Impact of modifier and grain refiner on the feeding effectivity of the cast EN AC-42100 alloys

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Abstract

The EN AC-42100 (AlSi7Mg0.3) aluminum alloy is commonly used in various applications due to its favorable combination of mechanical properties, corrosion resistance and casting characteristics. Non-adequate feeding of this hypoeutectic alloy leads to the formation of shrinkage porosity. Addition of grain refiners and modifiers into aluminum melt can be beneficial directing to better feeding ability of this cast alloy. Thermal (cooling curve) analysis has been routinely used at aluminum foundry floors for assessment the efficiency of master alloys additions into aluminum melt. Cooling curve analysis can additionally provide information regarding to characteristic solidification temperatures such as: liquidus, dendrite coherency point, rigidity and solidus. These temperatures are important parameters of solidifying aluminum alloys, which mark transitions between five types of feeding mechanisms: liquid feeding, mass feeding, interdendritic feeding, burst feeding and solid feeding. This work will show how ***IDECO thermal feeding analysis system*** *can be used to quantify different feeding regions of cast EN AC-42100 alloy. First time under industrial conditions, operators at the foundry floors will be capable to control the impact of master alloys additions on the feeding effectivity of cast aluminum alloys. Collected parameters can be used to feed existing simulation data bases with more correct information and on that way improve their accuracy.*

Key words: EN AC-42100 aluminum alloys, feeding, modifier, grain refiner, thermal analysis, Simulation

Introduction

The EN AC-42100 (AlSi7Mg0.3) alloy is a type of cast aluminum-silicon hypoeutectic alloys with addition of magnesium as a major alloying element. This alloy may find application in a variety of general engineering and structural components where a balance of good mechanical properties, corrosion resistance, and metallurgical properties (fluidity and castability) is required. Two major alloying elements, silicon, and magnesium in combination with some other minor alloying elements (Sr, Ti, Fe, Mn, B, Zn…) outline the metallurgical, mechanical, and structural properties of this alloy [1, 2]. As cast structure of the EN AC-42100 alloy characterized the presence of primary α-aluminum dendritic structure, primary aluminum-silicon eutectic as well as magnesium-rich intermetallic phases. Moderate amount of silicon gives this alloy good fluidity, while added magnesium improve its strength, hardness and fatigue properties. During liquid-solid transformation, most metals and alloys contract, reducing their volume. The aluminum-silicon cast alloys also decrease their volume during solidification in the range of 4 to 8 % [3]. Silicon is one of few elements that during transformation from liquid to solid state increase its volume. Thanks to that property, silicon will to some degree compensate the volume decrease of aluminum-silicon alloys during solidification. In the available literature [4] it has been mentioned that feeding capability is closely related to the aluminum-silicon eutectic characteristic formed during solidification. The higher amount of magnesium extends the solidification range of these alloys, reducing their feeding ability. The aluminum-silicon alloys without magnesium characterized narrow solidification range with significant amount of liquid eutectic. Therefore, the feeding of the liquid eutectic by those alloys should be relatively easy. Presence of magnesium in these alloys, noticeably extends their solidification range, making feeding of the last liquid eutectic portion during solidification difficult and causing the formation of shrinkage porosity. According to Campbell [5], five feeding mechanisms (liquid, mass, interdendritic, burst and solid feedings) occur during solidification of cast aluminum alloys. The liquid and mass feedings, which appear at the beginning of solidification process, are uncomplicated due to low melt viscosity, wide active feeding path and relatively elevated melt temperature. The numbers of dendrites, which start to develop immediately after liquidus temperature, is still not so significant to slow down melt movement. As the melt temperature decreases during further solidification, growing dendrites start to impinge on each other forming coherent dendritic network, which additionally slows down the flow of the remaining melt. The temperature at which this happens is called Dendrite Coherency Temperature (DCT). This temperature borders the transition from mass to interdendritic feeding regions in all cast aluminum alloys [6 - 14]. Further solidification decreases the liquid fraction, and the stress is spread over larger distances through the rigid solid skeleton [15, 16]. According to Campbell [5], at the rigidity temperature, the stress will exceed the strength leading to breakdown of solid dendritic skeleton. The rigidity temperature marks the moment when the interdendritic feeding stops and burst feeding starts. The solid feeding starts at the solidus temperature when the last drop of melt is transformed into the solid.

Characteristic solidification temperatures such as liquidus, dendrite coherency temperature, rigidity and solidus temperature have been recognized as important parameters of solidifying aluminum alloys, which can be used to mark transitions between several types of feeding mechanisms [8 - 14]. All those characteristic solidification temperatures as **Figure 1** illustrates can be easily determined using IDECO thermal feeding analysis system and apply to boundary those feeding regions.

