Effect of vibration on structure and properties of cast billets

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Abstract. The influence of vibration on the processes of crystallization, structure formation and the properties of cast billets has been studied on iron-carbon and aluminium alloys. It is established that the imposition of vibration oscillations on solidified billets essentially reduces the area of columnar crystals, accordingly increases the zone of equiaxed crystals, grinds the macro- and microstructure of the billets, and enhances the properties of the metal. The dispersed crystal structure thus obtained over the entire section of the vibrating preforms virtually eliminates the anisotropy of the properties over their zones.

1. Introduction
The modern trends in the development of production technologies and metal casting are characterized by the stricter requirements that are imposed on the quality of metal products. At the same time, the system of technological operations, which is aimed at improving the quality of the cast billet, including the influence of the external factors on the solidifying metal, is gaining more and more importance. Of particular interest from the position of technological effectiveness and the effectiveness of the impact on the processes of crystallization and the formation of cast billets, in our point of view, is the vibratory treatment of solidifying metals. In this paper, let us present the results of studies of the effect of the vibration on the structure and properties of cast billets from iron-carbon and aluminium alloys.

2. Materials and methods
The objects of the research were cast billets with a diameter of 63 mm from steels 60 (steel with 0.6% mass C) and Kh18N9T (steel with 0.15% mass C, 18% mass Cr, 9% mass Ni, 1% mass Ti) and aluminium alloys AK5M2 (aluminium alloy with Fe -1.3%, Si -3%, Mn – 0.6%, Cu – 3%, Mg – 0.7%, Zn – 1%, Al - other) and AD31 (aluminium alloy with Fe <0.5%, Si -0.5%, Mg – 0.6%, Zn – 0.2%, Al - other) cast in a laboratory installation of semicontinuous casting (Figure 1) which consists of a filling funnel (1), a copper water cooled crystallizer (2), a working platform (3), racks (4), shank (6), traverses with pulling mechanism (7), springs 8 and vibrator (9). Impulses from the vibrator (9) through the shank (6) were transmitted directly to the workpiece (5). The vibration parameters were adjusted within the following limits: frequency 0 ... 100 Hz, amplitude 0 ... 2 mm.

The steel was smelted in an induction furnace, LPS-37, and the aluminum alloys - in an electric furnace SAT-0.15. The casting temperature of the metal was 50°C above the liquidus temperature for the corresponding alloys. For the metallographic and differential thermal analyses, as well as for determining the density and mechanical properties of the metal from different zones of the blanks, the
templates and samples were cut out. The etching of the samples to reveal the macro- and microstructure was carried out with the standard reagents. The discontinuous samples were tested in accordance with GOST 1497-84, and the shock samples were tested in accordance with GOST 9454-78.

![Figure 1. Laboratory installation for semi-continuous casting of billets](image)

3. Analysis of the results
To evaluate the results that were obtained, let us carry out a theoretical analysis of the process of the effect of vibration on the crystallization and structure formation of alloys. When vibration is applied to a liquid metal, the mass forces change instantly and large pressure gradients appear on the stationary branches of the dendrites. The pressure gradients, arising at the boundary of the phases, destroy the primary and secondary branches of the dendrites. The magnitude of this pressure depends on the amplitude $A$ and the oscillation frequency $\omega$, which changes the forces of dynamic action on the solid-liquid zone of the solidifying alloy and is determined from the dependence [1]:

$$P = \pm \rho A \omega^2 H,$$

(1)

where $\rho$ is the density of the medium; $H$ is the distance from the melt’s open surface.

The destruction of the branches of the dendrites is carried out under the action of bending stresses, which appeared under the pressure of an elastic wave. The maximum bending stress $\sigma_i$ due to the dendrite resistance to the shock wave of a viscous liquid is determined from the expression [1]:

$$\sigma_i = \frac{8\pi^2 d^2 L^2 \rho \omega^2 \cdot A}{b^3},$$

(2)

where $d$ is a diameter of the dendrite branch; $L$ is a length of the dendrite; $b$ is a diameter of the neck of the dendrite.

Obviously, the destruction of dendrites occurs when the following condition is met:
where $\sigma_i$ is the ultimate strength of the dendrite at the crystallization temperature.

