ARCHIVES of FOUNDRY ENGINEERING

10.24425/afe.2022.143953

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

ISSN (2299-2944)
Volume 2022
Issue 4/2022

79 – 84

11/4

The Process of Vacuum Formation in the Shrinkage Cavity at Castings Crystallization

V. Khrychikov [a], O. Semenov [a,*], H. Meniailo [a], Y. Aftandiliants [b], S. Gnyloskurenko [b, c]

[a] Ukrainian State University of Science and Technologies, Ukraine
[b] National University of Life and Environmental Sciences of Ukraine, Ukraine
[c] Physical and Technological Institute of Metals and Alloys, National Academy of Sciences of Ukraine, Ukraine
* Corresponding author: Email address: aldmsem@gmail.com

Received 21.06.2022; accepted in revised form 16.09.2022; available online 16.12.2022

Abstract

The formation process of one of the most common casting defects, a shrinkage depression concerned to shrinkage cavity, was studied. The methodology, device and the experimental set up were developed to study the shrinkage cavity growth. The kinetics of vacuum formation in the cavity of the spherical casting of Al-Si-Mg alloy at its solidification in the sand-and-clay form was investigated. The data were analysed taking in mind the temperature variation in the centre of crystallizing casting. The causes of the shrinkage depression in castings were clarified. It was determined that atmospheric pressure leads to the retraction and curvature of metal layer on the surface of the casting with lower strength below which the shrinkage cavity is formed. To avoid such defects it was recommended to use the external or internal chills, feeders and other known technological methods. Deep shrinkage cavities inside the castings could be removed with an air flow through a thin tubular needle of austenitic steels for medical injections.

Keywords: Shrinkage depression, Causes of defects, Shrinkage cavity, Device for measuring vacuum

1. Introduction

One of the most common defects in castings is a shrinkage depression that appeared as hollow with smooth rounded edges on the upper surface of casting due to shrinkage of metal at solidification [1-3]. A shrinkage cavity having a large rough surface with traces of dendrites is distinguished with shrinkage depression. The former is formed due to reducing a metal volume during successive faster solidification of the alloys on the sides and bottom of castings and ingots, and slower solidification on the upper free surface of the casting, which solidify before the massive central parts.

The reasons of shrinkage depression appearance were not explained in the theory of foundry processes, although its placement is associated with hot spots and closed shrinkage cavities under the surface defects [4-8]. Figure 1 demonstrates the casting with an inner shrinkage cavity [8]. However, at the top of the casting it is seen not a cavity but a shrinkage depression with rounded edges. The shrinkage cavity is located below the shrinkage depression in thermal centre of the casting with a short surface and traces of dendrites.

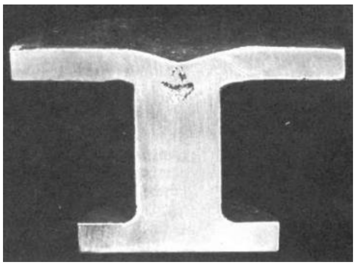

Fig. 1. Sectioned casting exhibiting internal shrinkage cavity and depression [8]

In the previous study it was suggested that the reason of shrinkage depressions (1 in Fig. 2) is the formation of hot spots in massive parts of the casting [9]. Liquid metal filtrates from such thermal centres to the solidified layer on the surface of the casting.

When the melt move from the hot spot in its centre in case of shrinkage, a shrinkage cavity (2 in Fig. 2) and a vacuum (P_0) are formed. Therefore, atmospheric pressure (Pat) leads to the retraction and curvature of the hardened layer of metal with lower strength (see 1 in Fig. 2) on the surface of the casting.

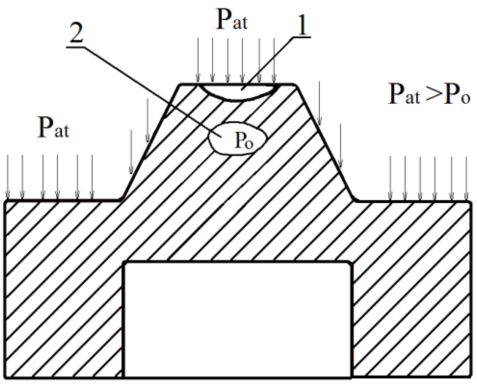

Fig. 2. Typical view of the shrinkage depression (1) in the thickened part of the casting with a shrinkage cavity (2): P_0 - vacuum in the shrinkage cavity; Pat - atmospheric pressure

