Experimental casting of forging ingots from model material

Ján Moravec[1], *Peter* Kopas[2,*], *Lenka* Jakubovičová[2], *Bohuš* Leitner[3]

[1]University of Zilina, Faculty of Mechanical Engineering, Department of Technological Engineering, Univerzitná 8215/1, 010 26, Zilina, Slovak Republic
[2]University of Zilina, Faculty of Security Engineering, Department of Technical Sciences and Informatics, Univerzitná 8215/1, 010 26, Zilina, Slovak Republic
[3]University of Zilina, Faculty of Security Engineering, Department of Technical Sciences and Informatics, Univerzitná 8215/1, 010 26, Zilina, Slovak Republic

Abstract. The paper describes the process of casting ingots from the model material into a special mold made for these tests. The material was chosen stearin, which proved to be suitable for this type of laboratory test. During the solidification process of the ingot model under laboratory conditions, it was observed how gradually the layer formed on the contour of the casting. Gradual cooling of the ingot resulted in a decrease in the volume of the liquid phase in his body. The fog is readily observable by the naked eye and this is manifested by the formation of a gap between the ingot mold wall and the ingot body. A silicone oil has been used as a separating melt separating layer and the wall of the ingot that has reliably fulfilled this task. Casting was done in two ways, with a standing and lagging mold. The process of filling the cavity itself was to create conditions for the linear flow of the melt. Observation of the ingot after its solidification confirmed the fact that the filling of the cavity proceeded under such conditions in terms of the melt flow rate.

Keywords: ingot, mold, stearin, solidification, casting

1 Introduction

In technological practice we constantly search for methods and ways that can ensure comparably usable parameters for a real process, obtained in experiments [1-4]. The following text focuses on one of the several ways enabling shrinkage formation in the body of the ingot, and also on the study of the shrinkage process using modelling materials. For quite a long time experimental work has been done using easily melt able materials [5-8].

1.1 Ingot casting – practical aspects

In terms of the theory of solidification and crystallisation, the most preferred way is casting of dimensionally smallest ingots. This is used when the aim is to achieve optimal homogeneity – both chemical and structural. Practical manufacture of steel ingots is a

* Corresponding author: peter.kopas@fstroj.uniza.sk

Reviewers: *Andrej* Czán, *Ján* Vavro *Jr.*

challenging technical and organisational process and a problem depending on several factors, such as: basic type of cast steel (killed and rimmed steel); required shape of the ingot for further processing; chemical composition of the material; size of the production unit; cycle of ingot mould set preparation; method of ingot casting (bottom, top); number of ingot types and production capacity of the forge. Methods of experimental research into the solidification process are divided into direct and indirect.

Direct methods:
- Discharge of liquid metal from the ingot mould and measuring the thickness of the remaining solidified melt.
- Monitoring the solidification process by means of a bar immersed in the liquid steel at a certain angle (bar test).
- Dipping a mandrel into the steel.

Indirect methods:
- Measurement of the steel temperature using thermocouples.
- Addition of trace elements or radioisotopes to the liquid steel.
- Disturbance of steel crystallisation by mechanical effects (shock, vibration).
- Modelling using low-melting compounds.

Of great importance for good formability (malleability, ductility) is the size and arrangement of crystals and segregates in ingots, which are influenced by the number of crystal nuclei and rate (velocity) of crystallisation, as well as by the volume change in the melt's transition into a solid state [9]. The most commonly used ingot for forges is an ingot with a wider top end. In case of small ingots, solidification occurs simultaneously in the whole cross-section of the part of the ingot in the ingot mould. Although dendritic segregation can be detected in these ingots, but the chemical composition is uniform all over the cross-section. Hardly any differences are manifested in the content of individual elements between the surface and the centre. There are only a few differences between the top and bottom parts of the ingot. A large ingot of fully killed steel features various regions corresponding to the course of crystallisation.

