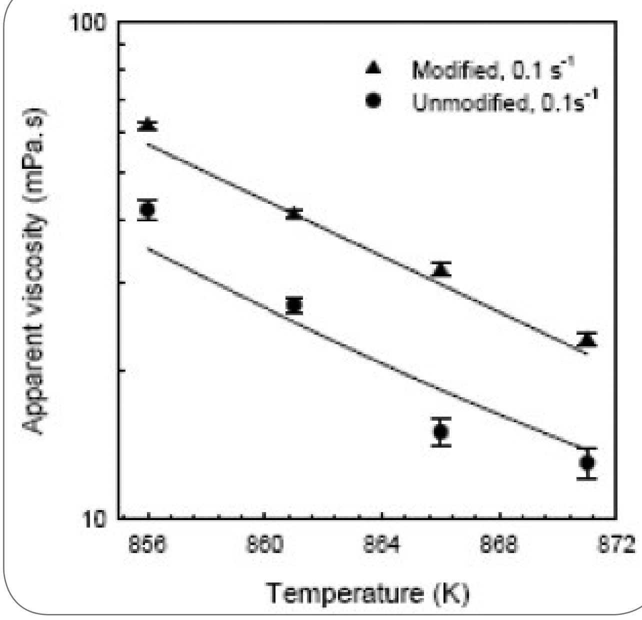

Fig. 6 ***Change in viscosity of an Al-Si alloy with the addition of 230ppm Sr [18].***
Variazione della viscosità di una lega Al-Si con l'aggiunta di 230 ppm di stronzio. [18].

the die surface and reduces the contact area and the reaction between the two.
High temperatures and high melt velocity are process conditions which lead to soldering.
Of the two, high temperature is the most important to avoid in order to prevent soldering.
This can most effectively be done through careful design of the die. By configuring the part and optimizing the design of the die cooling system, the potential for soldering can be greatly reduced. It is very important to consider this during the design phase of a die because once a die is manufactured it is very difficult to reduce any hot spots. Other potential solutions include using additional spray in the high solder areas to reduce temperature or the use of inserts with high conduction coefficients.
Impingement velocity is important to control as well. The die surface should be coated with lubricants and is likely oxidized from prior treatment. A high impingement velocity can wash these protective coatings off of the die surface, exposing the die steel to the aluminum alloy and begin erosion of the die surface. Both of these effects will promote the beginning of die soldering.
SSM processing can help to reduce both the temperature and velocities apparent in the casting system, and should help reduce die soldering [12].
Die coatings can be useful as a diffusion barrier between the steel in the die and the aluminum in the cast alloy. An effective coating must be able to withstand the harsh conditions at the surface of the die, however. Coatings which are sometimes used include CrN+W, CrN, (TiAl)N and CrC [19]. Additionally, surface treatments such as nitriding and nitro-carburizing can help to strengthen the surface and prevent erosion, which accelerates the soldering process by roughening the surface and creating local temperature excursions at the peaks of the die surface which solder very quickly.
Accurate modeling of the casting process during the design phase is very important to an effective control against die soldering. All of the previously mentioned controls require additional cost during the design and manufacturing of the die, and it must be understood how badly soldering will affect the process before the costs of any of those controls can be justified.

CONCLUSIONS

Though these three alloy characteristics seem tangentially related, they are factors that influence castability. In order to control these castability indices, it is necessary to develop experimental methods until robust quantitative analysis is possible. Once quantitative data can be extracted, the improvement in our understanding will occur. In the case of die soldering, multiple possible avenues to reduce the problem have been identified. Even when the initial intention was to resolve problems occurring in sand and permanent mold castings, such as hot tearing, the information gleaned about how stresses develop in liquid metal has wider applicability. Though die casting usually assures good fluidity through the use of pressure, if fluidity (and the factors which influence its variation) are well understood, it is possible to operate within tighter processing windows.

REFERENCES

1] D.V. RAGONE, C.M. ADAMS, H.F. TAYLOR, AFS Trans. 64, (1956), p.640.
2] D.V. RAGONE, C.M. ADAMS, H.F. TAYLOR, AFS Trans. 64, (1956), p.653.
3] M.C. FLEMINGS, Brit. Foundryman 57, (1964), p.312.
4) M.C. FLEMINGS, Solidification Processing. McGraw-Hill, New York (1974).
5] M.C. FLEMINGS, E. NIYAMA, H.F. TAYLOR, AFS Trans. 69, (1961), p.625.

6] J.E. NIESSE, M.C. FLEMINGS, H.F. TAYLOR, AFS Trans. 67, (1959), p.685.
7] J. CAMPBELL, Castings. Butterworth-Heinemann, Oxford (1993).
8] A.K. DAHLE, L. ARNBERG, Materials Science Forum, 217-222, (1996), p.259.
9] A.K. DAHLE, L. ARNBERG, Materials Science Forum, 217-222, (1996), p.269.
10] L. BACKENRUD, E. KROL, J. TAMMINEM, Solidification Characteristics of Aluminum Alloys Volume 1: Wrought Alloys. (1986).
11] L. BACKENRUD, G. CHAI, J. TAMMINEN, Solidification Characteristics of Aluminum Alloys Volume 2: Foundry Alloys. (1986).
12] Science and Technology of Semi-Solid Metal Processing. North American Die Casting Association, (2001).
13] G.K. SIGWORTH, AFS Trans. 104, (1996), p.1053.
14] A.S. METZ, M.C. FLEMINGS, AFS Trans. 78, p.453.
15] D.G. ESKIN, K.L. SUYITNO, Progress in Materials Science, 49, (2004).
16] G. CAO, S. KOU, Met. Trans. A. 37A, (2006), p.3647.
17] S. SHANKAR, A Study of the Interface Reaction Mechanism Between Molten Aluminum and Ferrous Die Materials, Ph.D. Worcester Polytechnic Institute, (2000).
18] S. SHANKAR, M.M. MAKHLOUF, Internal ACRC Report, May 2005.
19] J. Wallace, A Guide to Correcting Soldering. North American Die Casting Association, (2006).

ABSTRACT

MISURE DI COLABILITÀ PER LEGHE DA PRESSOCOLATA: FLUIDITÀ, CRICCABILITÀ A CALDO E INCOLLAGGIO AGLI STAMPI

Parole chiave: alluminio e leghe, pressocolata

Tautologicamente si può affermare che la colabilità rappresenta un requisito fondamentale in ogni processo di pressocolata. Tradizionalmente, si pensa che sia la colabilità in sabbia sia le applicazioni in stampi permanenti dipendano dalla fluidità e della criccabilità a caldo. Se si considerano poi gli investimenti in capitale per gli stampi, anche i fenomeni di incollaggio diventano un aspetto critico da non sottovalutare. Nella presente memoria si discutono metodi quantitativi ed efficaci per garantire la ripetibilità delle colate di metallo per applicazioni in pressocolata, analizzando i tre aspetti. La necessità di ridurre il peso richiede di conseguenza l'impiego di sezioni sempre più sottili, che a loro volta dipendono da livelli affidabili di fluidità. L'analisi quantitativa della criccabilità a caldo permette di comprendere come si sviluppano e si manifestano le tensioni quando la lega solidifica, con implicazioni sulle distorsioni del pezzo, anche quando le tecniche di pressocolata sono in grado di evitare rotture da criccatura a caldo.

La comprensione del meccanismo alla base dell'incollaggio della lega agli stampi permette di sviluppare metodi per evitare costosi tempi morti e di prolungare la vita degli stampi stessi. Attraverso la comprensione dei tre parametri di colabilità è possibile ottenere un maggiore controllo sul processo di pressocolata.