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ARTICLE

Impact of Cooling Rate on the Results of Vibration Treatment of the Aluminum Casting

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ABSTRACT

The effect of vibration (50 Hz) on the formation of aluminum castings of 99.5% purity at various cooling rates was studied. It was found that the presence of vibration leads to an increase in the cooling rate of the castings. It was found that the higher the speed without vibration, the stronger the effect of increasing the speed when vibration was applied. Apparently, this effect is associated with additional mixing of the melt by free-floating crystals.

Keywords: Casting; Cooling rate; Vibration; Structure; Grain size

1. Introduction

To improve the structure and quality of castings, various methods, from Taguchi's method of optimization of casting parameters [1] and the use of artificial intelligence [2] to various influences on the casting process are widely used.

There are many different special casting methods, such as centrifugal casting [3,4], liquid stamping method [5], casting method involving the mixing of two alloys [6] and soon.

Another approach involves methods that assume a specific effect on the melt—a magnetic field (mainly the effect was to stir the melt during crystallization) [7,8], treatment with current—as direct [9], as pulsed (to reduce thermal impact) [10-13], vibration. The latter case is presented in the scientific literature by works on both ultrasonic [14,15] and low frequency, in combination with other methods [16] independently. It notes a beneficial effect of vibration on increasing the density of castings and reducing shrinkage defects [17].

Such studies are mainly devoted to the role of frequency, amplitude, and duration of oscillations.

It was found [18] that increasing the frequency

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from 15 to 41.7 Hz and the amplitude from 0.125 to about 5 mm enhances the effect of grain refinement (alloy Al-12.3 wt.% Si). A similar effect was observed on the Al—2% Cu alloy [19] and the hypoeutectic Al-Si alloy [20]. For the A356 alloy, the effect of vibration of 10-59 Hz with a duration of 5-15 min was investigated [21]. It was found that the maximum grain refinement of α-Al (53%) and the highest density of 2.68 g/cm^3 occurred during treatment at 50 Hz for 15 min. It can be concluded that there is a general tendency—"intensification" of vibration processing that leads to grain refinement.

It should be noted that in the process of producing castings, depending on the type and method of casting, different cooling rates occur, which can affect the vibration processing efficiency. This question is the subject of our study.

2. Experimental procedure

The studies were conducted on A5 grade aluminum (Ukrainian classification), the composition of which is given in **Table 1**.

Aluminum of this composition was melted in a furnace and kept at a temperature of 750 °C for 30 min, alloy was melted in a resistance furnace with a cast iron crucible coated from the inside with a refractory mixture. The crucible capacity was about 3 liters, and melt amount was about 5 kg by weight. After bringing the melt to the temperature of 750 °C, the melt was held for 20 min and the dross was removed from the melt mirror. Pouring was carried out in cylindrical molds (cavity ø 40 mm × 60 mm). The cooling rate was adjusted by different types of molds. Four types were used, the parameters of which are given in **Table 2**.

The molds were installed on a heat-insulated platform; with the help of an external fastener, chromel-aluminum thermocouples were installed in the center of the mold, from which the temperature was recorded to determine the cooling rate. Two series of experiments were carried out: Without vibration and with platform vibration at a frequency of 50 Hz (which was noted as effective [21]) and an amplitude of 0.2 mm. The molds were cooled in air, the castings were removed, cut in the middle of the height and the section was polished and etched. Photographs of the cross-sections were used to determine the average size of an equiaxed grain and the thickness of columnar crystals in the middle part.

3. Results

The cooling rates observed in the present experiments are shown in **Figure 1**. The characteristics of the forms can be determined by the M 1-M 4 codes, see **Table 2**.

As shown in the figure, the cooling rates of castings increase when subjected to vibration. The structures of the resulting castings are shown in **Figure 2**. The cooling rates increased from M 1 to M 4.

Table 1. Chemical composition of the material, wt. %.

Al	Fe	Si	Mn	Ti	Cu	Mg	Zn	Ca
min 99.5	0.3	0.25	0.05	0.02	0.02	0.03	0.06	0.03

Table 2. Parameters of the molds, used in experiments.

Mold code	Mold material	Thermal conductivity coefficient λ, W/(m·K)	Wall thickness, mm	Dimensions of internal cavity, mm
M 1	Vologran*	0,14	25	ø 40 × 60
M 2	Steel	47	1	ø 40 × 60
M 3	Steel	47	10	ø 40 × 60
M 4	Steel	47	20	ø 40 × 60

* composite material (50% kaolin fiber and 50% high alumina cement).

