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Research of Casting and Solidification of Steel Ingots by Application of Low-Melting Materials

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Abstract

The article describes the simulation of the casting of the low-melting material stearin into a mold, which serves as a real simulation basis for monitoring the displacement during the solidification of steel ingots. The physical properties and occurrence of shrinkage are comparable for both liquid stearin and molten steel. In this way, it is possible to easily monitor the solidification of ingots after casting, while the entire simulation takes place at low temperatures, which is experimentally simpler and more practical than trial casting steel at high temperatures. The process is convenient, simple, fast and cheap. The essence is therefore the application of a new perspective on the mentioned process and its transfer into foundry practice. The temperature drop in the entire volume of the sample was monitored from filling the mold to cooling to ambient temperature and the formation of shrinkage, which was monitored and evaluated in the internal body of the ingot. The tests confirmed the suitability of selected material for this method of experimental work because they were able to capture the real behavior of the cast steel in the mold. The method proves to be suitable for industrial applications where similar multidimensional castings are produced.

Keywords: Casting process, Mold, Shrinkage, Temperature course

1. Introduction

Foundry production belongs to the supporting industries, which are significantly involved in engineering production. Foundry is a broad scientific field that covers a whole range of scientific fields. Large losses in foundry production are losses of liquid metal that occur during the production of castings, but also defects caused by solidification. Improper and undirected solidification is the cause of the formation of various types of defects in castings. Currently, not only classical methods of research on casting and solidification of metal materials are used, in this case steel ingots, the so-called bottle shaped [1]. The article deals with the use of metal casting molds, which are commonly used in practice. In production, non-standard methods are used to a small extent, which in some cases exceeds normal technical solutions. This is the field of application of similar materials, which, instead of expensive operational tests or simulations from the point of view of ecology, preferentially use material that has a low melting temperature and does not burden the environment in any way [1, 2]. The knowledge in the text is obtained based on experiments in laboratory conditions. The article is only a small contribution to the large mosaic of this interesting issue.

1.1. Stress in castings - defects in steel castings

Each ingot is made up of detritus. Despite the small size of the crystals, tiny intracrystalline cavities and pores remain between them. By applying hot forming pressure, these cavities close, the metal is denser and more homogeneous. During further forming, the metal acquires a fibrous structure, which is advantageous in most cases. The fact that steel at forging temperatures occurs in the system of a solid solution - austenite - also applies favorably to forging [3]. The same is true for ductile alloys. If the forging is to be optimally forged, reshaped, the cross-section change must be sufficient. It is important that the steel solidifies upwards from the bottom of the ingot. This creates a supply of liquid steel in the upper part of the mold, which complements the lower and faster solidifying part of the ingot. The upper part of the ingot solidifies eventually, and the shrinkage is limited to this area only. Such a solidification procedure guarantees a mold with a wide cross-section at the top. In a mold with a wide cross-section at the bottom, solidification often proceeds equally quickly from the bottom as well as from the top, because the upper space is smaller. For this reason, the shrinkage often reaches very deep into the ingot and thus reduces its quality. The concentration of shrinkage in the upper part of the ingot is also achieved by placing an extension on the mold, lined with fireclay lining to limit heat loss. The attachment has a similar role as a spigot on a casting in foundries. It is a reservoir of steel kept in a liquid state, from where the cavity created by shrinkage in the mold is filled and the shrinkage is then moved to the so-called lost head. Even today, there is still quite a lot of ambiguity in questions about the formation of tension in castings [4]. This topic is always relevant due to the constant development of industrial technologies. Stresses in castings are caused by both external and internal forces. The effect of external tension is also transmitted to the interior of the casting, where it induces internal tension [5,6]. The cooling casting expands according to the value of the coefficient of free enthalpy of expansion of its material. The resistance of the mold to these expansions causes the so-called shrinkage in the casting. thermal mechanical stress. This temporary tension exists only as long as the resistance to free thermal expansion lasts. Internal tension develops spontaneously in the casting when the individual parts of the casting act on each other in expansions [7]. The internal thermal stress is caused by the different cooling processes, so there are temperature differences inside the casting. This causes deformations and defects in the castings. The factors affecting casting defects are clearly the material (thermal conductivity), the mold material (heat dissipation) and the construction of the casting [8,9].