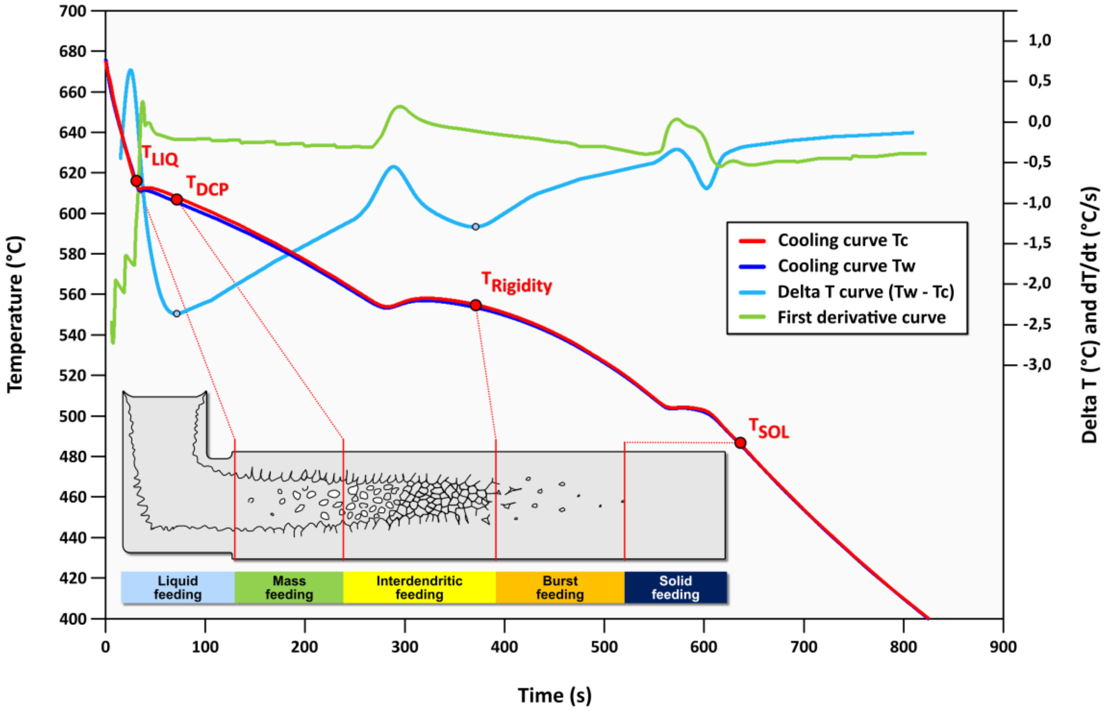


Figure 1. Bordering five feeding mechanisms using characteristic solidification temperatures determined from the cooling curve.

In the available literature, it has been documented that the solidification feeding behavior of cast aluminum alloys is affected by their chemical compositions [17,18]. J. Cho et al. [18] found that copper has significant impact on the feeding characteristics of cast aluminum-silicon alloys. Added magnesium prolongs the freezing time, extends eutectic mushy zone influencing feeding ability and causing formation in large amount of microshrinkage porosity [19]. Dash and Makhlouf [17] found in their paper that besides the cooling rate, which plays significant impact on feeding issue chemistry also has some contribution. According to their results, iron, silicon, magnesium and copper present in the aluminum alloys during solidification form various intermetallics compounds such as $Al_5Mg_8Cu_2SI_6$, needle like Al_5FeSi or Al_2Cu. All these compounds form a net like structure that hinder the flow of the melt leading to formation of shrinkage porosity. The main aim of this work is to analyze the impact of modifier and grain refiner on the various feeding regions of cast EN AC-42100 alloy applying a new IDECO thermal feeding analysis system and try to quantify them.

Experimental Procedure

Materials and melting procedures

Four experiments have been carried out at IDECO technical center in Bocholt Germany using Rheinfelden primary hypoeutectic EN AC-42100 (AlSi7Mg0.3) alloy. The **Table 1** summarizes the chemical composition of investigated alloy, after being melted in an electric resistance furnace capacity 4 kg.

Table 1. Chemical composition (wt%) of the investigated alloy – first experiment.

Alloy	Si	Mg	Sr	Ti	Cu	Fe	Mn	Zn
Al Si7 Mg0.3	7.138	0.337	0.0001	0.125	0.001	0.056	0.002	0.002

The **Figure 2** shows IDECO laboratory set up with following equipment: Nabertherm electric resistance furnace and IDECO SA800SN thermal feeding analysis system.

Figure 2. Layout of equipment during experiments at IDECO technical center.

Three kilograms of EN AC-42100 alloy were charged in the furnace and melted down. The melt was neither grain refined nor modified. During all experiments the melt was also not degassed. The melt temperature in the furnace during all experiments was kept constant at 720°C. Chemical composition of melted alloy has been determined using optical emission spectroscopy apparatus. Ten thermal analysis test samples have been run during the first experiment and their corresponding cooling curves have been collected and later used to quantify feeding effectivity of this alloy.

At the beginning of the second experiment 3,0 kg of EN AC-42100 alloy were added into the furnace and melted down. Additionally, 63,5 grams of Al10%Sr master alloy in the rod form has been also added into the melt to analyze the impact of modifier on the characteristic solidification temperatures and the feeding ability of EN AC-42100 alloy. Targeted concentration of Sr in the melt was approximately 75 ppm. **Table 2** shows the chemical composition of the melt applied during this experiment. In total, five cooling curves have been collected using modified EN AC-42100 melt.

Characteristic solidification temperatures determined from these curves have been used to border the various feeding regions of this alloy.

Table 2. Chemical composition (wt%) of the investigated alloy after addition of modifier – second experiment.

Alloy	Si	Mg	Sr	Ti	Cu	Fe	Mn	Zn
Al Si7 Mg0.3	6.866	0.337	0.0072	0.13	0.001	0.052	0.002	0.002

For the third experimental step, the modified melt from the previous trial has been mixed and grain refined by adding 32,4 g of AlTi3B1 master alloy in the rod form to analyze its impact on the solidification path of this alloy. **Table 3** displays the achieved chemical composition of the EN AC-42100 melt after addition of grain refiner. Five cooling curves have been collected using grain refined and modified EN AC-42100 melt and determined parameters from the curves have been used to evaluate impact of grain refiner and modifier on the feeding ability of this alloy.

Table 3. Chemical composition (wt%) of the investigated alloy after addition of grain refiner – third experiment – with Sr.

