The effect of directional flow of metallic melt on the mechanical properties of cast metal

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Abstract. The methods of mechanical treatment of ingots giving rise to formation of internal texture of metal are widely used. On the other hand, it is well known that the flow of metallic melt can result in dark streak pattern, clearly observed in an ingot. In the present work the influence of directional flow of metallic melt on physical properties of the solid metal was studied. The objects for investigation were copper, aluminum and gray cast iron. The metal solidified after the directional flow was found to have improved (7 to 23 %) hardness and better resistance to attrition. The hardness of the check samples, crystallized without directional flow, has data scattering less than 2% and their resistance to attrition - less than 5%

1. Introduction
There are a number of well known methods to improve a quality of metal by different physical or chemical treatments of the metallic melt. The improvement is reached due to formation of more homogeneous and fine-grained structure of a metal. According to paper [1] the “directional flow” treatment of molten metal results in dark streak pattern formation which may be clearly observed in crystallized metal.

To gain deeper insight into reasons of the streakiness formation in metallic crystals, the effect of “directional flow” treatment on overheated melt was studied in work [1]. The treatment implies that the metal overheated by 70 - 100 K over the melting point was sucked into quartz or alundum tube 30 - 40 cm length and 0.3 - 0.6 cm diameter with subsequent crystallization by cooling in air. The experimental conditions excluded the dominant influence of surface forces as well as orienting effect of substrate. It was shown by scanning electron microscopy, [1] that after such treatment the metal (aluminum, copper, nickel) consist of separate grains having streaky fragmentation, directed both radially and tangentially to the center. It is important that if a metal was sucked into tube and than was solidified in a crucible 5 - 7 times, the characteristics of the striation did not change. For comparison, the author of [1] has established that untreated metal made as a rod and then melted inside the tube, does not have any striation after crystallization.

The results of [1] testify that directional flow can lead to formation of striate structures clearly observed in crystallized ingot. The possible reasons are either direct partial inheritance of a liquid metal structure or relaxation process in the solid state.

The results of work [2] provide a good example of the influence of a liquid pre-history on the properties of formed crystals. In this work, the phenomenon of gypsum crystals twinning was studied. The experiments were carried out in several steps. At the first step, mixing of the reacting components was carried out in a glass using teflon stirrer. One of the next steps was pouring of the ready reagent solution into crystallizer through the siphon tube. Previously, it was found that crystal nucleation
occurs both during the mixing (less than 5%) and in cuvette during the first 1 - 3 minutes after pouring (more than 95%).

Authors of [2] revealed certain regularity. It was found that mechanical treatment of solution by pouring through the siphon before the crystallization, effects on the crystal pattern forming in the solution. The pouring of the reagent solution through the siphon results in large twinning of crystals.

In crystallization processes in the silicate glasses, the distinctive spherulitic aggregates consisted of great number of divergent needle-shaped crystals are frequently formed. To measure the velocity of these processes, Tamman used capillary tubes. He filled them with silicate melt [3]. It was found that the crystals of fibrous type grow in capillaries, whereas in parallel experiments in the “free space” the spherulites were formed. Tamman concluded that the reason of fibrous crystals formation is the restricted space were the melt crystallization is carried out.

Taking into account the foregoing data [1-3], in the present work the effect of the directional flow of molten metal on the physical properties of crystallized ingot (in particular, on its stiffness and abradability) was studied.

As is well known, the grains of a metal in solid state are being deformed and stretched under mechanical treatment. It leads to formation of texture and usually improves the running abilities of a metal. The main question under investigation is: is it possible to change the shape and size of grains in certain directions, to get the texture in solid metal, to change physical properties of a metal by treatment of the metal in molten state, when energy expenses on the deformation are negligible?

In the present work, the influence of directional flow of metallic melt on physical properties of the solid metal, in particular, stiffness and abradability, was studied. The objects for investigation were copper, aluminum and gray cast iron.

