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EFFECT OF THE THERMAL MODULUS AND MOULD TYPE ON THE GRAIN SIZE OF ALSI7MG ALLOY

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Abstract

Thermal analysis has been used for decades for melt control before casting aluminum alloys. However, obtaining a good grain refinement in a standard cup does not ensure that the grain refinement is correct in real parts which may solidify at very different cooling rates. For this study, the effect of cooling rate on AlSi7Mg alloy with different metal qualities in terms of grain refinement was tested. The correlation between grain sizes measured on the standard cup with those obtained in cylindrical test parts with various diameters cast in sand and metallic moulds has been investigated. It was found possible to set up a formula for the grain size of the cylindrical test parts in function of their modulus and of the grain refinement obtained on the standard thermal cups. Corrective actions can then be taken in order to improve the metallurgical quality before casting.

Introduction

Aluminum-silicon alloys are the most used alloys for manufacturing cast parts in aluminum because they have a high castability and may be adapted to span a large range of mechanical properties. A large part of their mechanical properties is related to melt treatment, amongst which grain refinement which is based on the addition of particles that act as nuclei of primary (Al) grains upon solidification. Grain refinement effects positively various characteristics of the cast parts, e.g. reduces porosity and decreases the tendency for shrinkage formation [1-3].

On the other hand, the quality of melt preparation can be checked by means of thermal analysis which has been regularly applied to aluminum-silicon alloys and more particularly to AlSi7Mg alloys during the past decades [3-13]. The effect of grain refinement on the cooling and solidification curves relate to parameters associated with solidification of the primary (Al) phase such as undercooling, recalescence and solidification time. This has led to a significant number of reports in the literature albeit mostly on cooling curves recorded with standard thermal cup [9-13]. On the contrary, very few works dealt with microstructure prediction in real parts which most generally present variation in local cooling rate. This latter is essentially determined by the so-called thermal modulus of the part and by the type of mold used [8, 9].

In the present work, we establish a relation between parameters issued from thermal analysis with standard cup using Thermolan-Al [12] and the microstructure of parts consisting in cylinders with various thermal moduli. The cooling rates achieved during solidification ranged between 1.5 and 30°C/s depending on cylinder's modulus and mold's material. This approach has been applied to alloy AlSi7Mg with different additions of grain refiner.

Experimental details

Table 1 gives the chemical composition of the alloys used in this work, they all satisfy the AlSi7Mg label with Mg content varying in between 0.28 and 0.50 wt.%. All alloys were prepared using ingots of AlSi7Mg and a given percentage of returns so as to reproduce manufacturing conditions encountered in industry. In some of the alloys, strontium has been added for modification of the (Al)-Si eutectic. Varying grain size was achieved by adding various amounts of Al-5%Ti-1%B (mass percents) master alloy as grain refiner. The amount of grain refiner added to alloys I and II was approximately half the usual one while all other alloys received the usual amount, namely 400 g of master alloy for 100 kg of alloy.

Table 1. Chemical analysis of the investigated AlSi7Mg alloys (mass %).

Ref.	Si	Fe	Cu	Mn	Mg	Zn	Ti	Sr
I	7.3	0.11	<0.01	<0.01	0.41	<0.01	0.12	<0.003
II	7.1	0.13	<0.01	<0.01	0.50	<0.01	0.16	<0.003
III	7.0	0.16	<0.01	<0.01	0.35	0.02	0.16	0.010
IV	6.6	0.14	<0.01	<0.01	0.28	<0.01	0.14	<0.003
V	6.9	0.19	0.02	<0.01	0.39	<0.01	0.16	0.009
VI	6.8	0.09	<0.01	<0.01	0.31	<0.01	0.14	0.011
VII	6.3	0.13	0.03	<0.01	0.32	0.05	0.19	0.013

All alloys have been cast in sand molds containing 6 cylinders with various thermal moduli. Furthermore, alloys I, V, VI and VII were also cast in metallic molds with a similar design (figure 1). In both molds, the height of the cylinders was equal to their diameter. The values of the thermal moduli (ratio of the volume over outer surface of the cylinders) are listed in table 2. A thermocouple was located at the centre of each cylinder for recording the temperature during cooling and solidification.