Alloy	Si	Mg	Sr	Ti	Cu	Fe	Mn	Zn
Al Si7 Mg0.3	7.019	0.328	0.0072	0.154	0.001	0.057	0.0020	0.002

For the fourth experiment, the original (no grain refined and modified) Rheinfelden EN AC-42100 alloy in the quantity of 2,5 kg was charged in the furnace and melted down. After remelting, 32 g of AlTi3B1 master alloy in the rod form has been added into the melt to analyze only the impact of grain refiner on the solidification path of this alloy. **Table 4** displays the achieved chemical composition of the EN AC-42100 melt after addition of grain refiner. Five cooling curves have been collected using grain refined EN AC-42100 melt, and their characteristic solidification temperatures have been applied to evaluate the impact of grain refiner on its feeding ability.

Table 4. Chemical composition (wt%) of the investigated alloy after addition of grain refiner – forth experiment – without Sr addition.

Alloy	Si	Mg	Sr	Ti	Cu	Fe	Mn	Zn
Al Si7 Mg0.3	7.188	0.327	0.0001	0.123	0.001	0.054	0.002	0.002

Thermal Feeding analysis procedure

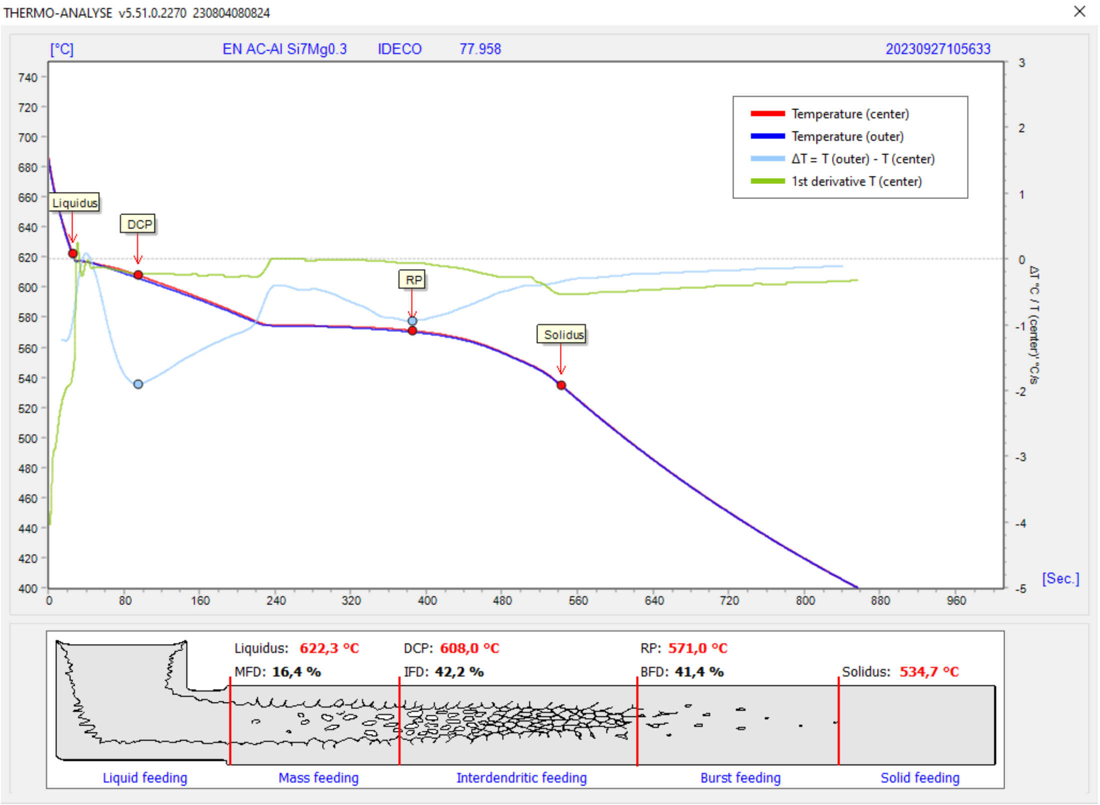
Thermal analysis test samples with masses of approximately 220 ± 20 g were poured into IDECO thermal analysis ceramic test cup with a height of 59,5 mm and a diameter of 54 mm. Two calibrated K type thermocouples were inserted into the melt and temperatures between 700 and 400 °C were recorded. As **Figure 3** illustrates, one thermocouple was placed in the center of the cup (T_C), while the second one was placed ≈ 5 mm from the cup wall (T_W). The tip of the thermocouple was kept always at the constant height of ≈ 20 millimeters from the bottom of the ceramic cup. The cooling conditions were kept constant during all experiments. During all trials, the acquisition system read ten data sets (temperature/time/sensor) per second.

Figure 3. Thermal analysis ceramic cup and samples with two thermocouples.