As a result of the conducted studies, it was found that vibration has a significant effect on the processes of crystallization and structure formation of the alloys used as evidenced by the results of the metallographic analysis of the samples given in table 1 and in figures 2 and 3 [2-6].

\[ \sigma_i \geq \sigma_v, \]  

\textbf{Table 1. Width of structural zones of billets, mm}

| Metal grade  | Conditions for solidification | Cortical zone | Zone of columnar crystals | Zone of equiaxed crystals |
|--------------|-------------------------------|---------------|----------------------------|---------------------------|
| Steel 60     | free                          | 3             | 20                         | 9                         |
|              | with vibration                | 2             | 10                         | 20                        |
| Steel Kh18N9T| free                          | 3             | 29                         | -                         |
|              | with vibration                | 2             | 15                         | 15                        |
| AK5M2        | free                          | 3             | 15-20                      | 9-15                      |
|              | with vibration                | 2             | 8-14                       | 16-22                     |
| AD31         | free                          | 3             | 20-28                      | 5.0-7.5                   |
|              | with vibration                | 2             | 10-13                      | 20-23                     |

It can be seen that the imposition of vibration leads to an almost complete elimination of surface and subcortical defects (see Fig. 3a, b). When vibration is applied to the solidifying melt, the growing branches of the dendrites break off at the solidification front and in the melt, which greatly increases the number of crystallization centers and results in the grinding of the macrostructure of the experimental preforms. Vibrational mixing diffuses the centers of crystallization throughout the volume of the preform, thereby ensuring the production of a dispersed dendritic structure (Table 2).

\textbf{Figure 2.} Macro-structures of longitudinal templates of billets from stainless steel Kh18N9T a – without vibration; b – with vibration
Figure 3. Macro-structures of longitudinal templates of billets from aluminium alloy AD31 a – without vibration; b – with vibration

Table 2. Parameters of dendritic structure of billets

| Metal grade | Conditions for solidification | Dimensions of columnar dendrites | Dimensions of equiaxed dendrites |
|-------------|-----------------------------|----------------------------------|----------------------------------|
|             |                             | length, mm                       | width, mm                       | length, mm                       | width, mm |
| Steel 60    | free                        | 4.98                             | 0.45                            | 2.34                             | 2.15      |
|             | with vibration              | 2.90                             | 0.18                            | 1.48                             | 1.36      |
| Steel       | free                        | 20-25                            | 0.3-0.5                         | 2.5-3.0                          | 0.5-0.8   |
| Kh18N9T     | with vibration              | 15-18                            | 0.2-0.3                         | 0.7-1.0                          | 0.25-0.30 |
| AK5M2       | free                        | 1.0-1.5                          | 0.1-0.2                         | 1-3                              | 1-2       |
|             | with vibration              | 0.05-0.1                         | 0.01-0.02                       | 0.05-0.1                         | 0.05-0.1  |
| AD31        | free                        | 1.5-2.0                          | 0.1-0.3                         | 2-5                              | 2-3       |
|             | with vibration              | 0.05-0.1                         | 0.01-0.03                       | 0.1-0.2                          | 0.1-0.2   |

The calculation conducted, for example, for billets from steel 60 verifies the correctness of the specified vibration parameters: A = 2 mm; Ω = 100 Hz. It has shown their compliance with the critical conditions under which the dendrite collapses and the dispersed crystal structure is formed. Investigations by various authors [7, 8] have established that at a temperature above the solidus temperature, both the ultimate strength $\sigma_c$ (up to $5 \div 10$ kg/cm$^2$) and the plasticity and deformation capacity of carbon steels drop sharply. Thus, at a temperature of 1460 °C for article 3 the tensile strength $\sigma_c$ has a value of 10 kg/cm$^2$, for the article 45 – 7 kg/cm$^2$, and for article 80 – 3.5 kg/cm$^2$ [7]. In the calculations for article. 60 in the range of the crystallization interval, the value of the tensile strength $\sigma_c$ is taken as 5.5 kg/cm$^2$. Parameters of the dendritic structure of the billet from steel 60 under vibration treatment have the following values (see Table 2): L = 2.9 mm; d = b = 0.18 mm. The bending stress ($\sigma_i$), which arises in the case of dendrites with the experimental values of the vibration parameters, is determined from the dependence (2), which is 6.5 kg/cm$^2$ and corresponds to the condition $\sigma_i > \sigma_c$, due to which their destruction occurs. It follows from the calculations that the main reason for the destruction of dendrites before the crystallization of billets from steel 60 is the action of bending forces that arise under the action of the pressure of an elastic wave.
The changes in the dendritic structure lead to significant changes in the microstructure of the alloys, the parameters of nonmetallic inclusions, and the nature of their distribution. For example, the steel structure of the 60 control metal is ferrite-pearlitic. The pre-eutectoid ferrite in the form of interlayers borders the boundaries of austenite grains in the form of a grid, and the structure of the body of the grains is perlite with a large "step" (the distance between ferritic and cementite). The size of the austenitic grain according to GOST 5639-82 corresponds to point 1, and in some areas even higher. The structure of the experimental metal is bainitic, and pre-eutectic ferrite is practically absent. The grain size corresponds to point No. 3 and No. 4 [9]. The size of the austenitic grain in the experimental steel of the Kh18N9T steel was 0.07-0.1 mm against 0.5 mm in the control ingot [10].