Figure 2 is a typical example of cooling curve recorded with AlSi7Mg alloy during its solidification. The insert shows an enlarged view of the part related to the solidification start where the various parameters considered as characteristic of nucleation of the (Al) primary phase are illustrated. These parameters are defined as [9-11]:
- ΔT_{Al} is the recalescence, i.e. the difference between the maximum $T_{Al,max}$ and minimum $T_{Al,min}$ temperatures;
- KF16 is defined as the difference between the temperature when the cooling rate is 2°C/s and the temperature recorded 16 s later;

- $t_{f,Th-Al}$ is the time difference between the moment corresponding to the minimum in temperature and the time at which that temperature is again reached after recalescence.

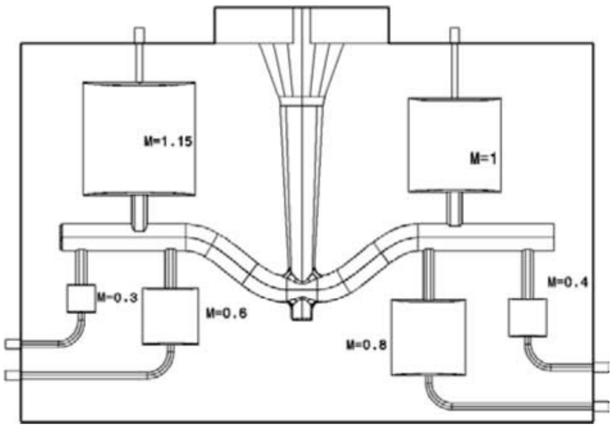


Figure 1. Schematic of the metallic mold designed for casting test cylinders with various thermal moduli (indicated in the schematic). The design was similar for the sand molds.

Table 2. Thermal modulus of each of the test cylinders.

Mold	Thermal modulus (cm)						
Sand	1.5	1.15	1	0.8	0.6	0.4	-
Metallic	-	1.15	1	0.8	0.6	0.4	0.3

With each alloy was also cast one standard thermal cup [15] for analysis with Thermolan-Al and estimation of the above parameters. Using a database of 500 records, these parameters were found to be the most significant for the prediction of grain size [12]. The values of the parameters for the standard cups and the corresponding predicted grain size TG_{Th-Al} are listed in table 3.

Table 3. Values of some parameters characterizing primary (Al) solidification evaluated on cooling curves recorded with Thermolan-Al on standard thermal cups. Values of the estimated grain size TG_{Th-Al} (see text) are also listed.

Ref.	$t_{f,Th-Al}$ (s)	KF16 (ºC)	ΔT_{Al} (ºC)	TG_{Th-Al} (mm)
I	6.4	4.80	0.2	0.73
II	7.0	3.50	0.2	0.60
III	4.0	4.33	0.1	0.51
IV	1.7	5.28	0	0.47
V	2.4	5.18	0	0.47
VI	1.6	4.74	0	0.46
VII	0.4	5.78	0	0.44

After casting, all cylinders and thermal cups were cut and prepared for metallographic observation. For grain size estimation, the samples were submitted to the electrolytic Baker's etching and observed under polarized light in an optical microscope. The grain size was estimated by the intercept method.

