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STUDY OF THE POSSIBILITY OF CONTROLLING THE FORMATION OF CRYSTAL STRUCTURE OF METAL ALLOYS

Introduction. *The modern trend in the development of engineering is characterized by ever-increasing demands on the quality of the metal products used for this. It is impossible to improve the quality of metal products without improving technologies for the smelting and casting of metal alloys.*

Problem Statement. *It is known that metal products made from the cast billets with a dispersed crystalline structural structure have a minimum level of licensing and favorable results of non-metallic inclusions, and have the highest level of mechanical properties. To obtain a cast metal with such a structure, it is necessary to ensure the maximum crystallization rate and the amount of supercooling at the phase boundary, which, when real billets are formed, progressively decrease as the thickness of the hardened metal crust increases (5—10 times).*

Purpose. *Development of scientifically based technological methods for controlling the formation of a cast structure of metal billets by means of thermo-force external influences on liquid and hardened metal.*

Materials and Methods. *An alloy of camphene with tricycylene, which, like metals, crystallizes in the temperature range (45—42 °C) with the formation of a dendritic structure, and also has the following original properties. Aluminum of technical purity A5, which crystallizes with the formation of a very wide transcrystallization zone, was used as a metal system in the work. And it is convenient to evaluate the relative effectiveness of the impact of various methods of external influences on the formation of the crystalline structure of metals by their influence on the width and dispersion of the transcrystallization zone.*

Results. *Experimental studies have confirmed the ability to control the formation of the structure of cast metals using various methods of external thermo-force effects on liquid and hardened melt.*

Conclusions. *The results obtained open up the prospect of developing new metallurgical technologies for the effective management of the cast metal structure at the first stage of production of billets.*

Keywords: melt, subcooling, overheating, cooling intensity, vibration, crystallization, billet, and structure.

The quality of the final metal products is largely determined by crystal structure of cast billets at the first stage of their production. The main task is to obtain billets with a dispersed crystal structure and a high physical and chemical homogeneity. To obtain a cast

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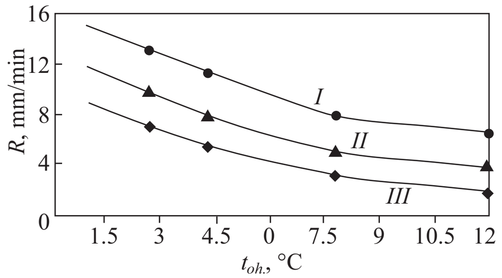

Fig. 1. Dependence of model alloy crystallization rate on overheat temperature and hardening melt cooling rate: *I* — W_{cool}= 35 °C/min; *II* — 16 °C/min; *III* — 6 °C/min

metal with these properties, it is necessary to ensure the maximum crystallization rate and the degree of supercooling at the phase boundary, which depends on several factors and, while shaping real workpieces, progressively decreases as the thickness of solidified skin increases. These processes can be actively controlled by external influences on liquid and crystallized metal [1—4].

During the melt-crystal phase transition, melts can be in a non-equilibrium state on both sides of the process because of a slow variation of their microscopic characteristics. The process of melt transition into a microscopically homogeneous state can be accelerated by external influences on it [5—8], and the establishment of regularities of these influences on the formation of the structure of cast billets is an urgent task to be solved. The properties of crystalline structure of cast metal are determined by the two parameters: crystallization rate (R) and degree of supercooling at the phase boundary (Δt_k). These parameters depend on several factors: metal fineness, overheat temperature, melt cooling rate, etc. and are interrelated as [3]:

$$R = k \cdot \Delta t_k, \tag{1}$$

where k is solidification coefficient.

The dispersion of the dendritic structure of cast metal also depends on the rate of melt crystallization [6]:

$$\lambda_1^4 = \frac{A \cdot C}{G \cdot R}, \tag{2}$$

where λ_1 is the distance between the first order axes; A is experimental coefficient; C is the initial concentration of segregating impurities; G is the temperature gradient in front of the solid phase boundary.

Also, the length of fringe crystals (L) is determined by the above mentioned parameters (R, G) [8]:

$$L = \frac{t_{л} - t_{с}}{G} - \frac{D}{R}, \tag{3}$$

where $t_{л}$, $t_{с}$ is liquidus and solidus temperatures of the alloy; D is the diffusion coefficient of impurities..