Results and discussions

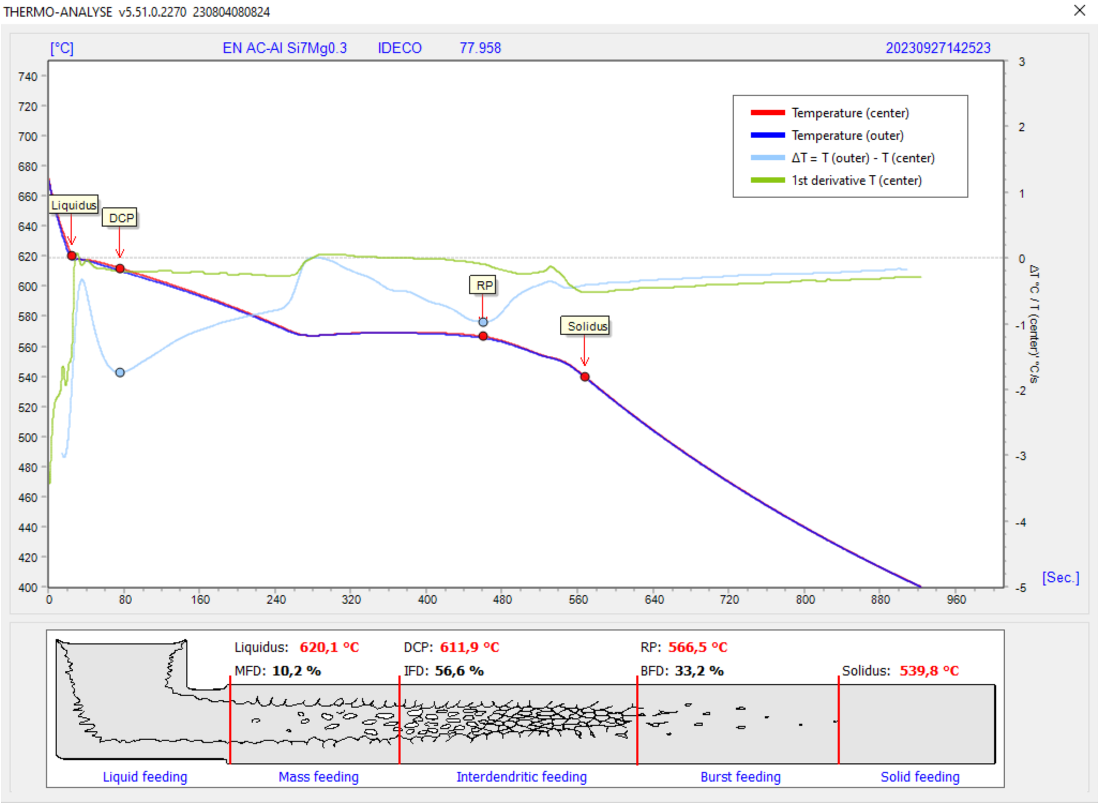
To meet strict industrial requirements, IDECO developed and implemented a novel thermal feeding analysis system. The new system can define the solidification path of any cast aluminum alloy and quantifying its feeding ability as a function of temperature, time, and fraction solid. The stable test sample mass, optimal test cup and melt sampling technique together with applied high resolution K type thermocouples allows high level of repeatability and reproducibility of each measurement as well as unbiased analysis. System is user friendly and easy to operate.

IDECO thermal feeding analysis system has been applied in all experiments with the main aim to analyze the impact of modifier and grain refiner on the characteristic solidification temperatures of EN AC-42100 alloys. Modifiers and grain refiner are important additives used in the casting of aluminum alloys to improve their microstructure and mechanical properties. Modifiers are added to aluminum alloys to modify the size, shape, and distribution of the silicon phase in the solidified microstructure. The primary purpose of modifiers is to improve the feeding ability of the alloy by promoting the formation of fine, globular silicon particles. Grain refiners are added to aluminum alloys to reduce the size of primary α-aluminum grains and to enhance the feeding ability of the cast aluminum alloys. Additionally, these additives can help to reduce casting defects and ensure more reliable and uniform casting structures. **Figures 4 to 7** show cooling curves, their first derivative curves and corresponding delta T curves ($T_W - T_C$) for EN AC-42100 alloy without addition of modifier and grain refiner (**Figure 4**), with addition of modifier (**Figure 5**) with addition of modifier and grain refiner (**Figure 6**) and with addition of only grain refiner (**Figure 7**). The cooling curve, its first derivative curve and delta T curve have been used to determine liquidus, dendrite coherency, rigidity and solidus temperatures of the investigated alloy. These temperatures delineate the five feeding regions of this alloy.



Liquidus: 622,3 °C
MFD: 16,4 %
DCP: 608,0 °C
IFD: 42,2 %
RP: 571,0 °C
BFD: 41,4 %
Solidus: 534,7 °C

Figure 4. The cooling curve, its first derivative and delta T curve for EN AC-42100 alloy without addition of modifier and grain refiner.