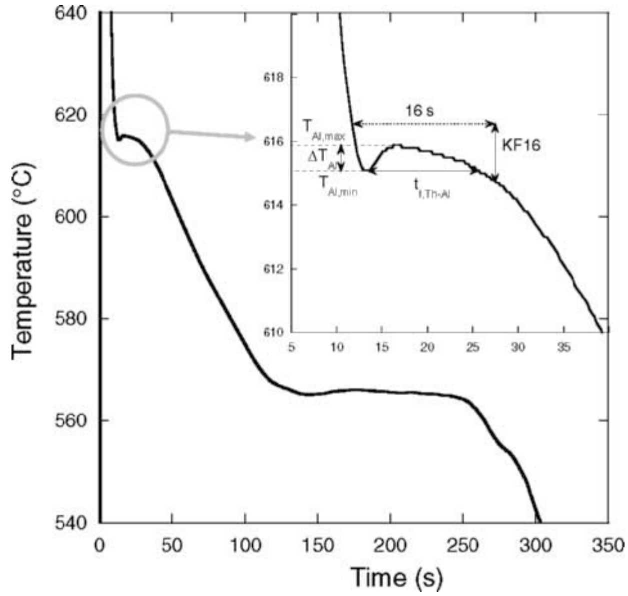


Figure 2. Example of cooling curve with definition of characteristic parameters for primary (Al) growth shown in the enlarged view of the insert.

Results and discussion

The effect of grain refinement on the microstructure of standard thermal cups is illustrated in figure 3 where the grain size changes from 0.44 to 0.73 mm depending on the alloy. It may be checked that there is no simple relation between the amount of Ti-bearing master alloy added and grain refining. It thus appears that the effectiveness of grain refinement depends also on the Ti content of the alloy before the addition of the Ti-bearing master alloy, as the dissolution of the latter in the melt may depend on its initial Ti content [15]. As a consequence, chemical analysis of the metal is not sufficient to give information, on grain refinement efficiency.

The effect of the thermal modulus (i.e. the cylinder diameter) on the cooling curve is illustrated in figure 4 in the case of alloy IV, for both sand (a) and metallic (b) molds. Decreasing casting modulus leads to higher cooling rate and to a decrease of both the start of solidification and (Al)-Si eutectic temperatures, as well as to smaller overall and eutectic solidification times. In both graphs of figure 4 has been superimposed the cooling curve recorded on the thermal cup. It is seen that its cooling rate is much lower than the one for any cylinder in the metallic mold while it appears located in between the curves for 0.8 and 1 cm modulus for mold casting. Considering the whole series of cooling curves, the cooling rate at the start of solidification varied in between 1.5 and 30°C/s.