This elementary analysis has shown that adjusting these parameters, one can control the formation of the crystalline structure of cast metal. The results of studying the influence of overheat temperature, cooling rate, and vibration on the formation of the structure of model (camphene) and metal (aluminum alloy A5) alloys obtained in this research have confirmed this.

The influence of overheat temperature and heat dissipation intensity on the solidification of the model alloy can be estimated by change in its crystallization rate (Fig. 1). One can see that as melt overheat increases from 3 to 12 °C (that corresponds to carbon steel overheat by 100—300 °C), the crystallization rate decreases more than three times, depending on the heat dissipation intensity. Here, one can see that the negative effect of excessive overheat on the crystallization rate can be partially compensated by regulating the intensity of heat dissipation from a solidifying melt (Fig. 1, curves *I*, *II*, and *III*). Consequently, according to dependence (2), it is possible to influence the dispersion of the dendritic structure, which has been confirmed by the data of Fig. 2.

The influence of the melt overheat temperature and the cooling rate manifests itself not only in increasing or decreasing the linear rate of melt crystallization, but also in changing the rate of nucleation and morphology of seeds (Fig. 2). In this case, the most favorable dispersion of the crystalline structure of the model alloy is reported in the case of minimum overheat of the melt (Fig. 1, *a*—*c*). These results correlate well with the foundry practice, in which the steels are cast

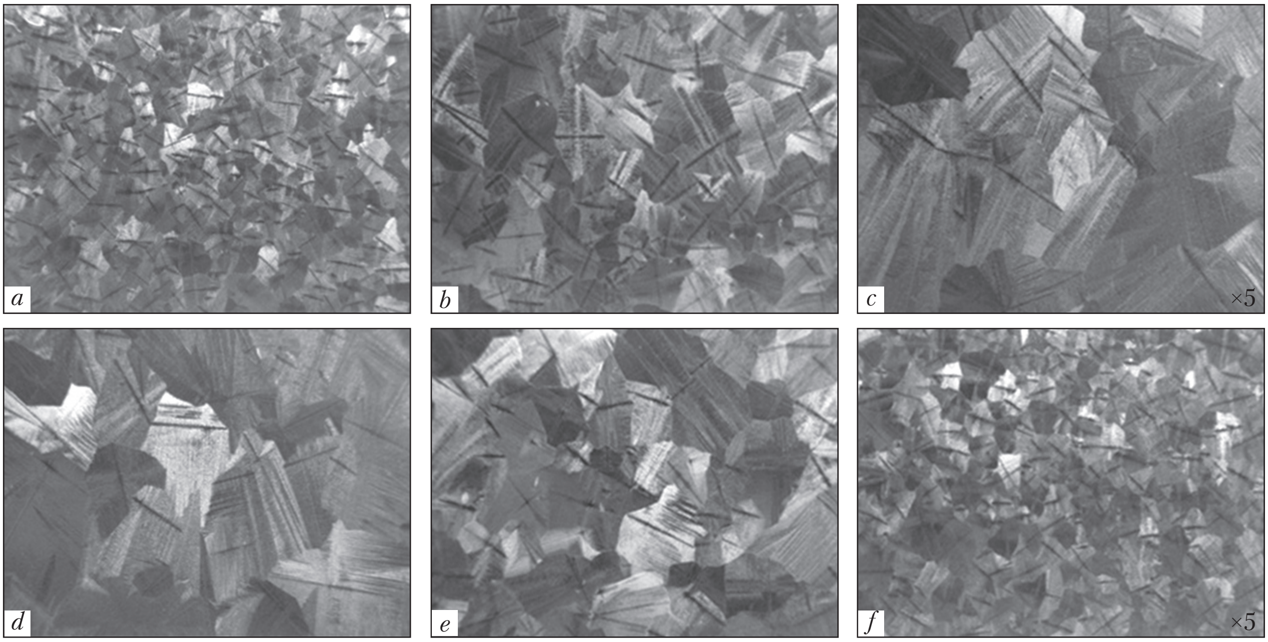

Fig. 2. Camphene macrostructure depending on overheat temperature and hardening melt cooling rate (×5): *a, b, c* — W_{cool}= = 6 °C/min; $\Delta t_{oh.}$ = 2, 4, 8 °C respectively; *d, e, f* — $\Delta t_{oh.}$ = 8 °C; W_{cool} = 6, 16, 35 °C/min, respectively

within the range of at most 30—50 °C above the liquidus temperature. At a higher overheat temperature, the crystallite size increases and the inter-crystallite boundaries are enriched with nonmetallic inclusions [9].