Castings after solidification have very low strength and poor plastic properties, which is why cracks appear in the area of solidification. The solidification process is characterized by different temperatures along the axis of the casting at individual moments of time. Temperatures change over time. A crack starts to form if the primary crystallization has progressed so that the nascent and growing crystals interlock, i.e. they form a skeleton, while the created skeleton is acted upon by the force of shrinkage, which induces tensile stress. This strength in the cooling cast originates from the inhibited shrinkage of the skeleton. According to Přibil (stress in castings), tensile stress arises when the solid phase tries to shrink immediately after formation [10,11]. Cracks are formed when the two-phase zone reaches the thermal axis of the casting (the free melt has disappeared), and the gravitational force prevails over the shrinkage forces. Shrinkage creates cavities in the thermal axis, in which there is a shrinking mushy substance [12,13]. The mushy conglomerate of primary grains loses its support underneath so that space is freed up by shrinkage. This is how cracks are formed due to shear stress, which originates from the cavities in the thermal axis. The thermal axis is the geometric location of the point at which the last particles solidify in the cross-section of the casting [14].

The shrinkage rate is authoritative to produce models that have a linear shrinkage rate greater than the finished castings. However, it does not affect the creation and size of downloads [15]. For the casting shrinkage value ε0 expressed by thermal shrinkage, it is true that:

$$\varepsilon_0 = \alpha_1 . (T_1 - T_2) \tag{1}$$

And for the stress in the casting, it is true that:

$$\sigma_0 = E_0 . \varepsilon_0 = E_0 . \alpha_1 . (T_x - T_{med.}) \tag{2}$$

Where:
E_0 – modulus of elasticity,
α_1 – coefficient of linear shrinkage,
Tx – temperature of zero fluidity,
Tmed. – average temperature of the wall in which we observe the voltage development.

The Tx temperature is higher than the Tmed temperature. The Lower the Tmed, the higher the shrinkage stress. From a certain temperature Tmed. the stress does not increase further because the strength of the casting exceeds the strength of the mold. In the initial stage of solidification, the elasticity of the solid layer is negligible, therefore the stress σ_0 is developed by the solid resistance of the mold [16,17]. In response to the action of the casting, a compressive stress arises in the mold, for which the following applies:

$$\sigma_f = E_f . \varepsilon_f \tag{3}$$

Where:
E_f – mold modulus of elasticity,
ε_f – mold deformation, is a measure of the value of compressive stress in the mold.

The relative deformation ε after casting is given by the difference in casting shrinkage ε_0 and the mold deformation ε_f.

$$\varepsilon_{p0} = \alpha_1 . (T_x - T_{med.}) - \varepsilon_f \tag{4}$$

If the flexibility of the mold ε_f is zero, the maximum stresses corresponding to relation 1 arise in the casting. On the contrary, if the deformation capacity of the mold is high, the stress in the casting will be lower [18]. For the balance of the forces acting in the casting, the following applies:

$$\sigma_0 . S_0 = \sigma_f . S_f \tag{5}$$

Where: S_f – surface of the mold and S_0 – cross-section of the casting. Substituting into equation 3 for the shrinkage stress in the casting holds:

$$\sigma_0 = \frac{\alpha_1 . (T_x - T_{med.})}{\frac{1}{E_0} + \frac{S_0}{S_f . E_f}} \tag{6}$$

The stress in the casting depends on the physical properties of the casting, the mold, and the temperature interval. It follows from the equation that the shrinkage stress does not depend on the length of the casting. Shrinkage is a problem caused by the physical reduction in volume of the metal during its solidification. The main shrinkage must remain at the top of the ingot. When it appears in the body of the ingot, it is the result of undersetting or low ingot height. The arrangement of crystals and segregates in the ingot is important, which is influenced by the number of crystals and the rate (velocity) of crystallization, as well as the volume change of the melt (Moravec). An ingot with a wide upper end is most often used for blacksmith shops. Small ingots solidify simultaneously in the entire cross-section. Although we can identify dendritic segregation in the ingot, the chemical composition is uniform throughout the cross-section [19-22]. In the ingot, there are different areas corresponding to the course of crystallization Fig. 1.