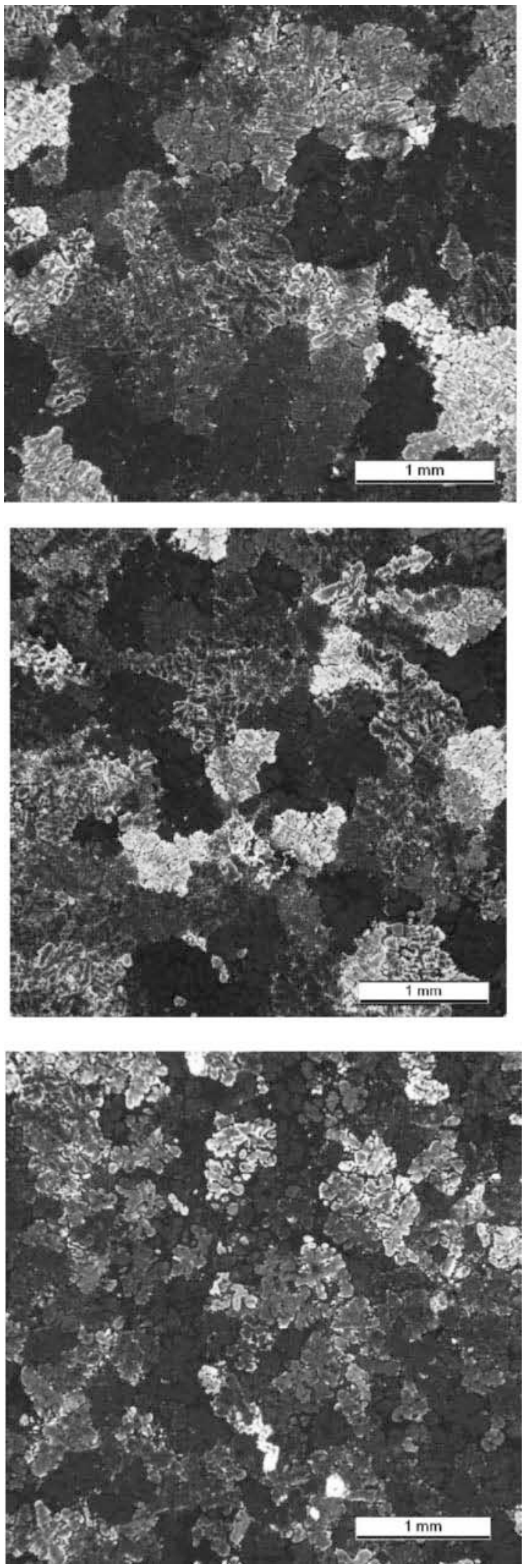


Figure 3. Micrographs illustrating the range of grain size observed in thermal cups (top: alloy I, $TG_{Th\text{-}Al}$=0.73 mm, middle: alloy III, $TG_{Th\text{-}Al}$=0.51 mm; bottom: alloy VII, $TG_{Th\text{-}Al}$=0.44 mm).

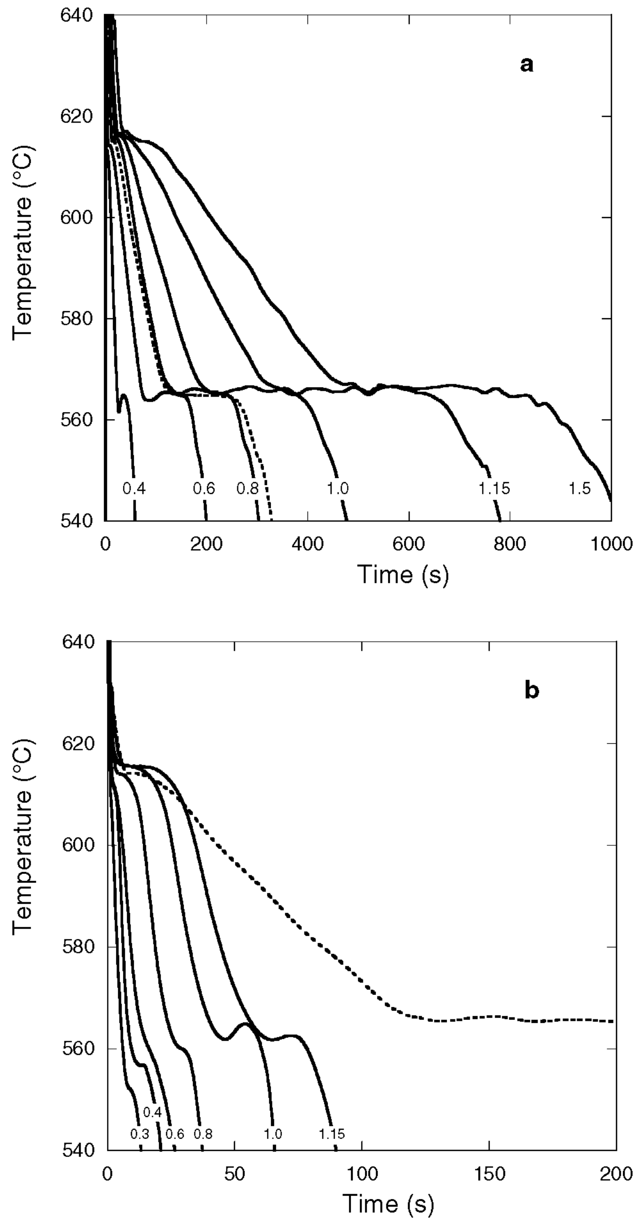


Figure 4. Cooling curves of alloy IV obtained from cyl:inders with various moduli cast in sand (a) and metallic (b) molds. The curves are labeled with the corresponding modulus, and the curve obtained on the thermal analysis cup appears dashed.