Sometimes, in practice, to bring a molten metal into equilibrium state, it is necessary to create a high overheat temperature that is the main reason for the formation of coarse-grained crystal structure [3, 10]. In such cases, the negative effect of overheat on the dispersion of the dendritic structure of workpieces can be practically leveled by regulating the rate of heat dissipation (Fig. 2, *d—e*).

At a significant overheat, it is not always possible to provide a high rate of crystallization of the melt to obtain a crystalline structure with a high dispersion. In such cases, external physical influence on hardening alloys, such as vibration, can be used as a means of controlling the formation of the structure and properties of cast billets. A significant influence of vibration on the processes of crystallization, formation of the structure and properties of metal alloys in the case of normal overheat of their melts (up to 50 °C) has been proved in [3, 4, 11, 12].

The data obtained as a result of the research have shown that vibration radically changes the macro- and microstructure of the model alloy even in extreme conditions, i.e. at a significant overheat of melts (Δt_{oh}= 12 °C) and low cooling rates (W_{cool}= 6 °C/min). These conditions are equivalent to overheat of medium carbon steels by 300 ° C and their hardening in a sand mold. One can see that in the reference experiment, the macrostructure of billet consists of large fringe and equiaxed crystals of irregular shape (Fig. 3, *a*). Under the action of vibration, a high- dispersion granular structure is formed almost along the entire cross section, except for a small zone of fine fringe crystals on the heat-dissipating faces of the mold (Fig. 3, *b*).

Under the influence of vibration, the dendritic structure of the model alloy changes as well. In the case of normal hardening of alloy, the dendritic structure has clear boundaries between indi-

