Vibration influence on structure and density of aluminum alloys

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Abstract. The results of study on aluminum alloys of grade AK9M2 AK12M2 are provided. Alloy crystallization time for alloys AK9M2 AK12M2 decreases, the intensity of reduction depends on the vibration amplitude. For alloys AK9M2 and AK12M2 the optimal amplitude is 2÷2.2 mm, allowing a dense cast alloy with a fine grain structure to be obtained. Density of samples from AK12M2, cut from the bottom part, is slightly increases with the rise of the vibration amplitude.

1. Introduction
Improvement of the cast alloys density and creation of a fine-grained structure have always been important tasks. The structure and density of the cast alloys, largely determine the basic properties of metal in the casts. One of the trends in the industry is a fundamental improvement in the metal quality, improvement of their technical and economic characteristics. There are many ways to increase the density of cast alloys. The solution of this problem is possible by active interference in the crystallization process using a vibration treatment. The defining parameters influencing the melt crystallization during vibration treatment are frequency and amplitude of vibration exposure.

2. Discussion of the problem and results
According to the data in [1, 2] and our own research the optimum vibration frequency for aluminum alloys is 50 Hz [3, 4]. Vibration loads were observed only in vertical planes. The amplitude of vibration was varied in the range from 0.5 to 5 mm. Studies were carried out on aluminum alloy of grade AK9M2 and AK12M2. Alloy overheating temperature remained constant at 835÷850 °C. The samples casting temperature also remained constant and was 750÷760 °C. The melt was poured into a cylindrical mold of the following dimensions: inner diameter 64 mm and height 145 mm. The mold was mounted on vibration unit, firmly fixed with special ties to the vibration exciter [4].

To study the effect of vibration impact on the crystallizing melt the unit was designed the diagram of which is shown in Figure 1.
Starting from casting and to the complete solidification the melt was subjected to vibration with different amplitudes. Further, from the obtained ingots the samples were cut from their center at the same distance from the bottom and from their bottom part. Samples density was measured by hydrostatic weighing. In addition to the determination of cast aluminum alloys density the temperature dependences were recorded using thermocouples installed in the center of the ingot and on its surface.

Metal quality depends on the alloys composition and features of their crystallization, which is characterized by crystallization heat and melt supercooling value. One of the main methods for determining the crystallization parameters is the differential thermal analysis. To perform this analysis the temperature dependences were recorded using thermocouples installed in the center of the ingot, on the contact boundary – mold, and the external temperature of the mold. For the continuous recording of the temperature dependence the automated measuring system was used on basis of a PC and controllers of type ICP CON 7018, 7520 [5].

The measured temperature was smoothed by the method of piecewise exponential spline-approximation [4] and dT/dτ was determined to obtain differential thermal curves. Besides, the heating rate of the ingot mold surface was determined.

It is known that the change of the temperature gradient in the ingot body (between its center and the surface) changes the length of the characteristic structural zones in the ingot macrostructure.

The main reason for the destruction of the dendritic crystals is the imposition of periodically changing during the wave motion of the liquid the pressure and depressions causing the elastic deformation and stresses.

In addition, the wave process also contributes to the activation of insoluble impurities already present in the melt, which serve as a substrate for the emergence of such centers. The effectiveness of crystals refinement during solidification of the molten metal depends on the type of vibration applied. In the process of crystalline structures formation the vibration energy is consumed not only for the destruction dendritic branches and creation in the system of additional crystallizing nuclei, but also for enhancement of the heat removal rate from the melt to the mold walls. This leads to an increase in the rate of melt crystallization and significant (by 25 ... 30%) acceleration of the ingot solidification.