Figure 5 shows the effect of the thermal modulus on grain size for both sand (a) and metallic (b) molds and for the various additions of grain refiner. As expected, the grain size decreases when the modulus is smaller or when, at given modulus, the mold is changed from sand to metal. It is of some interest to note that a linear relationship may be established between gain size and thermal modulus for the range investigated. The corresponding equations are given within the graphs of figure 5. It should be further stressed that the coefficients of this linear relationship are related to grain refinement as observed on the thermal analysis cup. For sand molding, it is thus observed that the constant and the slope in the linear relation decrease with grain refinement, the slope being 0.19 for the most grain refined alloy (VII) and 0.43 for that giving the coarsest grains (I). The same trends are observed for metallic molds, though the slopes are somehow lower than for sand casting. It is thus seen that the effect of grain refinement is hardly noticeable in small grain parts cast in metallic molds. In other words, the effect of modulus is more evident in case of coarse grains, in both sand and mold castings.

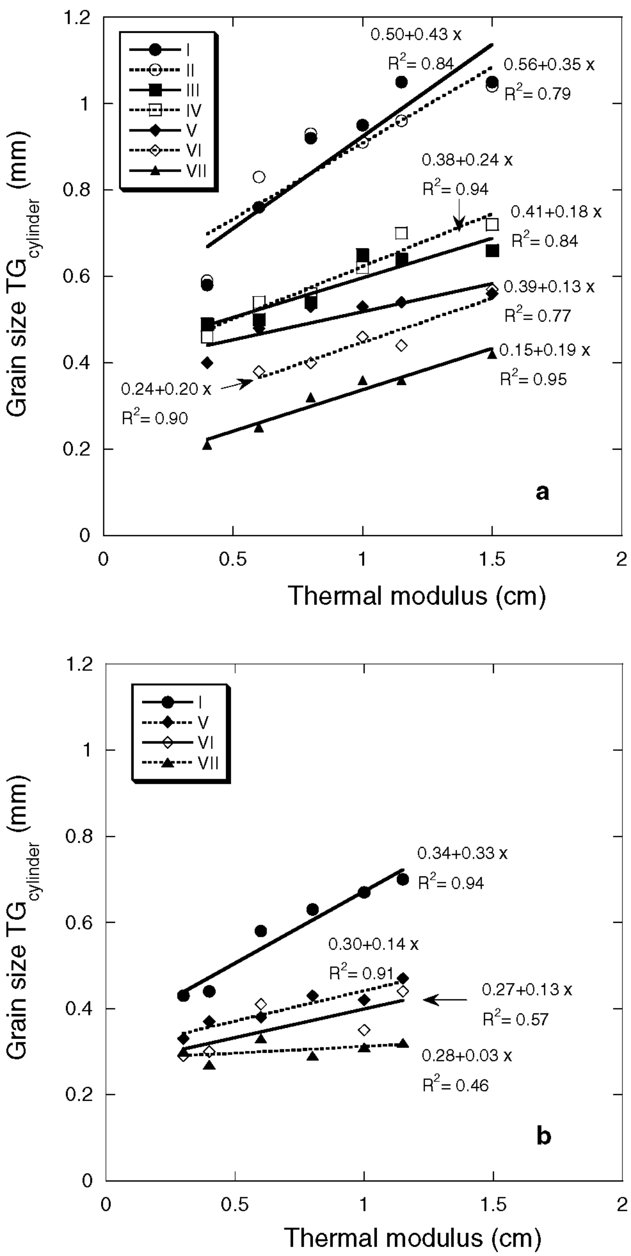


Figure 5. Grain size evolution versus modulus for sand (a) and metallic (b) molds. Symbols differentiate the AlSi7Mg alloys used, and least square fitting relations are indicated.