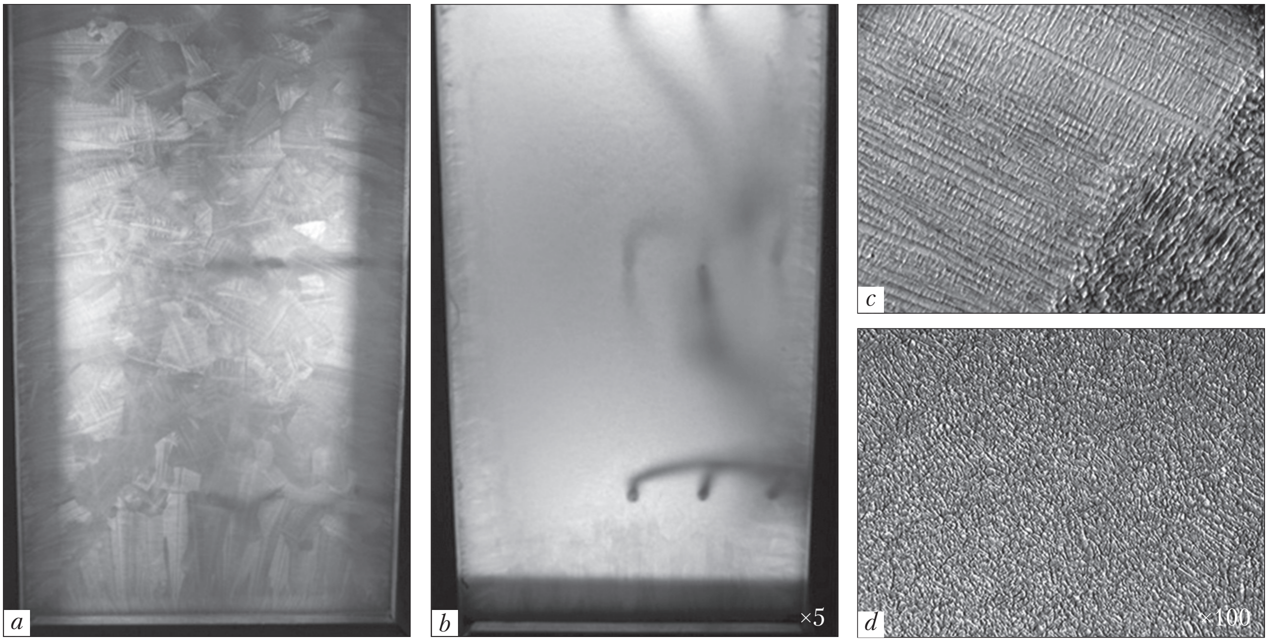

Fig. 3. Camphene macro- and microstructure in the case of melt overheat $\Delta t_{toh.} = 12$ °C and cooling rate $W_{cool.} = 6$ °C/min: *a, c* — without vibration (×0.5); *b, d* — under the action of vibration (×100)

vidual crystallites (Fig. 3, *c*). The microstructure of alloy that is hardened under the influence of vibration is characterized by the absence of dendrites because of their destruction, and the fragments of high-dispersion dendrites are evenly distributed over the section (Fig. 3, *d*).

The experiments with aluminum alloy A5 ($t_1 = 657$ °C) to study the effect of overheat temperature, heat dissipation, and vibration on the formation of the structure of billets made of it have confirmed the adequacy of the results of physical modeling. The chemical composition of the studied alloy is given in Table below.

The rate of heat dissipation from molten metal overheated to different temperatures ($t_{oh.} = 680$, 770 and 860 °C) widely varies in the experiments (Fig. 4), where the temperature is regulated by pouring the metal into molds with different thermal conductivity and heat capacity (vologran (refractory material) and steel molds with a wall thickness of δ = 1, 10 i 20 mm). For processing the hardening billets by elastic oscillations, the molds are fixed on a plate of vibrotable, which is oscillating with the parameters: A = 0.2 mm and ν = 60 Hz.

Chemical Composition of Aluminum Alloy A5

Components and their shares, %								
Al	Fe	Si	Mn	Ti	Cu	Mg	Zn	Ni
At least, 99.6	0.22	0.07	0.02	0.011	0.03	0.06	0.025	0.05

Fig. 4 shows that, depending on the material of the molds and the thickness of their walls, the cooling rate of hardening melts varies widely (from 0.3 °C/s for the vologran mold to 5 °C/s for the steel mold with a wall thickness of 20 mm). The total hardening time for the billets varies correspondingly to the cooling rates and, in the extreme cases, decreases about 6 times.

In the case of vibration treatment of hardening metal, there is a more intensive heat dissipation from it: on average, for all cases, the cooling rate of hardening melts increases 1.6 times, and the total duration of hardening decreases more than 1.5 times (Fig. 4, *b*).

The comparison has shown that the macrostructure of the billets made of the studied alumi-

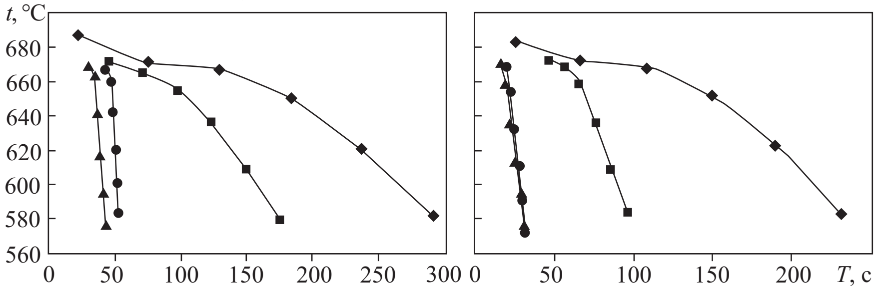

Fig. 4. Temperature curves of hardening aluminum alloy A5 cooling: ▲ – steel mold with δ = 20 mm; ● – steel mold with δ = 10 mm; ■ – steel mold with δ = 1 mm; ♦ – vologran mold; *a* – reference sample (without vibration); *b* – under the action of vibration: *A* = 0.2 mm; ν = 60 Hz