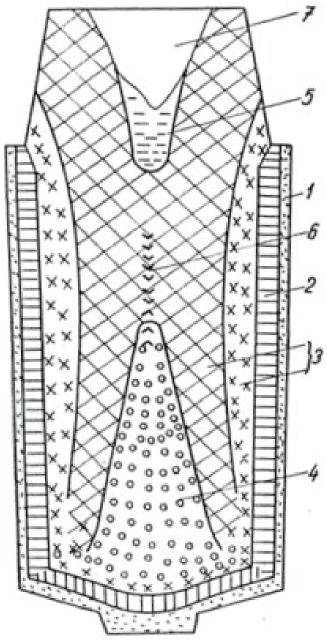

Fig. 1. Scheme of the structure in the ingot Area 1 Thin outer layer of fine, very clear polyhedral grains; Area 2 Columnar long axis, still very clear crystals; Area 3 Thick polyhedral grains; Area 4 Globular grains transformed into pyramid shape in bottom part of ingot; Area 5 Small zone just under the head of ingot; Area 6 Minimal homogeneity; Area 7 Head of ingot with shrinkage [23]

It is important that the shrinkage remains in the upper part of the ingot. In general, shrinkage is not considered a defect because it arises because of the physical phenome-none of volumetric shrinkage of liquid metal. It is a mistake if the contractions are formed inside the casting. In this case, the cross-section of the casting weakens and conditions the formation of cracks and tears [24-26]. The total volume loss of the liquid metal of the casting ΔV when the temperature drops from the casting temperature to the crystalliza-tion temperature and during its solidification is calculated according to the relationship:

$$\Delta V = \left[\alpha_v\left(T_{casting} - T_{crystal.}\right) + 0{,}01\,\varepsilon_{crystal.}\right] V_0 \qquad 5)$$

Where ΔV is the loss of volume of liquid metal during solidification of the casting (m^3),

αv – volume shrinkage coefficient of liquid metal (°C^{-1})

ε_{cr} – volume shrinkage of metal during metal crystallization (%)

V_0 – volume of liquid metal cast into the mold (m^3)

Shrinkage begins to form immediately after filling the mold with melt. The melt cools from the mold to the center, therefore a hard crust has already formed near the sur-face of the casting and there is a melt inside the mold. The predominance of volume loss begins to show; therefore the melt level separates from the upper solid layer at the top. The horizontal, still hot surface is affected by negative pressure from the inside and atmospheric pressure from the outside, so the crust can bend inward. After the total change from liquid to solid, a cavity remains in the casting - a contraction. The external brightness of the casting has decreased considerably compared to the original volume of the melt. In order to avoid the formation of shrinkage in the casting, a casting is made with a certain volume of melt and with a modulus greater than the casting model. The casting is cast with the casting and the surface of the metal in the casting is covered with an exothermic agent so that the liquid form lasts as long as possible (non-solidifying sur-face). A contraction is thus formed in the layer, and below it is an area affected by shrinkage porosity. The position of the shrinkage in the upper part of the casting is the result of the effect of gravity, which is subject to the displacement of the melt during solidification and contraction. Its influence prevails in the case of a macro volume of the melt. In that case, the influence of capillary forces recedes into the background.

The shape of the casting also affects the shape of the shrinkage, as it affects the size of the angle formed by the isosolids during solidification [27]. The smaller the angle, the thinner the draw. Some shrinkages can be eliminated. An open shrinkage can be re-paired by welding. It must be preceded by mechanical treatment of the shrinkage area. Welding and electrode must be from the same material, it is necessary to preheat the casting and then consider annealing the casting after welding [28].

The article presents the study of the solidification and shrinkage process in the in-ternal body of the ingot. Easily meltable materials can be used to verify the occurrence of shrinkage (in this case - stearin). With the help of stearin, we can simulate and then verify the shape of the shrinkage in the ingot. The results of such a simulation are relevant for steel castings. Paraffin, molten sodium sulphite or silver chloride can also serve for the same purpose [29-31]. Stearin is very suitable e.g. for the study of the formation of shrinkage defects in ingots and castings. Further benefits from experimental works and their results are expected. The contribution is complemented by a simulation that con-firms the suitability of using this type of material. The benefit for practice and research is that the casting device has been successfully tested.

Other defects can also appear in the ingots, such as shrinkage porosity caused by insufficient addition of liquid steel. Or complete porosity resulting from insufficient de-oxidation. Type A and V drains are caused by normal segregation processes. Pronounced dendritic segregation is caused by too high a crystallization rate with a small number of crystallization centers. A common problem with ingots is also the formation of cracks, which are the result of tension during rapid casting or premature removal of the ingot from the mold and its rapid cooling [32].