The data in figure 5 have been fitted by least square method differentiating each casting. The slopes of the fitting lines, thus obtained, have been reported in figure 6-a versus the corresponding grain size, TG_{Th-Al}, estimated from the thermal cup records. It is seen that a line can be drawn through the results of each type of castings, and the associated R^2 value is 0.85 for sand and 0.91 for metallic molds. The slope of these latter lines is the same, equal to 1.08.

On the other hand, it was found appropriate to use the solidification time $t_{f,Th-Al}$ as the parameter for plotting the constant of the lines in figure 5. This is illustrated in figure 6-b where it is seen that two lines are again found, one for each type of mold. The fitting parameter R^2 is high enough at 0.82 for metallic and 0.83 for sand molds. Associating the fitting values for slopes and constants give the following equations between the grain size in a cylinder $TG_{cylinder}$ (mm), the solidification time $t_{f,Th-Al}$ and grain size TG_{Th-Al} for the thermal cup, and the modulus M (cm) of the cylinder:

$TG_{Cylinder}=0.20+0.051\cdot t_{f,Th-Al} + [(1.08\cdot TG_{Th-Al}-0.31)\cdot M]$
for sand molds, and

$TG_{Cylinder}=0.27+0.011\cdot t_{f,Th-Al} + [(1.08\cdot TG_{Th-Al}-0.39)\cdot M]$
for metallic mold.

Figure 7 shows the values of the grain size measured in the cylinders with respect to the values calculated by means of the above equations.

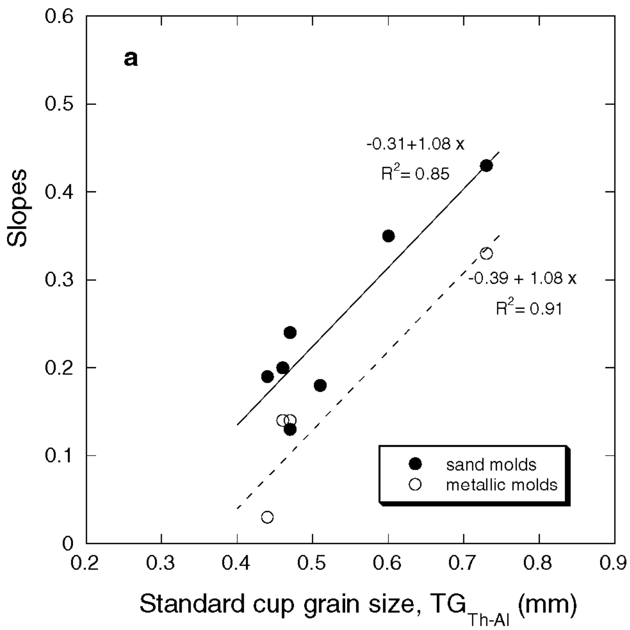
In a previous work [13] was used another approach based on the statistical analysis of parameters measured on the cooling curves of the thermal cups and of the cylinders. This gave a fitting equation with an excellent regression factor R^2 at 0.99. However, the drawback of this first approach is that it needed the calculation of the liquidus temperature of the alloy which relates to the knowledge of the exact alloy composition. Other authors have measured grain size in various locations of a cylinder head looking for changes in grain refinement as determined by thermal analysis [9]. From this, they draw a diagram of grain size for different locations in the cast part versus grain size prediction in the TA cup. While the output of this study is of interest, its use is limited to the same parts as the one they investigated. On the contrary, the present work proposes a method to evaluate grain size in various locations of a part by knowing only the local thermal modulus and evaluating two parameters from the cooling curve of the standard cup used to check melt preparation.