Assumptions in [4] about the occurrence of shrinkage depressions in the art casting of bronze were eliminated by moving atmospheric air into the shrinkage cavity on a thin tubular needle. The tube has a diameter of 0.80 mm, cavity with a diameter of 0.49 mm and length of 32 mm. It is made of austenitic stainless steel and it is used for medical injections [9]. One end of the tubular needle was placed in the centre of the hot spot of the art casting. The other end of the tube was connected to the atmosphere [4]. It helped to avoid the formation of shrinkage depressions on the outer surface of the casting, to reduce the cost of the gating system and minimize minting the surface of the art casting. In addition, the other end of the tube was installed in the mould from the non-working surface of the casting, which is not available for inspection.

Vacuum formation in the shrinkage cavity was confirmed by the indirect studies. It was established by Dunphy R. P. et all. that vacuum exist in the shrinkage cavity of castings of 101.6×101.6×294 mm [11]. But it concerns nodular cast iron only and the formation of shrinkage depression was not studied.

In the study the water manometer was connected to two quartz tubes, installed in the centre of the cavity formation. One tube was closed, whereas the other one was opened and filled with a sand mixture to prevent the penetration of nodular cast iron. Authors considered that the closed tube provided stabilization of the initial pressure caused by the expansion of air at heating of tubes. However, the air occupies a volume of about 30 % in the gaps between the sand mixture in the open tube. The calculation of the weighted average heat accumulation coefficient ($b = \lambda^{0.5} \cdot c^{0.5} \cdot \rho^{0.5}$) of air (A) and sand mixture (S) in the tube in the first approximation is equal to: $b_{A\text{-}S} \approx 438.0$ W·s$^{0.5}$/m^2·K, when the value of the accumulation coefficient of heat of sand $b_S \approx 623.5$ W·s$^{0.5}$/m^2·K (thermal conductivity coefficient - $\lambda_A = 0.0257$ W/m·K; specific heat - $c_A = 1005$ J/kg·K; density - $\rho_A = 1.205$ kg/m^3) and air $b_A \approx 5.6$ W·s$^{0.5}$/m^2·K [13].

Thus, the coefficient of heat accumulation with a tube with a sand is about 78 times higher, then the tube with air ($b_{S\text{-}A}/b_A$). It affects the accuracy of vacuum estimation in the empty shrinkage. The described results in [11] are important, but it is necessary to reduce the impact of measurement devices on the crystallization process.

The authors in [5] presented the model for predicting the formation of shrinkage defects explicitly as a function of the interacting continuum phenomena, i.e. free surface flow, heat transfer, and solidification as 3-D numerical problem. It allowed identifying the distinction between surface depression, surface connected cavities and internal cavities under deficiency in feeding flow. As it was stated, there is no commercial software to simulate the phenomenon perfectly. Therefore, experimental studies of the process of shrinkage depression formation in aluminum castings can improve the accuracy of model calculations.

The purpose of the present study is to develop the methodology of the experiment and to study the kinetics of vacuum formation in the shrinkage cavity, which causes formation of shrinkage depression.

2. Experimental methods

The object of the study is a ball-shaped casting, which provide the concentration of the shrinkage cavity almost in the geometric centre with a slight upward shift. The diameter of the model is equal to 120 mm. Al-Si-Mg alloy was used for the experiments and casting was cooled in sand-and-clay mixture. A parting-line gating system was used with metal supply along the connector with a trapezoidal gate with an area of 6.2 cm^2 which is tangent to the lower part of the ball. Next part of the system is a dirt trap in the upper half-shape with an area of 6.3 cm^2. The last is a sprue with a diameter of 3.2 cm^2 and a pouring basin. The mould was not dried. An air gate of Ø 3 mm in the upper part of the ball provided air outflow from the mould during melt pouring.

Temperature control was performed with Cr-Al thermocouples of Ø 0.5 mm. Thermal electromotive force (TEMF) was recorded by the AT4208 digital meter with a recording interval of 1 s and sensitivity of 0.1 K. The allowable total instrumental error (G_Σ) of the thermoelectric kit (thermocouple, compensation wires and meter) was determined by the formula [12]:

$$G_\Sigma = \sqrt{G_T + G_K + G_P}, \quad (1)$$

where G_T is the allowable error due to the deviation of the TEMF from standard calibration;

G_K - error due to the difference between TEMF of thermocouples and compensation wires;

G_P - reduced error of the measuring instrument

The difference between TEMF of thermocouples and compensation wires (G_K) was taken equal to zero because the thermocouples were attached directly to the terminals of the meter. The error of the digital meter was G_P = 1.1 K. The calibration of Cr-Al wire using standard measuring instruments showed an error G_T = 1.0 K, and the total error value G_Σ = 1.4±0.5 K.