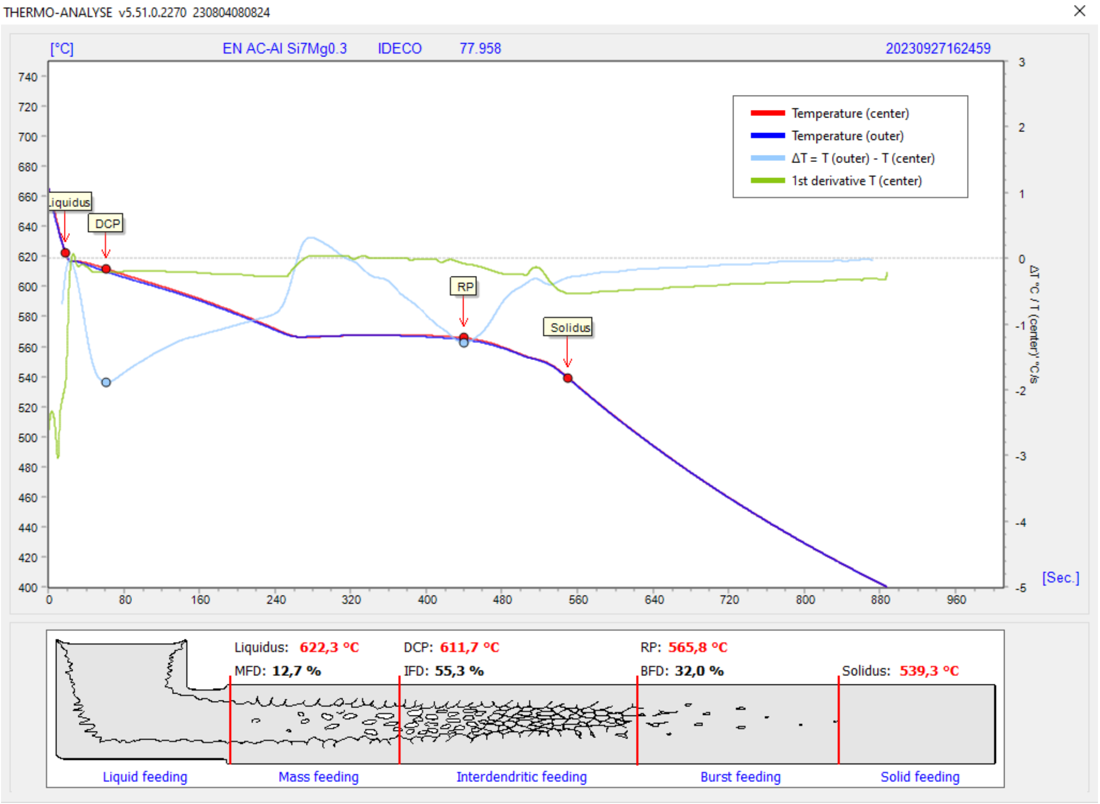


THERMO-ANALYSE v5.51.0.2270 230804080824

[°C] EN AC-Al Si7Mg0.3 IDECO 77.958 20230927142523

Liquidus: 620,1 °C
MFD: 10,2 %
DCP: 611,9 °C
IFD: 56,6 %
RP: 566,5 °C
BFD: 33,2 %
Solidus: 539,8 °C

Figure 5. The cooling curve, its first derivative and delta T curve for EN AC-42100 alloy with addition of modifier.



THERMO-ANALYSE v5.51.0.2270 230804080824

[°C] EN AC-Al Si7Mg0.3 IDECO 77.958 20230927162459

Liquidus: 622,3 °C
MFD: 12,7 %
DCP: 611,7 °C
IFD: 55,3 %
RP: 565,8 °C
BFD: 32,0 %
Solidus: 539,3 °C

Figure 6. The cooling curve, its first derivative and delta T curve for EN AC-42100 alloy with addition of modifier and grain refiner.

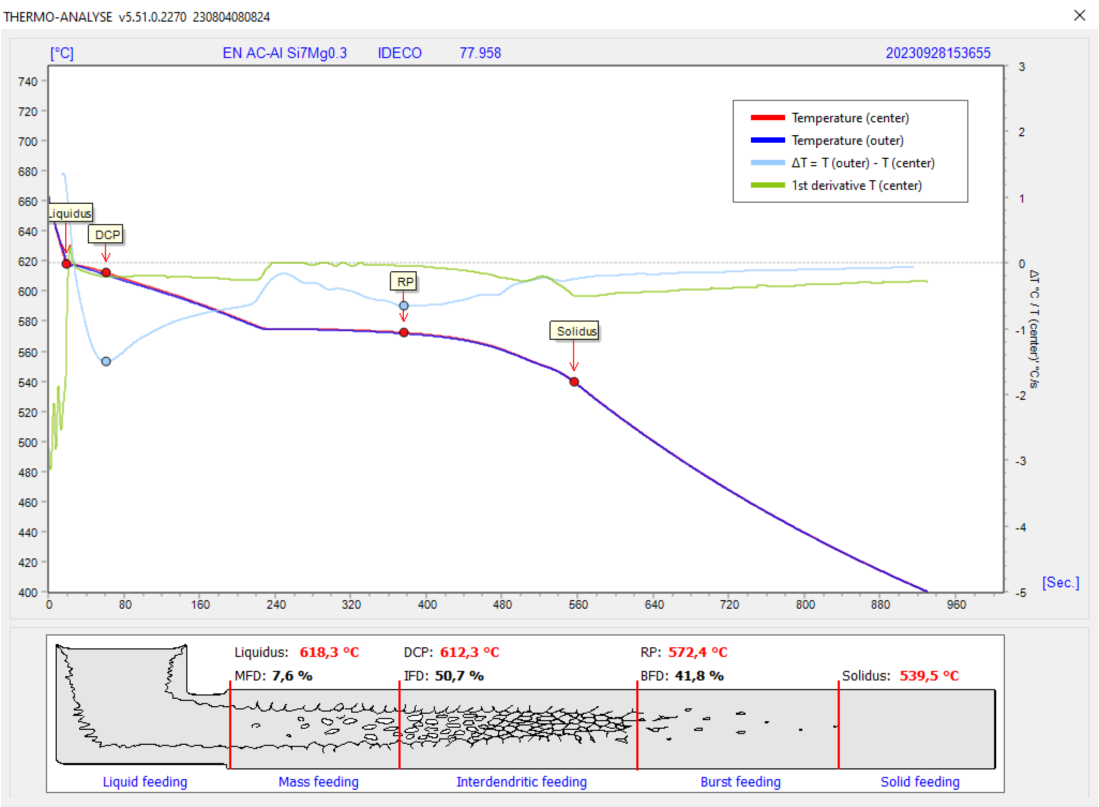


Figure 7. The cooling curve, its first derivative and delta T curve for EN AC-42100 alloy with addition of grain refiner.