Metallographic studies have established that in the samples of control billets made of carbon steel, nonmetallic inclusions (sulfides) are in most cases localized in the veins of the pre-eutectoid ferrite, which are located along the boundaries of large austenite grains, and their size is 5-8 µm. In the samples of the experimental blanks, the sulphides are noticeably smaller (1.2-1.4 µm), while they acquire a rounded shape and are arranged arbitrarily with respect to the grain boundaries. Dimensions of silicate inclusions decreased from 24-30 microns to 6-7 microns. The size of the oxide inclusions in the stainless steel preform was 1-3 µm against 4-8 µm in the control one, and the dimensions of the nitride inclusions decreased from 16-18 µm to 4-8 µm. The effectiveness of the effect of vibration on nonmetallic inclusions is achieved through intensive mixing of the melt and its accelerated crystallization.

The structure of the peripheral zones of all blanks from aluminum alloys is crystals of an \(\alpha\)-solid solution based on aluminum and eutectic \(\alpha + Al\), which is crystallized in interdendritic spaces. As they move toward the center of the blanks, double \(\alpha-Al+FeAl_3\) and complex AISiFe eutectics appear in the structure. In control billets, the crystallization character leads to an increase in the central parts of the amount of the double eutectic, as well as the number of nonmetallic inclusions and fine pores. In blanks, hardened by vibration, a more even distribution of the eutectic component and nonmetallic inclusions was noted. As the eutectic colony \(\alpha + Fe\) grows, the impurities escape to its periphery, where conditions for the crystallization of the triple eutectic are created. Triple eutectics contain iron form skeletal crystals in both control and experimental billets [11].

All blanks contain a small amount of non-metallic inclusions, which in the most "contaminated" places correspond to 1 point according to GOST 1778-70. Stringent nonmetallic inclusions are absent.

The above-mentioned changes in the macro-microstructure of blanks from various alloys under the influence of vibration caused changes in the qualitative characteristics of the metal, reducing their anisotropy in the zones. The results of hydrostatic weighing of samples cut from various zones of blanks showed that vibration significantly increases the density of metal at various levels in both peripheral and central zones (Table 3).

| Metal grade | Conditions for solidification | Level and billet zones |  
|-------------|-------------------------------|------------------------|
|             |                               | top | center | bottom |   
|             |                               | edge |        | edge | center |
| Steel 60    | free                          | 7588 | 7582 | 7684 | 7685 |
|             | with vibration                | 7705 | 7652 | 7785 | 7747 |
| AD31        | free                          | 2656 | 2630 | 2685 | 2655 |
|             | with vibration                | 2700 | 2695 | 2707 | 2702 |

The above-mentioned factors of change in the process of crystallization and structure formation of cast billets under the influence of vibration caused a noticeable change in the mechanical properties of the metal in the preforms (Table 4).
Table 4. Mechanical properties of metal in billets

| Zones by section                  | σv, MPa | σT, MPa | δ, % | Ψ, % | KCU, J/cm² |
|-----------------------------------|---------|---------|------|------|------------|
| Steel 60 (cast state)             |         |         |      |      |            |
| Zone of columnar crystals         | 825     | 635     | 7,4  | 6,1  | 32         |
|                                   | 775     | 605     | 6,4  | 3,95 | 31         |
| Zone of equiaxed crystals         | 640     | 575     | 9,6  | 6,0  | 35         |
|                                   | 625     | 550     | 6,8  | 3,8  | 34         |
| Steel Kh18N9T (cast state)        |         |         |      |      |            |
| Zone of columnar crystals         | 570     | 310     | 45,0 | 45,0 |            |
|                                   | 560     | 315     | 35,5 | 32,5 |            |
| Zone of equiaxed crystals         | 615     | 310     | 47,0 | 46,0 |            |
|                                   | 545     | 305     | 41,3 | 40,3 |            |
| Alloy AD31                        |         |         |      |      |            |
| Zone of columnar crystals         | 86      | 79      | 28,5 | 35   |            |
|                                   | 67      | 61      | 25,5 | 32   |            |
| Zone of equiaxed crystals         | 99      | 78      | 30   | 36   |            |
|                                   | 62      | 60      | 27   | 33   |            |

Note: numerator – with vibration; denominator – without vibration

From a comparative analysis of the data of Table 4, it is clear that the mechanical properties were directly dependent on the crystal structures of the preforms. Strength indices for vibration treatment for steels increase by 8-10%, and plastic properties – by 14-50%, depending on the grade of alloy and the structural area of the workpiece. For aluminum alloy AD31, on the contrary, the ductility indexes increase insignificantly (9-11%), and the strength indices are significant (28-60%).

4. Conclusion
Thus, the vibration treatment of solidified billets from various alloys causes a regular grinding of the macro- and microstructure, provides grinding and uniform distribution of non-metallic inclusions, increases the density and mechanical properties of the metal in the cast state.

5. Acknowledgments
The results of the work have been obtained within the framework of the State task of the Ministry of Education and Science of the Russian Federation №11.3613.2017/PCh

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