Cr-Al thermocouple was placed in a two-channel mullite-silica tube with an external Ø 2.8 mm and an internal Ø 0.7 mm. The hot junction of the thermocouples was welded with a Kvant-12 laser device. It was also protected with a quartz tip with an external Ø 7.0 mm and an internal Ø 4.0 mm.

The developed device includes a medical needle for measurement pressure changes in a shrinkage cavity (Fig. 3). The needle is made of stainless steel with a 90 mm base, an outer diameter of 0.7 mm and an opening of Ø 0.44 mm [10]. The needle (1) was welded with a steel cork (5) and then with a tube (2).

The mullite-silica tube (3) of Ø 2.5 mm and an internal hole Ø 1.0 mm was pushed onto the needle (1) to prevent possible curvature of the needle due to the possibility of hydro- and thermal shock when pouring liquid metal. The air gap additionally protects the attachment from heating between the mullite-silica tube (3) and the needle (1).

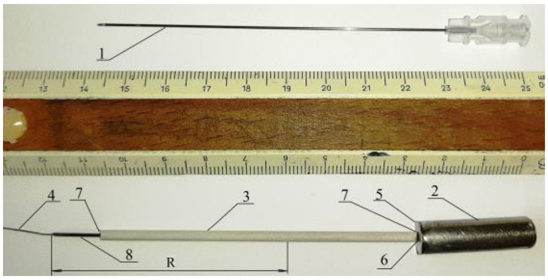

Fig. 3. Appliance for measurement vacuum in a shrinkage cavity: 1 - medical spinal needle Ø 0.7 mm x 90 mm; 2 - steel tube with the outer Ø 8 mm and wall thickness 1 mm; 3 - tube; 4 – wire Ø 0.2 mm; 5 - steel plug; 6 - zone of head welding 1 with steel cork; 7 - zone of sealing with ceramics gap between mullite silica tube 3 and head 1; 8 - part of the head without thermal insulation; R - depth of introduction into liquid metal, 60 mm

The gap was sealed (7) with a dental ceramic at a temperature of 760°C for 5 minutes in order to prevent air flow between the needle (1) and the tube (3) when pouring metal. The part of the needle of 12 mm without thermal insulation (8) was placed in the geometric centre of the ball mould of 60 mm in radius with an upward displacement of 8 mm.

General view of the set up to study pressure changes is shown in Figure 4. U-shaped manometer (4) of quartz tubes filled with distilled water and fixed in a vertical position realized a measurement error of ± 0.4 mm taking into account the water wettability of the quartz glass and the calibration of the scale. The silicone tube (5) has an internal hole Ø 7.5 mm, a side thickness of 2.0 mm and a length of 1.0 m. It connects a U-shaped manometer with a device for measuring the vacuum in the shrinkage cavity (Fig. 3).

The chemical composition of alloy is as follow (weight, %): Al - 85.392; Si - 3.034; Mg - 9.002; Cu - 0.611; Fe - 0.920; Mn - 0.247; Zn - 0.650; Ni - 0.069; Ti - 0.056; Cr - 0.01. It was melted in an induction furnace with graphite crucible. The surface of the melt was protected with charcoal and the slag was removed from the surface after 1-2 min holding at 740°C. After that the melt was poured into the mould of 28°C. Mould coating was not used to reduce the possibility of gases entering the melt due to paint destruction.

Fig. 4. General view of the set up used in the experiment to study pressure changes in the centre of the spherical casting: 1 – casting mold; 2 - load; 3 - funnel for pouring metal; 4 - U-shaped water manometer; 5 - silicone tube connecting the manometer to the needle; 6 - video recording of manometer readings; 7 – AE4808 device for temperature measuring

3. Results and discussion

It was found that the pressure starts to decrease after 10 s after pouring the melt into the mould, which is shown as water level difference in Figure 5. Average rate of manometer indication of lever changes was of 0.15 mm/s within 30 s. It increased to 0.57 mm/s from 30 s to 60 s.