All four characteristic solidification temperatures (liquidus, dendrite coherency, rigidity and solidus) from four previously described trials have been summarized in **Table 5**.

Table 5. Impact of modifier and grain refiner on characteristic solidification temperatures of EN AC-42100 alloy. The characteristic solidification temperatures, derived from an average of multiple measurements.

Alloy	TLIQ	DCP	Rigidity	TSOL
Al Si7 Mg0.3	621.2	610.4	571.3	535.6
Al Si7 Mg0.3 + Sr 0.0072	620.4	612.6	566.3	540.0
Al Si7 Mg0.3 + TiBor 0.154 + Sr 0.0072	625.4	612.8	565.8	540.8
Al Si7 Mg0.3 + TiBor 0.123	620.0	612.2	569.4	538.0

As **Table 5** and **Figure 5** show, strontium has significant impact only on rigidity temperature. Addition of 72 ppm strontium reduced the rigidity temperature from 571.3 °C to 566.3 °C. The depression of rigidity temperature caused by adding modifier in the EN AC-42100 alloy leads to an extension of the Inter Dendritic Feeding (IDF) region by 5 °C. Added grain refiner (0.154 wt.% of Ti) into the modified melt has no impact on the rigidity temperature as **Figure 7** shows, but impacts the dendrite coherency temperature, increasing it by 2.2 °C. Addition of grain refiner into EN AC-

42100 melt in the amount of 0.123 wt.% as **Figure 7** and **Table 5** indicated, does not significantly change the rigidity temperature and has some moderate impact on dendrite coherency temperature, increasing it by 2.4 °C compared to the melt without any addition of grain refiner and modifier.

Shrinkage porosity is one of the most common defects in aluminum cast parts caused by non-proper feeding ability. Understanding the feeding behavior of aluminum - silicon alloys is an important aspect for sound casting production. In the available literature, only a few papers attempt a quantitative description of some feeding regions in aluminum-silicon alloys using the beam and scales principle [19, 20, 21]. By measuring the time of mass and total feeding during solidification in cast parts, Engler and Michel [19-21] established two criteria that can be employed to describe mass feeding (up to the dendrite coherency point) and total feeding (from the dendrite coherency point up to the solidus temperature). The main disadvantage of these criteria was their inability to quantitatively describe feeding regions such as interdendritic feeding or burst feeding. Especially interdendritic and burst feedings are of great importance in producing sound cast parts through gravity and high-pressure die casting processes. Those regions are mostly responsible for defects formation in the as-cast structure, such as shrinkage porosity, hot tearing, and segregation. In addition, it is well known that time is an intensive property that is very sensitive to the mass of solidified samples. Any difference in the size of thermal analysis test sample can significantly influence the total solidification time and impact the accuracy of quantitatively described feeding regions. Therefore, the foundry industry needs a better analytical description of those two feeding regions. A new IDECO thermal feeding system proposes three equations based on the previous work [22] which can be used quantitatively to describe following three feeding regions of any cast aluminum alloys:

$$MF = \frac{TLIQ - TDCP}{TLIQ - TSOL} x\, 100 \qquad (1)$$

$$IDF = \frac{TDCP - TRigidity}{TLIQ - TSOL} x\, 100 \qquad (2)$$

$$BF = \frac{TRigidity - TSOL}{TLIQ - TSOL} x\, 100 \qquad (3)$$

where:

MF – temperature ratio for mass feeding, %
IDF – temperature ratio for interdendritic feeding, %
BF – temperature ratio for burst feeding, %
TLIQ – liquidus temperature, °C
TDCP – dendrite coherency temperature, °C
TRigidity – rigidity temperature, °C
TSOL – solidus temperature, °C

From **Figure 1** it is obvious that four characteristic solidification temperatures (liquidus, dendrite coherency, rigidity and solidus) are needed parameters for quantitative description of different feeding intervals. Applying equations (1 - 3) and calculated corresponding temperature ratio for various feeding regions, the impact of grain refiners and modifiers can be quantified.