2. Materials and Methods

Methods of experimental research of the solidification process are divided into direct and indirect.

Direct:

- Discharging the liquid metal from the mold and measuring the thickness of the remaining solidified melt,
- Monitoring the progress of solidification using a rod immersed in liquid steel at a certain angle,
- Immersion of the mandrel into the steel

Indirectly:

- Temperature measurement with thermocouples,
- Adding trace elements or radioisotopes to liquid steel,
- Violation of steel crystallization by mechanical effect (vibration),
- Modeling using low-melting compounds.

The size and arrangement of the crystals in the ingots is important for good formability, which is not only affected by the number of nuclei and the crystallization rate, but also by the volume change during the transition of the melt to the solid state.

A frequently used ingot for forges is an ingot with the wide end up (bottle shape). In the case of small ingots, solidification occurs simultaneously in the entire cross-section. Although it is possible to detect dendritic segregation in these ingots, the chemical composition is uniform throughout the cross-section. There are almost no differences in the content of individual elements between the surface and the center, and only very little be-tween the bottom and the top of the ingot. In a large ingot of completely quenched steels, there are different regions corresponding to the course of crystallization [33].

Tested material Stearin is a mixture of free fatty acids, palmitic acid and stearic acid. The melting point is given as 55-60 °C. The material was cast at 60 °C into a metal mold. Form steel H11, height 140 mm; ø100 mm. The height of the ingot is 120 mm, the upper diameter is ø 40 mm; lower diameter ø 26 mm. The mold was treated with silicone oil before casting, which helps to separate the casting from the mold more easily. Fig. 2 represents a bottle-shaped form designed for experimental work. The solidification pro-cess was monitored using thermocouples in the casting and analyzed by an ALMENO 2890-9 Ahlbonn measuring station. Thermocouples were placed in the center of the ingot and close to the wall. The values are shown in the graph (Fig. 3). From previous research measurements, a suitable casting temperature of 60 °C was determined, when the mold cavity is best filled. Casting conditions are worse with superheated stearin melt. It was cast by gravity; the flow was linear and the cavity filling time was 20 s.

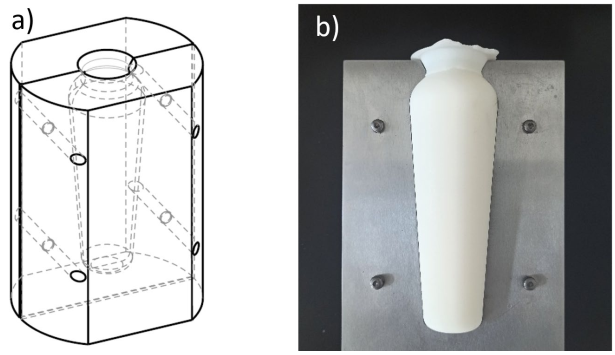

Fig. 2. a) metal mold; b) stearin casting

3. Results

This section provides a brief and precise description of the experimental results. Solidification was analyzed mainly in the vertical axis, the gradual formation of shrinkage on the surface of the casting was observed. The volume of the melt decreased with cooling, therefore, the mold has a deliberately designed wide neck, for better observation and a clear appearance of shrinkage. Shrinkage is easily visible with the naked eye and is manifested by the formation of a gap between the wall of the mold and the body of the ingot. Based on the measured values of the temperature, graph of the dependence of temperature on time during the cooling of the ingot was constructed.