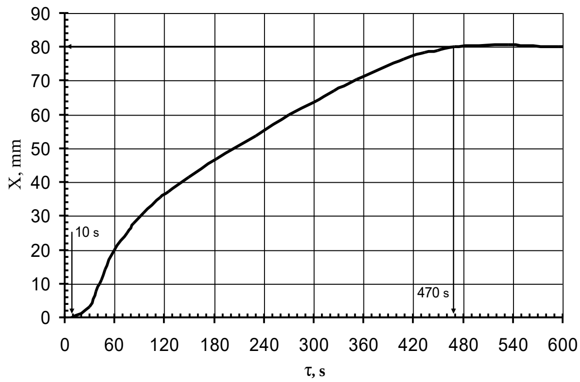

Fig. 5. Variations in water columns (X) level difference in the manometer with time (τ) reflected pressure decrease in the centre of the shrinkage cavity of casting

The obtained results coincide with the results of the kinetics of solidification of the melt in the form of a sphere with an accelerated solidification in the first stage. Later a gradual pressure decrease occurs with an average vacuum formation rate of 0.28 mm/s in the range of 60 s - 120 s and of 0.16 mm/s from 120 s to 240 s. The pressure changes were slowed down and completed at 480 s.

Thus, the manometer recorded a maximum vacuum of 80 mm of water column for 7 min 50 s. This moment corresponds to a temperature of 618ºC (Fig. 6) on the experimental cooling curve of the central part of the sphere, i.e. 13ºC below the maximum recoalescence temperature (t_L = 631ºC). So, shrinkage formation is slowed down approaching temperature t_L probably due to the formation of most of the alloy solid phase at this temperature. It can be confirmed by the duration of cooling delay (227 s - 131 s = 96 s) at temperature t_L, while this delay is 2.3 times less at solidus (1069 s - 1027 s = 42 s).

Volume of the shrinkage cavity (V_{vac}) in the first approximation was calculated based on the difference of the water columns level (Δh = 4 cm, see Fig. 5) of U-shaped quartz tube of 0.55 in inner diameter. Thus, the volume was equal to V_{vac} = 0.95 cm^3.

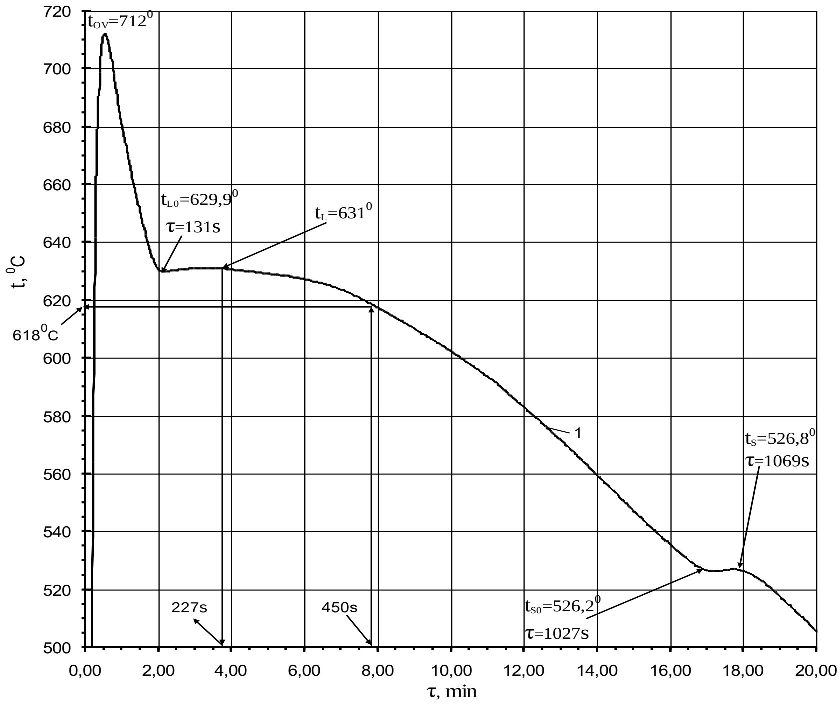

Fig. 6. Experimental cooling curve (1) of the centre of the sphere Ø120 mm of Al-Si-Mg alloy in sand-and-clay casting mold: t_{L0}, t_L and t_{S0}, t_S - temperature of the beginning ($_0$) and end of the temperature arrest at t_L and t_s, respectively; τ – time

The melt temperature decreased from 712ºC to the point of the temperature arrest t_{L0} = 629.9ºC (Fig. 6), when a slight supercooling was recorded with further increase to t_{L0} = 631ºC. The obtained results are within the error of the measuring instruments, although, they well correspond to the known crystallization processes of alloys [13]. At solidus supercooling was even less (t_{S0} = 526.2ºC and t_S = 526.8ºC).