2. Experimental

The metals were melted in alundum crucibles in a furnace with graphite heater. Overheating above meting point does not exceed 100 K. The directional flow of the metals was organized by passing of the melts through the capillary tubes. To do that, in a bottom of a crucible the bunch of 10 alundum tubes (1.4 mm inner diameter and 90 mm length each) were attached using refractory cement. After melting, the metal streams down through the tubes into another, less heated, crucible and crystallizes. The solidified metal was heated up again to melting and cooled down with the rate 0.2 - 0.3 K/s to avoid casting pipes formation. To prepare the reference samples the same metals were melted and solidified by the same temperature regime, but without of directional flow through the capillaries.

Due to the existence of oxide film, the molten aluminum does not flow out of a crucible through the tubes of small diameter (1.4 mm). Therefore, the directional flow of molten aluminum was carried out through the quartz tubes 2.9 mm inner diameter.

The obtained cylindrical ingots were divided into equal parts. During the cutting, the cutting aria was washed with special liquid for smear and cooling to prevent the changes of the physical properties. The plain surfaces of the samples were manually polished up to high luster. The samples of aluminum and cast iron were 30 mm diameter and 10 mm of height, copper - 20 and 7 mm respectively. Totally there were 8 samples for each metal, four of which were reference ones (without treatment by directional flow).

The chemical composition of these metals was controlled with spectral chemical analysis. It was found that the tube material does not contaminate metals during contact time.

The abradability of metals was studied by comparative method. The losses of samples mass were measured after friction cycle under identical conditions. The experiments were carried out using apparatus for study of friction properties of the rocks and minerals. The samples were weighed on an analytical balance with precision of $\pm 2 \times 10^{-4}$ g. Calculated relative error of the abradability determinations is 5%.

The metal samples after treatment with the directional flow was found to have advanced resistance against attrition. In our experimental sets, the reduction of the mass lost of the treated samples
compared with the reference samples was 15-20% for cast iron, 11-15% for copper and 10-11% for aluminum.

The metals hardness was determined by Brinell hardness test using TIII-2M apparatus. The diameter of the indenter ball was 10 mm; indentation time was 10 s for cast iron, 30 s for copper and 60 s for aluminum. The sample hardness was measured on each of two horizontal surfaces. The stamp diameter was measured by microscope with the scale-division value 0.05 mm. Brinell hardness numbers (HB) were calculated according to equation:

\[ HB = \frac{2P}{\pi \cdot D \left( D - \sqrt{D^2 - d^2} \right)} \]

were \( d \) is the stamp diameter, \( P \) - weight, and \( D \) - ball diameter.

The results are listed in table 1. The hardness values of copper and aluminum were computed as the mean of two independent experimental sets. The sets were carried out in the different time to study the reproducibility of the revealed phenomenon. The hardness data scattering of the reference samples in series and between series does not exceeds 2%, whereas the same for samples after directional flow is 4%. The accuracy of the measuring instrument was controlled before each experimental set by standard hardness sample, applied to the device. The relative uncertainty of the hardness determination was calculated as 2%.

### Table 1. The effect of directional floe of molten metal on the ingot hardness

| Metal       | The hardness number (HB)\(^a\) | The metal sample after directional flow in a liquid state |
|-------------|---------------------------------|----------------------------------------------------------|
| Aluminum    | 20.0 ± 0.1                      | 21.7 ± 0.1                                               |
| Copper      | 56.2 ± 1.1                      | 63.2 ± 1.4                                               |
| Cast iron   | 162 ± 3.2                       | 189 ± 5.0                                                |

\(^a\)Confidence interval of the hardness number mean values was computed at confidence probability equals 0.95.

Conclusion
The results of our experiments give every evidences of effect of the directional flow of molten metal on the hardness and the resistance to attrition of crystallized ingot. The metal, solidified after the directional flow, was found to have improved (by 7 to 23%) hardness and better resistance to attrition (by 10 - 20%). The improvement of the mechanical properties of metals is caused rather by texture, formed during the directional flow, but not by variations of the chemical composition.

References
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