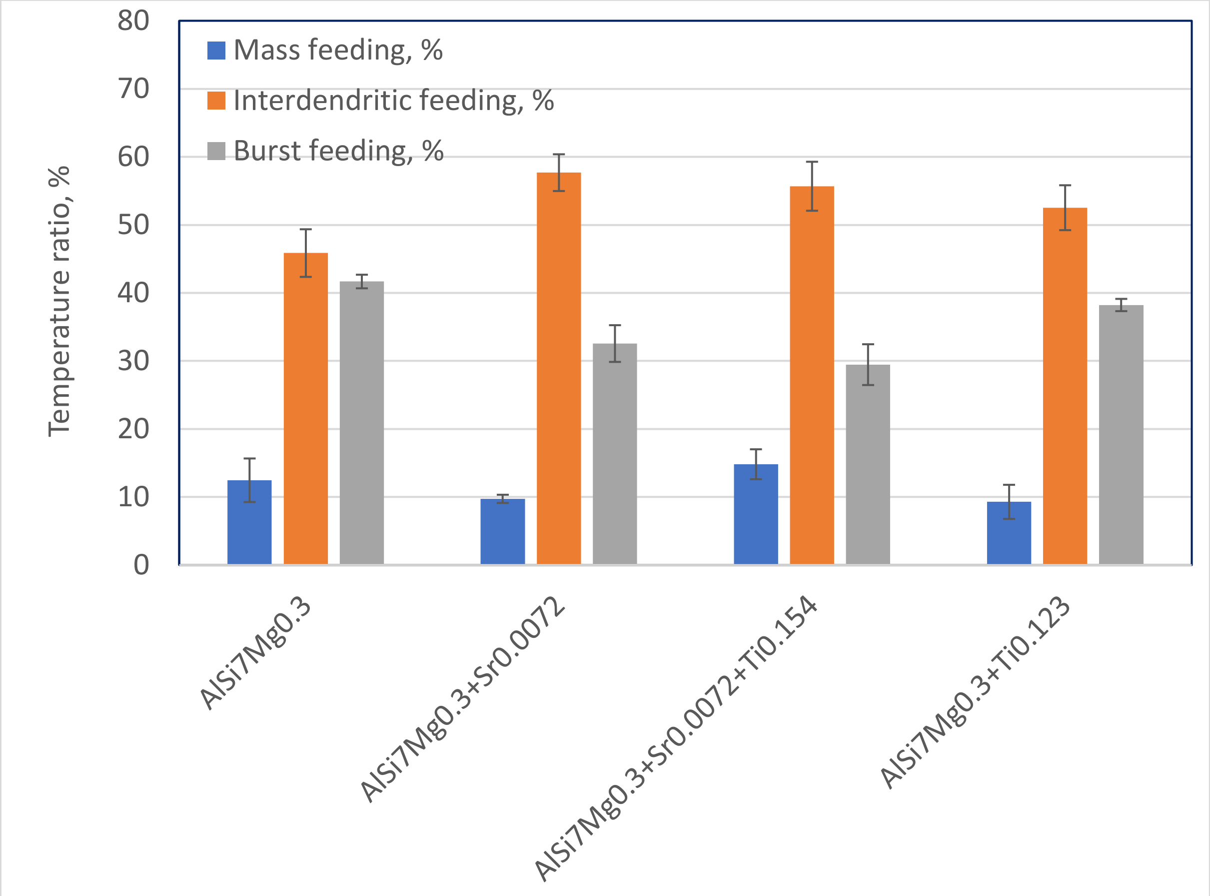


Figure 8. The impact of adding modifier and grain refiner (separately or together) on the temperature ratio of different feeding regions. All values associated with these feeding regions are derived from averaging multiple measurements. The vertical lines on the bars represent the standard deviations of the corresponding measurements.

Figure 8 illustrates, that the introduction of strontium led to an approximate 12% extension of the Interdendritic Feeding (IDF) temperature ratio, concurrently resulting in a notable 9% reduction in the Burst Feeding (BF) temperature ratio. The influence of strontium aligns with expectations. It is widely recognized, that strontium does not impact dendrite coherency temperature but significantly lowers the rigidity temperature, thereby expanding the interdendritic feeding region [21]. Particularly, grain refiners, commonly based on elements such as titanium or boron, are incorporated into aluminum alloys to refine the grain structure. They facilitate the formation of smaller and more uniformly distributed grains within the alloy. A finer grain structure enhances the feeding capacity of the alloy by providing more nucleation sites for the growth of solidification fronts. This, in turn, promotes a more uniform and controlled solidification process, mitigating the risk of shrinkage defects and ensuring proper mold filling. Analyzing **Figure 8,** the addition of titanium (0.154 wt.%) to a non-modified aluminum melt (Experiment #4) increased IDF temperature ratio by approximately 7% and decreased BF temperature ratio by around 3.5%. Simultaneous incorporation of a modifier and grain refiner into the aluminum melt resulted in a 10% expansion of IDF temperature ratio and a 12% reduction in BF temperature ratio. The low standard deviation observed in **Figure 8** indicates the high repeatability of all measurements, demonstrating IDECO feeding thermal analysis's ability to quantify the various feeding ranges with high accuracy.

Simulation in the modern aluminum casting foundries has been applied as a routine procedure in their everyday works, drastically reducing the number of experiments, improving quality of final cast products as well as reducing the costs for developing new products. On that way, foundry engineers are capable to shorten the period of a new development and earlier launch a novel product to customer. To be capable to achieve these tasks, the simulation software packages need to have an accurate data base for various aluminum cast alloys. Presently applied data bases are using thermal, physical, and chemical parameters for standard types of aluminum alloys with exact chemical compositions. These data bases are not sensitive enough to accommodate any changes in the actual chemistry of applied alloys. The impact of grain refinement, modification and/or influence of minor alloying elements on the solidification paths of cast aluminum alloys are usually not considered in those standard data bases. Commercial software suppliers usually only provide parameters for standard alloys with predefined chemical compositions in their databases. If additional material parameters for advanced alloy compositions are needed, they need to be purchased, measured, or calculated. Therefore, it is necessary to find out other sources that can update an existing data base with more accurate information. As it has been demonstrated in this paper, a good way to obtain a new information is IDECO thermal feeding analysis system. This system makes it possible to find missing parameters such as characteristic solidification temperatures, corresponding amount of fraction solid at each characteristic temperature, amount of latent heat, temperature range of various feeding regions and improve the accuracy of simulation.

Conclusions

In the available literature there is limited information related to the quantitatively description of each of the five feeding mechanisms proposed by Campbell. This paper analyzed the impact of modifier (AlSr10) and grain refiner (AlTi3B1) on the different feeding regions of EN AC-42100 alloy using IDECO thermal feeding analysis system. The three novel criterions to characterize the feeding behavior during the solidification process, such as temperature ratio for mass free feeding, temperature ratio for interdendritic constrained feeding and temperature ratio for burst feeding have been proposed. These criterions assume that solidification parameters such as liquidus temperature, dendrite coherency temperature, rigidity temperature and solidus temperature mark transitions between different types of feeding mechanisms. It was found that addition of modifier and grain refiner has influence on the temperature ranges of inter dendritic (IDF) and burst feeding (BF) regions. Added strontium up to 72 ppm increases IDF temperature ratio for 12% and reduces BF temperature ratio for 9%. Grain refiner (0.123 wt.% Ti) increases the IDF temperature ratio for 6.7% and decreases the BF temperature ratio for 3.5%. Combined addition of modifier and grain refiner (72 ppm Sr and 0.154 wt. % Ti) increase the IDF temperature ratio for 10% and decrease the BF temperature ratio for 12%. This paper demonstrated that the IDECO thermal feeding analysis system can be used accurately to quantify various feeding regions and feed existing data base with new data that so far have not been applied in simulation.