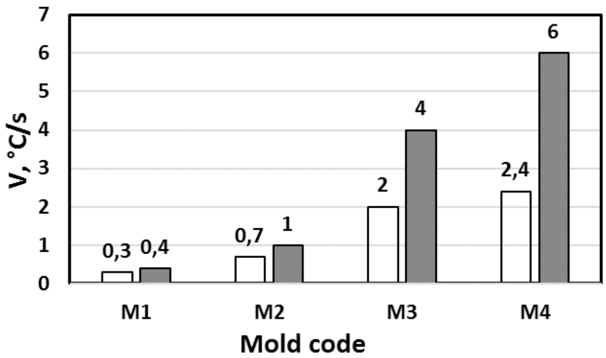

Figure 1. Cooling rates of castings; cast in various molds without (empty columns) and with vibration (shaded columns).

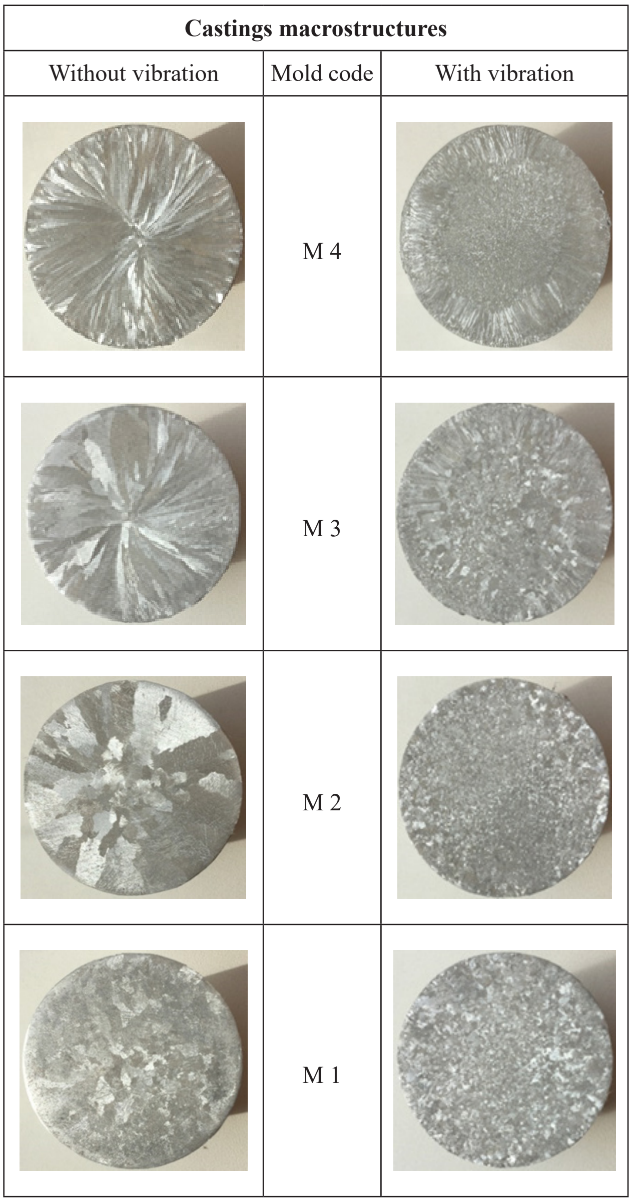

Figure 2. Macrostructures of castings without and with vibration. The characteristics of the grain structure of the castings are given in **Table 3**.

Table 3. Characteristics of the grain structure of the castings.

Grain type	Presence of vibration	Grain size, mm			
		M 1	M 2	M 3	M 4
Columnar grains	–	0	4.37	2.4	1.5
	+	0	0	0.95	0.63
Equiaxial grains	–	3	3.8	0	0
	+	1.29	1	1	0.5

4. Discussion

4.1 General characteristics of the structure

Looking at the structures shown in **Figure 2**, the general trend is an equiaxed structure at low cooling rates and the appearance of a columnar structure at high rates is observed both in the absence and under the influence of vibration. Externally, the picture looks like the following: If in the absence of vibration, there is a full cycle of structural changes with an increase in the cooling rate: (completely equiaxed) → (equiaxed + columnar) → (completely columnar), then with vibration there is an incomplete cycle: (completely equiaxial) → (equiaxed + columnar). If we compare M 2 (without vibration) and M 3 (with vibration); one gets the impression that by type (equiaxed + columnar) these are similar structures, differing only in grain dispersion. The transition from an equiaxed to a columnar structure with an increasing cooling rate is widely known in both experimental [22] and theoretical works [23]. In our study, we note that the presence of vibration creates conditions for the existence of equiaxed grains in the region of higher cooling rates. Since the existence of a gradient in the melt is necessary for the existence of a columnar temperature, it is obvious that the melt flows generated by vibration lead to the fact that higher cooling rates are necessary for its occurrence.