Besides, the source of more intensive crystallization during vibration is the formation of the supercooled micro volumes of melt not only on the boundary of vertical front of solidification, but also around each of the growing floating crystal. The structure refinement, increase in the gas yield, decrease in porosity during vibration treatment of the melt influences on the alloy density making it increase. The forced vibrations of the melt very effectively refine the crystals and influence the cast macrostructure. The destruction of dendritic crystals takes place with the formation of additional
nuclei formation. To control the size and shape of the grain it is necessary to know the mechanism of the influence of vibration on the growing crystal and the places of crystals origin in the solidified cast.

The refinement degree depends on the type of vibrations, which are located in the sequence: no vibration, vibration with amplitude orientation in the vertical plane, vibration with the amplitude orientation in the horizontal plane, vibration with circular amplitude in the horizontal plane. The most effective in terms of structure refinement is vibration with circular amplitude in the horizontal plane.

In the analysis of the impact of dynamic pulses of inertial forces on the mass of the liquid alloy we need to consider not only the variation range of their acceleration values, but the average value of these accelerations acting during each half-cycle of oscillations.

The most likely places of crystals separations are the mold surfaces and the opened surfaces of the liquid metal subjected to vibration. The increased concentration of segregates at the crystallization front contributes to obtaining narrow neck-shaped crystals on the mold surface, untimely formation of a stable crust of solidified metal, crystals uncoupling with the mold wall and prevention of remelting of the already separated crystals in the inner mold volumes. Vibration is significantly affects the processes of destruction and dispersion of dendrites branches growing on the boundary of crystallization.

Reduction in the temperature gradient between the center of the ingot and its surface increases the tendency of the alloy to the volumetric crystallization, reduces the zone of columnar crystals and, accordingly, increases the equiaxed crystal zone.

The ingots subjected to vibration have hardening boundaries of two types: at the directional heat sink to the bottom part of the mold it has a parabolic shape, and with the full heat sink – tapered. The disperse crystalline structure of the ingots is formed, primarily due to the breaking under vibration impact of peaks of columnar crystals, growing from the cooled walls and the mold bottom under the vibration impact – further about 20% (of the total) of disperse crystals are formed.

The nature of the vibration effects on the crystallization process and the formation of the alloy structure should also be linked to the thermal conditions of its solidification.

Thus, upon solidification of the ingot from the melt in the conditions of heat sink the intense peaks breaking of dendrites are observed, growing from the bottom and side walls of the mold under the influences of vibration. The intense flow of crystal fragments along the vertical solidification boundaries is noted. This movement is caused by the combined action of vibration and gravitational forces. Sinking debris of dendrites branches along the vertical solidification boundary become the centers of crystallization and provide an ingot with a fine crystalline structure.

3. Conclusions

The heating rate of the mold surface shows an increase in the crystallization rate of alloys subjected to vibration. It is found that the maximum surface temperature of the mold surface heating is observed in alloys AK9M2 AK12M2 subjected to vibration with an amplitude of 7 mm.

In the studied alloys AK9M2 AK12M2 subjected to vibration with an amplitude of 0.5 mm at the initial moment of time of cooling the maximal temperature gradient and its rate of change was low. The analysis of differential thermal curves allowed us to establish the following. Vibration treatment of the alloys shifts the critical points of the crystallization onset (liquidus) and the end of crystallization (solidus).

For hypoeutectic alloy AK9M2 at the increase in the vibration amplitude the liquidus temperature drops from 624.8 °C to 621.7 °C, and the solidus temperature decreases from 576.9 °C to 570.5 °C.

For hypereutectic alloy AK12M2 it was found that as the vibration amplitude increases the liquidus temperature increases from 605 °C to 607 °C, and the solidus temperature decreases from 576.4 °C to 574.3 °C.

Changes in critical points, the crystallization rate and interval affect the structure of aluminum alloys.

The following regularities of the influence of vibration modes on the structure were revealed. For AK9M2 composition, with the increase in the vibration amplitude up to 1 mm, the grain refinement in
1.33 times is observed. Further, when the vibration amplitude increases from 0.5 to 2 mm, the grain size increases in 1.9 times. This is apparently explained by the fact that the maximal amount of solid phase begins to be formed closer to the solidus line.