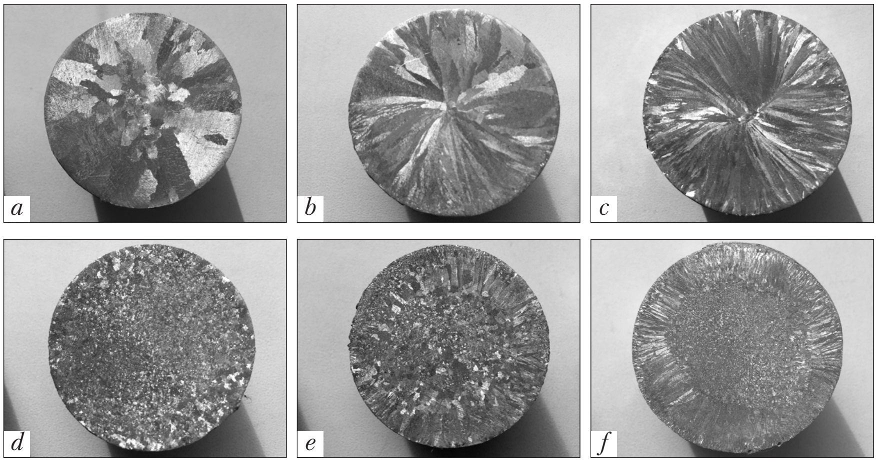

Fig. 5. Macrostructure of test billets made of aluminum alloy A5: *a, d* — steel mold with δ = 1 mm; *b, e* — steel mold with δ = 10 mm; *c, f* — steel mold with δ = 20 mm; *a, b, c* — reference sample (without vibration); *d, e, f* — пunder the action of vibration: *A* = 0.2 mm; ν = = 60 Hz

num alloy A5 with the positively correlates with that of the model alloy (Fig. 5). The structure of all reference billets has zones of fringe crystals, the dispersion of which is determined by the rate of heat dissipation (Fig. 5, *a*—*c*).

In the reference experiments, the macrostructure of billets is formed by fringe crystals of different dispersion; their size ranges from 5 to 15 mm and the size factor varies from 3 to 40 (Fig. 5, *a*—*c*). The crystallite boundaries are characterized by a large length and have a coarse structure.

Under the influence of vibration there is a completely different nature of the formation of billet structures. A significant part of macro sections of billets is occupied by a high-dispersion uniform granular structure (Fig. 5, *d*—*e*). Therefore, a slight enlargement (5 times) does not enable detecting the grain boundaries by optical microscopy. They can be barely visualized at 100 times magnification. Because of poor detection of boundaries, even with such enlargement, it is difficult to provide statistically significant data on grain sizes. Considering the detected grains, it can be stated that their size does not exceed 100—200 μm, and the size factor is 1—1.3. That is, the macrostructure is close to equilibrium one. The width of the grain boundaries is, at least, 5 times lower than the grain boundaries in the reference sample, without vibration. It should be noted that at a high rate of heat dissipation (solidification of billets in metal molds with a wall thickness δ = 10 and 20 mm), in the cross section of billets there remains a small area of dispersed fringe crystals (Fig. 5, *d* and *e*, similar to physical modeling (Fig. 3, *b*)).

The effect of vibration manifests itself in the microstructure of the aluminum alloy (Fig. 6, *a*—*c*). The structure of all billets in the surface zone is practically the same and consists of dispersed crystals of solid aluminum solution (Alα) and eutectic Alα + Si with a size of 50—150 μm and a size factor of, at least, 5—10. Towards the center, in