4.2 Grain size

As for columnar grains, they are formed in the process of directed crystallization because of competition among neighboring grains depending on the ratio of the direction of the temperature gradient and the direction of preferential growth of 100 aluminum dendrites (details of such competition are discussed in detail [24]). As shown in this work, when the conditions of directed growth are far from a cellular and even more flat front and dendritic growth occurs, the rules of competition do not depend on the growth rate, and thus the fineness of the resulting structure depends on the number (density) of crystals nucleated on the surface of the mold. Obviously, an increase in the cooling rate increases the number of such crystals and, accordingly, a decrease in the width of each individual crystal, which corresponds to the trend observed in **Figure 2** for columnar crystals—a fairly smooth dependence of a decrease in size from 4.4 mm for a cooling rate of 0.7 °C/s to 0.63 mm for 6 °C/s.

Regarding the size of equiaxed grains growing in the volume of the supercooled melt, note that their size is determined by the ratio between the frequency of nucleation and the growth rate (in the case of a real casting, it is also necessary to take into account crystals brought into the supercooled volume, for example, detached from the walls of the mold). Therefore, at high supercooling and high growth rates corresponding to them, one or two nucleated crystals have time to fill (absorb) almost the entire volume of the melt; due to this simple "be no place" for other grains to nucleate, and the entire casting will consist of several grains. Alternatively, if the growth rate is not high, and the nucleation is intense, the resulting crystals slowly increase in size and leave free a large volume of super cooled melt, in which more and more new crystals can "born".

For a case without vibration (see **Table 3**) it is difficult to talk about the dependence of the size of equiaxial grains on the cooling rate, since they were observed in only two experiments. In experiments with vibration, their size in the speed range of 0.3-4 °C/s did not change significantly (1.3-1 mm) and significantly decreased at 6 °C/s—0.5 mm.

4.3 Cooling rate

The change in the cooling rate under the influence of vibration (see **Figure 1**) is nonlinear. The dependence of the cooling rate with vibration on the cooling rate without vibration is shown in **Figure 3**.

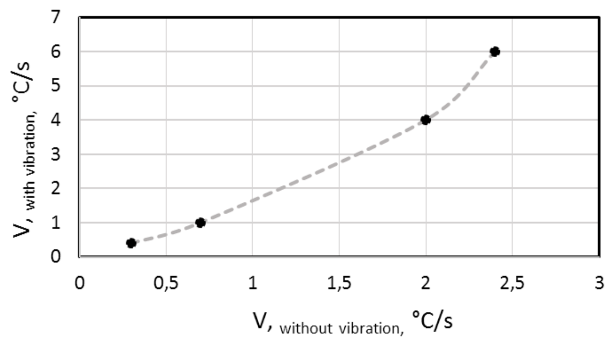

Figure 3. The ratio of the cooling rates of castings in various molds (from left to right from M 1 to M 4) with vibration and in the absence of vibration.

As shown in the figure, vibration leads to an increase in the cooling rate, the more it was without vibration. In our experiments, different cooling rates were achieved using molds from different materials with different parameters (**Table 2)**. However, the parameters of the internal cavity where the metal was poured in all experiments were the same, as were the vibration parameters. Thus, the different efficiency of mechanical vibration (see **Figure 3)** was not entirely clear. Moreover, the formation of a zone of columnar crystals, which reduces the diameter of the melt region should reduce the vibration efficiency, while we see the opposite effect. It seems reasonable to assume that the flows in the melt are created not only by the movement of the mold itself; but also by the presence of "free-floating" crystals in the melt, which; due to inertia; move in the melt when the mold is moved, creating the movement of the melt. An increase in the cooling rate (**due to changes in the parameters of the mold**) leads to an increase in the nucleation of crystals, which leads to an increase in the number of "free-floating" crystals, mixing the melt with them, which increases the cooling rate of the casting (**due to vibration**).

5. Conclusions

1) The presence of vibration during crystallization ensures the existence of equiaxed grains in the region of higher cooling rates.

2) The increase in the cooling rate of the casting

under the influence of vibration depends on the cooling rate without vibration. The higher this speed was without vibration, the greater the effect of vibration.

3) Apparently, this is because a high cooling rate (without vibration) leads to an increase in the number of "free-floating" crystals, which; under vibration, leads to melt mixing and an increase in the cooling rate.

Authors' Contribution

A.G. Borisov: Sample processing, metallography, discussion of results.

A. Nuradynov: Conducting experiments with vibration, and discussing the results.

V. U. Sheigam: Preparation of experiment materials, casting, discussion of results.

Conflicts of Interest

The authors declare that they have no potential conflicts of interest.

Data Availability Statement

The data of this work are in principle publicly available through the Institute of Scientific and Technical Information, Kyiv, Ukraine, but it does not operate under war conditions.

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