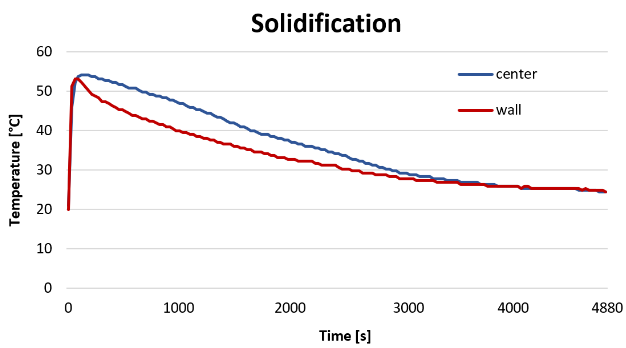

Fig. 3. Dependence of temperature on time during the cooling of the ingot

When the material solidifies, the volume decreases and the level of the liquid phase decreases, that is, the next layer of crystallizing material will be lower and, consequently, the level of the melt will decrease. This phenomenon persists until the solidification of the entire volume of metal [34-36]. The higher the temperature of the cast metal, the larger and deeper the shrinkage, on the contrary, a very low temperature will cause the formation of shrinkage due to insufficient filling of material. In the case of casting at a low speed, the volume of shrinkage will also decrease because part of it will be compensated by adding liquid material. Depending on the shape of the mold, the concentric contraction extends at different heights. In V-shaped molds, the distribution of concentric tension is most suitable (Fig. 4). An important factor is the optimal ratio of the height and width of the mold. Solidification of the metal already occurs during casting itself [37,38]. The solidified crust is deformed due to ferrostatic pressure. The differences in the volumes of withdrawals can be explained by the deformation of the solid crust, given the same dimensions of the ingots. The absolute size of the shrinkage increases with the height of the ingot H and with its diameter inversely proportional to the casting time of the ingot body. The relative size of the shrinkage, expressed as the ratio of the shrinkage volume to the total ingot, increases with the diameter of the ingot [39-42]. Its value de-creases slightly with the increasing height of the ingot. In practice, therefore, the depth of shrinkage has a significant impact on the quality and use of ingot steel.

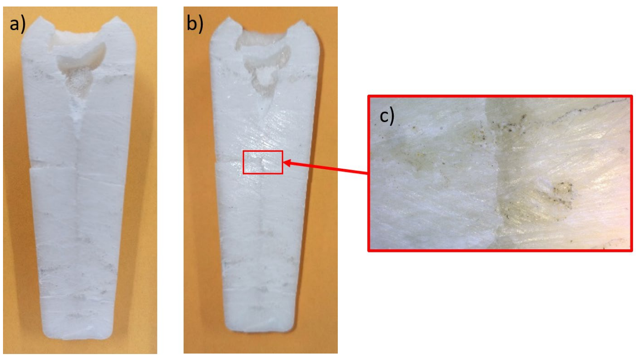

Fig. 4. Shrinkage in casted stearin a) left side; b) right side; c) detail

The course of the experimental work was verified by the ProCast software simulation. The numerical simulation process is a valuable computational tool for reliably predicting the parameters of a real casting operation [43-46]. The ProCast program uses finite element method calculations for numerical casting simulations. Using the above program, it is possible to simulate the casting process for any casting geometry, for different casting materials and molds, under user-defined boundary conditions. The soft-ware database will describe the material properties for the simulation process. In addition, any substance can also be specified manually using its thermophysical parameters [47, 48]. Solidification of the stearin casting and steel solidification were observed by simulation (Fig. 5). Although the materials are melted and cast at different temperatures, shrinkage is more easily observed with stearin. Experimentally, it is easier and cheaper to test stearin than to make steel castings for testing. According to Fig. 5 it can be seen that the tension voltage is located in the area of the inlet system, but the value of the tension is lower.

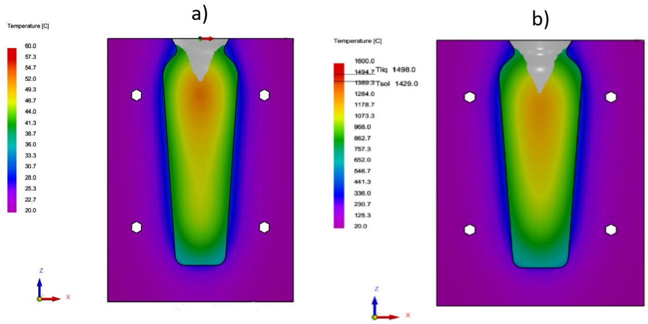

Fig. 5. Solidification process a) Stearin; b) high carbon steel.

According to Fig. 5 there is an obvious similarity in the solidification process, the difference can be seen only in the temperatures. For stearin, the temperature range varies from 20 to 60 °C, while for the cell it is from 400 to 1300 °C. This clearly demonstrates the practical purpose and effectiveness of the process. The simulation showed a match between the materials stearin and steel during casting, but sometimes it is necessary to practically verify the process and therefore it is easier to try it on another material. According to Brůna [49,50], the casting properties of aluminum alloys are similar to cast-ing water at 90°C. Which is similar evidence to the given experiment. In Tab. 1 presents the properties of stearin and steel [51].

Table 1.