With the vibration from 2 to 3 mm the grain refinement in 2 times takes place. With the amplitude more than 3 mm there is a slight increase in the grain size – in 1.36 times. For the composition of AK9M2, with the vibration amplitude from 0.5 to 2 mm the decrease in the eutectic phase content occurs in 1.2 times. With the increase in the amplitude from 2 to 3 mm, the increase of the eutectic phase formation is in 1.4 times. With the amplitude higher than 3 mm a slight increase in eutectic can be seen.

For the composition of AK12M2 the following conclusions can be drawn. With the amplitude of 2 mm the smallest grain size is observed. The increase of the amplitude from 2 to 3 mm or decrease from 2 to 1.2 mm there is an increase in the grain size in 1.4 times. With the increase in the amplitude from 0.45 mm to 2 mm a reduction in α-phase content is registered. With the increase in the amplitude higher than 2 mm there is a slight decrease in α-phase. The degree of crystals refinement depends on the type of vibration: vibrations with the amplitude oriented in the vertical or horizontal planes, and a vibration with circular amplitude in the horizontal plane. With the increase in the vibration amplitude from 0.5 mm to 2+2.15 mm there is an increase in the density in 1.2 times and in 1.15 times for AK12M2 and AK9M2 alloys respectively. Increase in the density of samples, cut from ingots, is due, primarily, with vigorous stirring of the molten metal layers, improvement of gas release during vibration, increase in the zone of more dense columnar crystals. A further increase in the vibration amplitude leads to a decrease in the density of the cast alloy (Figure 2), which can be explained as follows. At this mode of vibration the molten alloy mass partly (or completely) moving away from the solid phase surface, captures the gas particles into the intercrystalline space overlapping them above with the dropping from the liquid phase fine crystals. Samples density from alloy AK12M2, cut from the bottom part, with the increase in the vibration amplitude slightly rises. The increase in the amplitude up to 2 mm increases the samples density from 2.68 g/cm$^3$ to 2.71 g/cm$^3$. Further increase in the vibration amplitude slightly lowers the density of the samples.

Figure 2. Effect of vibration amplitude on the density of aluminum alloys.

During formation of crystalline structures the vibration energy is consumed not only for the destruction of the dendrites branches and creation in the system of additional crystallization nuclei, but
also for the enhancement of heat removal rate from the melt to the mold walls. This leads to the increase in the rate of crystallization and acceleration of the ingot solidification. The rate of crystallization for AK12M2 and AK9M2 alloys increases with the amplitude of 0.5 mm by 1.1 times and by 1.26 times, respectively, with the amplitude of 3 mm by 1.8 times and 2.25 times. The crystallization time for alloy AK12M2 decreases in 1.1 times at the vibration amplitude of 0.5 mm and in 1.43 times with the vibration amplitude of 3 mm.

Time for the crystallization of alloy AK9M2 decreases in 1.35 times with the vibration amplitude of 0.5 mm and in 2.34 times with the vibration amplitude of 3 mm. For alloys AK9M2 and AK12M2 the optimal amplitude is \(2 \pm 2.2\) mm, allowing the dense cast alloy with a fine grain structure to be obtained.

4. References

[1] Ivantsov A A and Krushenko G G 2003 Foundry Production 2 29–31
[2] Gladkov M I et al 2003 Poc. Higher Educ. Inst. Ferrous Metallurgy 9 56–60
[3] Usoltsev A A, Korotkikh I K and Kutsenko A I 2008 Proc. IV Int. Conf. on Technological Ensurance of Quality of Machines and Devices (Penza) pp 22–24
[4] Usoltsev A A et al 2009 Study of Foundry Processes: Textbook (Novokuznetsk: SibSIU) p 194
[5] Korotkikh I K et al 2005 Proc. V All-Russian Conf. on Automation Systems in Education, Science and Industry (Novokuznetsk: SibSIU) pp 424–426