Vacuum in the shrinkage cavity (P_{vac}) was calculated by the formula:

$$P_{vac} = P_{at} - h\rho_w g, \quad (2)$$

where P_{at} - atmospheric pressure;

h is the difference between the levels of water columns in the U-shaped quartz tube;

ρ_w is the density of distilled water at the temperature during the experiment;

g - acceleration of gravity.

The values of the parameters in Eq. 2 in Dnipro city at the time of the experiment were as follows: atmospheric pressure was equal to 101192 Pa according to the state meteorological station; the density of distilled water at a temperature of 28 ºC was of 996.2 kg/m^3 and the acceleration of gravity reached 9.8090 m/s². Thus, the vacuum in the shrinkage cavity of the casting was calculated to be equal to P_{vac} = 100410.2 Pa.

The volume of the cavity (V_{vac}) was calculated above and it is equal to V_{vac} = 1.9 cm^3. Heating the air up to 618ºC (see Fig. 6) will reduce the difference between the levels of water columns in the manometer at the end of the movement of atmospheric air (28⁰C) in the manometer by 470 s. However, it will increase the cavity volume to:

$$V_t = V_{vac}\,(1+\beta t) = 0.95\,(1+ 0.003661\cdot(618-28)) = 3.0 \text{ cm}^3, \quad (3)$$

where β is the coefficient of volumetric expansion of air.

The diameter of the casting after cooling (Fig. 7) decreased from 120 mm to 119.1 mm showing the shrinkage of 0.76%. It is difficult to increase the accuracy of shrinkage cavity volume calculation taking into account the effect of shrinkage of the casting by 0.76%, heating the air entering into the cavity from the silicone tube and manometer. Moreover, the heated air is displaced from the shrinkage cavity into the silicone tube and cools down to ambient temperature. Despite that the size of the device for measuring vacuum is minimum (see Fig. 3) the movement of air through the needle into the shrinkage cavity reduces the level of vacuum and the size of the shrinkage depression. It also affects the feeding the shrinkage of solidifying metal through the two-phase solid-liquid zone.

Regardless the complexity of the processes above the experiment confirms the assumption [9] that a shrinkage cavity and a vacuum (P_0) is formed in the casting below the shrinkage depression (see 2 in Fig. 2). Therefore, atmospheric pressure (P_{at}) leads to retraction and curvature of the solidified layer of metal (see 1 in Fig. 2) on the surface of the casting with lower strength, which is confirmed with the cast ball with shrinkage depression (2 in Fig. 7).

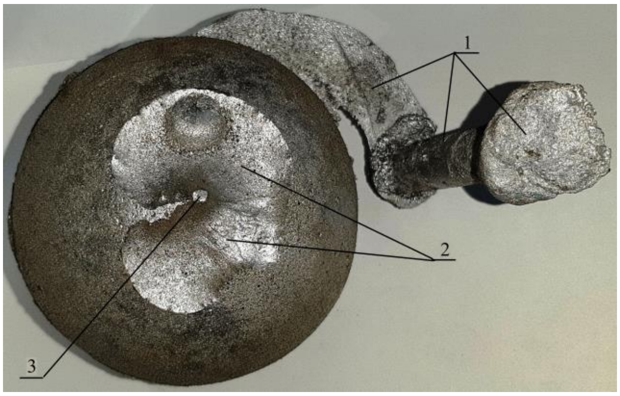

Fig. 7. Top view of the casting ball Ø 120 mm with the gating system (1), shrinkage depression (2) and remnant of an air gate (3)

"Shrinkage depression is a defect in the form of a recess with rounded edges on the surface of the casting, which was formed due to metal shrinkage during solidification" according to the current terms and definitions [1, No. 4.4.16]. Based on the obtained experimental results it is reasonable to treat of the above as *"Shrinkage depression is a defect in the form of a recess with rounded edges on the surface of the casting. It was formed as a result of metal shrinkage during solidification because of formation of the shrinkage cavity near the shrinkage depression, in which vacuum was formed"*.

To improve quality of cast products it is necessary to prevent the formation of shrinkage cavity with external and internal chill boxes or feeders and other known technological methods to remove the shrinkage depression. If it is impossible to remove the cavity inside the casting (like in art casting), it is necessary to ensure the movement of atmospheric air through a thin tubular needle made of austenitic stainless steel, which is used for medical injections [9,14].