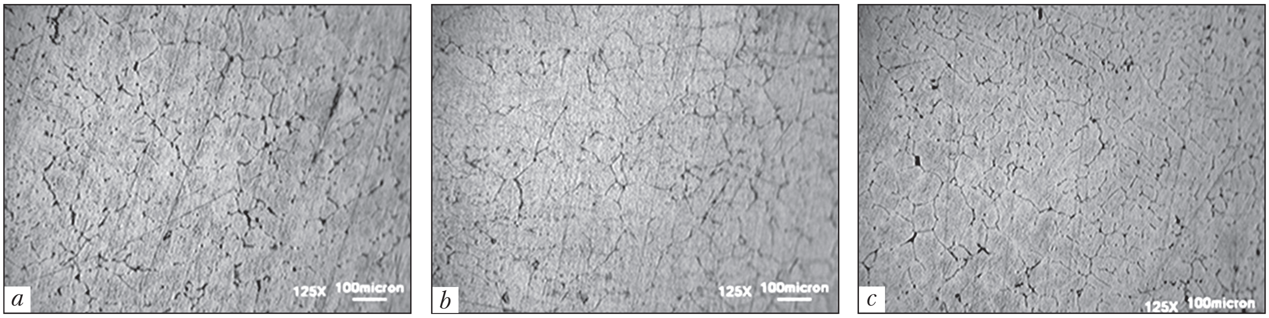

Fig. 6. Microstructure of axle zones of billets made of aluminum alloy A5: *a, b* — reference; *c* — option with vibration; *a, c* — steel mold with δ = 1 mm; *b* — steel mold with δ = 20 mm

the case of reference billets (obtained without vibration), the grain size increases and more complex eutectics Mg2Si, Mg5Si8 appear in the form of a dark grid at the grain boundary Al (Fig. 6, *a, b*).

After the action of vibration, the size of crystals decreases 3—5 times, on average, and their size factor decreases in the same proportion. After vibration, dispersed crystallites remain in the central zones as well, however there is reported a certain decrease in the volume fraction of eutectic that is more uniformly distributed (Fig. 6, *c*), which means the destruction of interatomic bonds in clusters such as MgxSiu. As a result, a supersaturated solid solution of aluminum with a higher microhardness is formed (microhardness increases by 30% as compared with the reference samples).

Hence, the obtained results open a prospect for developing new metallurgical technologies for effective control of the cast metal structure at the first stage of billets production. In addition, the considered methods for controlling the formation of the structure of cast billets in some cases can be an alternative to environment unfriendly operations related to chemical modification of metals and an effective factor in resource and energy saving

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ІННОВАЦІЙНІ ШЛЯХИ КЕРУВАННЯ ПРОЦЕСОМ ФОРМУВАННЯ КРИСТАЛІЧНОЇ БУДОВИ МЕТАЛЕВИХ СПЛАВІВ

Вступ. Сучасна тенденція розвитку машинобудування характеризується зростаючими вимогами до якості використовуваної металопродукції. Підвищити якість останньої неможливо без вдосконалення технологій з плавлення та лиття металевих сплавів..

Проблематика. Відомо, що металопродукція, виготовлена з литих заготовок із дисперсною кристалічною структурою, мінімальною ліквацією й сприятливим розташуванням неметалічних включень, має найвищий рівень механічних властивостей. Для отримання литого металу з такою структурою необхідно забезпечити максимальну швидкість кристалізації та величину переохолодження на межі фаз, які при формуванні реальних заготовок зі збільшенням товщини затверділої кірки металу прогресивно зменшуються (у 5—10 разів).

Мета. Розробка науково-обґрунтованих технологічних способів управління формуванням литої структури металевих заготовок шляхом термосилових зовнішніх впливів на рідкий та затвердіваю¬чий метал.

Матеріали та методи. Модельною речовиною слугував сплав камфена з трицикленом, який, подібно до металів, кристалізується в інтервалі температур 45—42 °С з утворенням дендритної структури, а також володіє низкою оригінальних властивостей. Як металеву систему у роботі використано алюміній технічної чистоти А5, який кристалізується з утворенням дуже широкої зони транскристалізації. Оцінювання відносної ефективності впливу різних методів зовнішніх впливів на формування кристалічної будови металів виконано за їхнім впливом на ширину й дисперсність зони транскристалізації.

Результати. Експериментально підтверджено можливість керування процесом формування структури литих металів, використовуючи різні прийоми зовнішніх термосилових впливів на рідкий та затвердіваючий розплав.

Висновки. Отримані результати є перспективними для розробки нових металургійних технологій ефективного управління структурою литого металу на першому етапі виробництва заготовок.

Ключові слова: заготовка, розплав, переохолодження, перегрів, охолодження, вібрація, кристалізація, структура.