Parameter	Stearin	Steel
Solidification point [°C]	53.8	1480
Specific weight [g.cm^{1}]	0.8 – 0.82	7.8
Volumetric shrinkage	7	5
Thermal conductivity [J.cm^{-1} sec°C]	6.7 x 10^{-4}	4.19 x 0.06

4. Discussion

The solidification of the ingot model under laboratory conditions was monitored as the contour layer of the casting was formed. Cooling caused a reduction in the volume of the liquid phase in the body of the ingot. Shrinkage is easily observed with the naked eye, it is manifested by the formation of a gap between the wall of the mold and the body of the ingot. Based on the temperatures read from the thermocouples, a graph was con-structed (Fig. 3 – dependence of temperature on time during ingot cooling).

In the field of solidification, it is desirable to continue determining the influence of the chemical composition of steels on the temperature of the liquid and solid. It is ap-propriate to deal with the determination of the heat transfer coefficient between the mold and the ingot for classical casting as well as for other casting techniques. The data is necessary for a better understanding of the numerical procedures to the actual conditions in the cooling of steel ingots. Special attention must be paid to the study of the solidification of heavy ingots from unalloyed steels because other properties of the forgings are largely influenced by the solidification and primary crystallization of the ingots. Solidification is directly related to the formation of macro segregation, shrinkage porosity and sedimentation cone. Heavy forgings are the basis of the development of mechanical engineering and chemistry. It is also important to study the solidification of the surface layer of ingots for the overall improvement of the surface quality of raw ingots and the limitation of cracks arising from thermal stress.

The study of solidification process is problematic in practical terms, either from the point of view of the necessity of many empirical tests or the technological complexity of conducting the tests, not to mention the financial complexity. For the stated reasons, physical modeling or mathematical modeling, or a combination of the mentioned methods, is used to simulate solidification. Shrinkage is caused by volume loss of the material during solidification. During the production of castings, it is possible to prevent the occurrence of shrinkage with suitable technological interventions. Nowadays, technological measures no longer consist only of guided solidification and economic molding, but also of the appropriate use of simulation programs and test experimental methods, which will facilitate production and help predict the casting [52]. Solidification of the casting takes place in two stages. In the initial stage of solidification, solidification progresses from the surface of the casting to its center. In this stage, the filling of the melt is unhindered and takes place intensively. In the final stage of solidification, at the moment of collision of the solidification zone in the thermal axis of the casting, the filling of the melt is limited and takes place only by filtration of the melt. Melt filtration during solidification refers to the flow of melt between dendrites in a two-phase solidification zone [53]. The skeleton of the dendrites prevents the mechanical movement of the melt, but due to the influence of the melt filtration, the movement of the melt is not completely interrupted [54]. A big disadvantage of stearin is its very low thermal conductivity. The solidification constant of steel in the mold is k0 = 1.51 cm. min0.5. The solidification constant of stearin when using a glass mold is ks = 0.1 cm. min0.5.

Regarding solidification, more research should be done to determine how the chemical composition of steels (high carbon and high alloy steels) affects the liquidus and solidus temperatures. The solidification direction is followed along the thermal axis of the casting. In addition, both in traditional casting and in continuous casting, it is necessary to determine the heat transfer coefficients between the ingot and the mold. The above in-formation is necessary to make the numerical techniques very close to the actual conditions that exist during the cooling of steel ingots. The study of the initial crystallization and solidification of very heavy ingots made from alloyed and unalloyed steels deserves special attention because it has a significant effect on other properties of the forgings. A big advantage is the use of simulation processes, which nowadays are no longer burdened with errors.

The chosen experimental tests were selected for their suitability and reproducibility. The primary purpose was to verify the applicability of the given solution in the field of laboratory validation of the simulation of the real process of casting steel into molds.

5. Conclusions

- The study describes the process of casting and solidification of the low-melting material stearin into a metal mold, which also serves as a real simulation base for monitoring the solidification of steel ingots.
- The paper's research shows that the physical properties and incidence of shrinkage are comparable for both liquid stearin and molten steel. It is possible to simply observe the solidification of the ingots after casting, while the whole process takes place at low temperatures, which is experimentally easier and more practical than casting the test steel at high temperatures.
- The essence is the application of a new perspective on the possibilities of trying and testing materials. The tests confirmed the suitability of the chosen material for this method of experimental work, because they were able to capture the real behavior of the cast steel in the form.
- A comparison of stearin casting and steel casting simulation is relevant and suitable as a complementary test method.

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