4. Conclusions

The methodology, device and experimental set up were developed for measuring vacuum variation in the shrinkage cavity that allowed to study its formation in Al-Si-Mg alloy casting in the sand-and-clay form during solidification. Clarifications were made to determine the nature of shrinkage depression arise. It was established that shrinkage depression on the casting surface is formed under atmospheric pressure acting on the metal layer below which shrinkage cavity is formed. The appropriate clarification was proposed to add to shrinkage depression definition.

To avoid such defects it was recommended use external and internal chills, feeders and other known technological methods in foundry. It is necessary to ensure the movement of atmospheric air when it is impossible to remove the cavity deep inside the casting. A thin tubular needle made of austenitic stainless steel may be used for this purpose.

References

[1] DSTU 9051:2020. Castings of cast iron and steel. Defects. Terms and definitions. Since 01.04.2021. Pg. 15. (in Ukrainian) http://ptima.kiev.ua/images/stories/Standart/IRONSTEEL/dstu19200-80.pdf

[2] Rowley, M.T. (2007). *International Atlas of Casting Defects*. American Foundry Society. ISBN: 978-0874330533.

[3] GOST 19200-80. Castings of cast iron and steel. Terms and definitions of defects. (1980). (in Russian).

[4] *Atlas of foundry defects*. (2004). 136 Summit avenue. Montvale, NJ 07645-1720. Institute of Foundry Casting. Technopark. Pg. 23.

[5] Reisa, A., Xub, Z., Tolb, R.V. & Netoc, R. (2012). Modelling feeding flow related shrinkage defects in aluminum castings. *Journal of Manufacturing Processes*. 14(1), 1-7. DOI:10.1016/j.jmapro.2011.05.003

[6] Voronin, Y.F., Kamaev V.A. (2005). *Atlas of foundry defects*. Moscow: Mechanical Engineering. Pg. 327. (in Russian). https://www.twirpx.com/file/914318/

[7] Chokkalingam, B. & Mohamed Nazirudeen, S.S. (2009). Analysis of casting defect through defect diagnostic study approach. *Journal of Engineering Annals of the Faculty of Engineering Hunedoara*. 2, 209-212. ISSN 1584-2665

[8] Beeley, P. (2001). *Foundry Technology*. 719. Oxford: Butterworth Heinemann. ISBN 0750645679. https://www.academia.edu/4161769/foundry_technology_by_peter_beeley/

[9] Khrychikov, V.E., Semenov, O.D., Menyaylo, O.V., Shalevskaya, I.A., & Myanovskaya, Ya.V. (2021). Elimination of weights in artistic castings with different wall thickness (Removal of shrinkage depression in art castings with different wall thickness). *Casting processes* (Затвердіння сплавів). 4(146). 14-21. (in Ukrainian).

https://plit-periodical.com.ua/en/arhiv/removal-shrinkage-depression-art-castings-different-wall-thickness
[10] GOST R ISO 9626-2020. (2021). Stainless steel needle pipes for the manufacture of medical devices. Requirements and test methods. Pg. 28. (in Russian).
[11] Dunphy, R.P., Akerlind, C.G. & Pellini, W.S. (1954). Solidification, feed characteristics of gray cast irons and nodular cast irons. *Foundry*. 82(6), 106-121.
[12] Rogelberg I.L, Beilin V.M. (1983). *Alloys for thermocouples (handbook)*. Moscow: Metallurgy. 76-77. (in Russian) https://knizhen-pazar.net/products/books/597200-splav-dlya-termopar
[13] Leibenzon, V.O., Pilyushenko, V.L., Kondratenko, V.M., Khrychikov, V.E., Nedopyokin, F.V., Bilousov, V.V. Dmitriev, Yu.V. (2009). *Hardening of metals and metal compositions.* Kyiv: Scientific thought. 447. (in Ukrainian. https://nmetau.edu.ua/file/tverdinnya_metaliv_i_metalevih_kompozitsiy._pidruchnik..pdf
[14] Khrychikov, V.E., Semenov, O.D., Menyaylo, O.V. (2021). Application for the patent № a202101129. Ukraine. IPC (2021.01) B22D 27/13 (2006.01), B22D 25/00. Method of removing weights in castings with thickened parts of wall. (in Ukrainian). https://base.uipv.org/searchInvStat/showclaimdetails.php?IdClaim=336807&resId=1