Conclusion

We have studied the effect of the cooling rate on grain size in AlSi7Mg alloys. The cooling rate varied from 1.5 to 30°C/s by means of cylinders of different sizes cast in instrumented sand and metallic molds. For this, seven alloys that were slightly or normally refined were considered. Thermal analysis with Thermolan-Al was used on standard thermal cups and the records from thermocouples positioned in the cylinders. The most important conclusions are:

- for each alloy and for each mold, a linear relationship was observed between grain size and thermal modulus;
- for a given refining treatment, the grain size was much more refined in metallic molds than in sand molds;
- for each kind of molds, it has been possible to formulate an equation giving the grain size as a function of the thermal modulus and of two quantities evaluated from the cooling curve recorded on the standard thermal cup, namely TG_{Th-Al} and $t_{f,Th-Al}$;

- knowing the thermal modulus and the type of mold, one can thus check from the standard thermal analysis if the grain refining treatment will be appropriate for the part being cast or if it has to be adjusted.



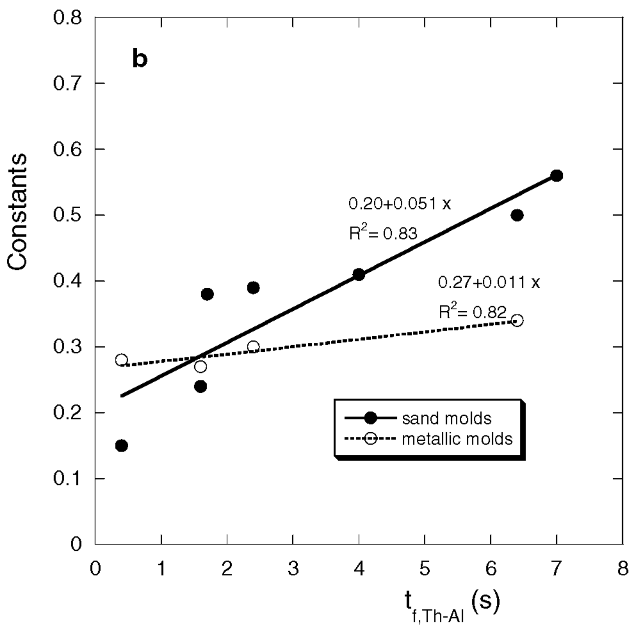


Figure 6. a. Evolution of the slope of the regression lines in figure 5 versus the grain size in the thermal cup TG_{Th-Al}. b: Evolution of the constant in the regression lines versus the solidification time $t_{f,Th-Al}$ in the thermal cup.

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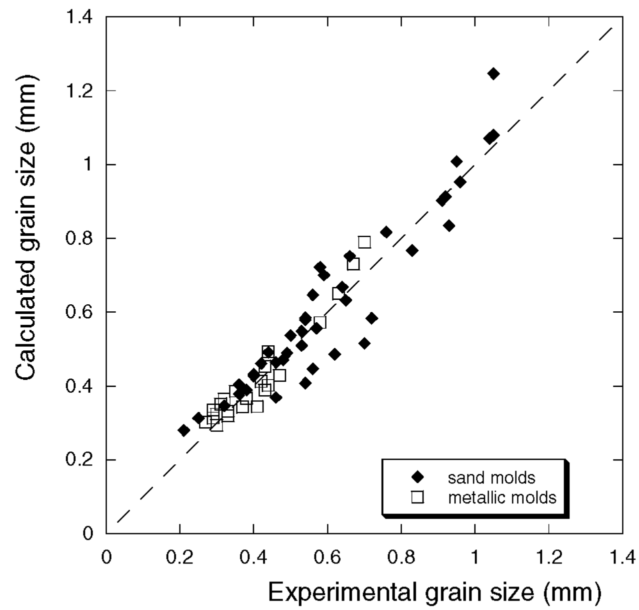

Figure 7. Plot of experimental versus calculated values of grain size in the cylinders. The dashed line is the bisector.

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