Literature

1. J. Gubicza, N.Q. Chinh, Z. Horita, T.G. Langdon, “Effect of Mg addition on microstructure and mechanical properties of aluminum“, Materials Science and Engineering A 387–389 (2004) 55–59.
2. A.M.A. Mohamed, F.H. Samuel and S. Alkahtani, “ Bewertung der Wirkung einer Magnesiumzugabe auf der Erstarrungsverhalten von Al-Si-Cu-Gusslegierungen”, Giesserei Praxis, 2013, Vol. 7-8, s. 286-294, ISBN 978-3-446-43169-0.
3. O. E. Okorafor, “Some Considerations of the Volume Shrinkage of Aluminium-Silicon Alloy Castings Produced in Full Moulds“,Transactions of the Japan Institute of Metals, Vol. 27, No. 6 (1986), pp. 463 to 468.
4. J. M. Kim at all., Porosity formation in relation to the feeding behavior of AlSi alloys, AFS Transactions 1997.
5. Campbell, J., “Feeding Mechanisms in Castings”. AFS Cast Metal Research Journal, 1969. 5: p. 1-8.].
6. Paul L. Schaffer, Young C. Lee and Arne K. Dahle; “The Effect of Aluminum Content and Grain Refinement on Porosity Formation in Mg-Al Alloys”, Magnesium Technology 2001, Edited by J. Hryn, TMS (The Minerals, Metals and Materials Society, 2001, pp. 87-94).
7. Arnberg, L.; Dahle, A.; Paradies, C.; Syvertsen, F., “Feeding Mechanism in Aluminum Foundry Alloys”, AFS Transactions, 1995, 115, 753- 759.
8. Arnberg, L.; Chai, G.; Backend, L., “Studies of dendrite coherency in solidifying aluminum alloy melts by rheological measurements”, Mater. Sci. Eng., 1993, A173, 101-103.
9. Chai, G., “Dendrite Coherency During Equiaxed Solidification in Aluminum Alloys”, Chemical Communications. No. 1, Stockholm University, Stockholm, Sweden 1994.

10. Chai, G.; Bäckerud, L.; Rolland, T.; Arnberg, L., “Dendrite Coherency during Equiaxed Solidification in Binary Aluminum Alloys”, Metall. Mater. Trans. A, 1995, 26A, 965-970.
11. Veldman, N.; Dahle, A.; St. John, D., “Determination of Dendrite Coherency Point”, Die Casting & Tooling Technology Conference, 22-25 June, 1997, Melbourne, Australia.
12. Claxton, R.J., “Aluminum alloy coherence”, Continuous Casting, AIME Metallurgical Society, New York (1973), pp. 341-352.
13. Zamarripa, R.C.; Ramos-Salas, J.A.; Talamantes-Silva. J.; Valtierra, S.; Calas, R., “Determination of the Dendrite Coherency Point during Solidification by means of Thermal Diffusivity Analysis”, Metall. Mater. Trans. A, 2007, 38A, 1875-1879.
14. Djurdjevic, M.; Kierkus, W. T.; Sokolowski, J. H., “Detection of the Dendrite Coherency Point of Al 3XX Series of Alloys Using a Single Sensor Thermal Analysis Technique”, 40th Annual Conference of Metallurgists of CIM 2001.
15. Eskin, D.; Katgerman, L.: “A Quest for a new hot tearing criterion”, Metallurgical and Materials Transactions A, 2007, pp.1511-1519.
16. Bäckerud, L.; Chai, G.; Tamminen, J., “Solidification Characteristics of Aluminum Alloys”, Vol. 2: Foundry Alloys, AFS/ScanAluminium, Oslo, Norway, 1990.
17. M. Dash, M. Makhlouf “Effect of key alloying elements on the feeding characteristics of aluminum–silicon casting alloys”, , Journal of Light Metals 1 (2001) 251–265.
18. J. Cho, C. Jeong, Y. Kim, S. Choi and C. Kang, “The effect of copper on feeding characteristics of aluminum casting alloys”, Proceedings of the 12th international conference on aluminum alloys, September 5-9, 2010, Yokohama, Japan, pp. 745-750.
19. Michel W. and Engler S; “Speisungskinetik von Aluminum-Silizium Gußlegierungen”, Giesserei 75, Nr. 14, 1988, s. 445-448.
20. Michel W. and Engler S; “Erstarrungsmorphologie und Speisungsablauf von Aluminium-Silizium Legierungen bei Kokillenguß“, Giesserei 77, Nr. 3, 1990, s. 79-82.
21. Michel W and Engler S., “ Speisungsverhalten und Porosität von Aluminium-Silicium – Gußwerkstoffen“, Giessereiforschung 41, 1989, Nr. 4, pp.174-187.
22. G. Huber, M. B. Djurdjevic and M. Rafetzeder, “Impact of silicon, magnesium and strontium on feeding ability of AlSiMg cast alloys”, Material Science Forum, 2016, Vol. 879, pp. 784-789, ISSN: 1662-9752.