1.2 Faults of steel ingots

Main shrinkage - in case of ingots with lost tops, the main shrinkage must remain in the ingot top. When it appears in the ingot body, it is the result of an under cast or too-little ingot top. Shrinkage porosities are caused by insufficient refilling of liquid steel. Total porosity is the result of insufficient deoxidation. Distinctive dendritic segregation occurs due to a too high crystallisation rate at a small number of crystallisation nuclei. Longitudinal cracks on the walls are the result of stress at too fast a hot casting, or at premature removal of the ingot from the ingot mould and its rapid cooling. Transverse and diagonal cracks are caused by obstacles in the shrinkage of the ingot – either by the ingot mould or by unsuitable casting temperature and rate.

2 Experimental work

The experimental material we used was stearin. It is a mixture of free fatty acids, in particular palmitic and stearic acids. The melting point is indicated as 55–59 ˚C. We used a steel ingot mould and cast experimental rollers. These were monitored with sodium thiosulphate. When applying stearin, differences became apparent in the quality of the cast samples. The bodies of samples after solidification in the ingot mould were relatively suitable for subsequent observations. Figure 1 shows the samples after completion of the experiment.

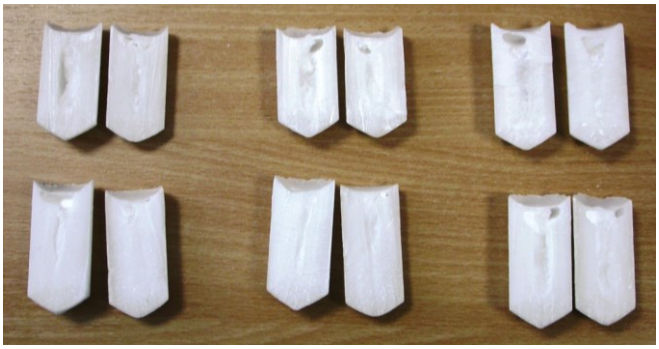

Fig. 1. Shrinkages and cavities in the samples

2.1 Model equipment

There was manufactured a model ingot mould. We used this ingot mould to carry out experimental work. Sensor wires were sealed using a sealing paste. To record the temperature we used three sensors at different heights. Values were read from each sensor at pre-defined time intervals. The values were then processed in a chart. We used ALMENO 2890-9 Ahlbonn measuring station. A bad casting was produced at a high melting temperature, but the result was better at a lower temperature. Optimum temperature proved to be 58 °C, when the cavity filling was best. Casting conditions turned much worse when overheating the melt.

2.2 Filling the ingot mould cavity

We used silicon oil as a separating layer to separate the melt from the ingot mould wall. Silicon oil reliably accomplished the task. Figures 2 and Figure 3 thoroughly illustrate the whole course of the process and provide a good overview of all monitored parameters.

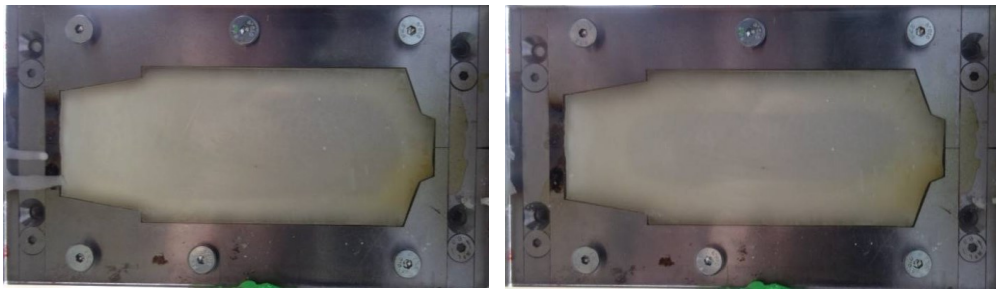

Fig. 2. Solidification of the model ingot in the longitudinal axis
left – after 20 minutes; right – after 40 minutes

Fig. 3. Shrinkages and cavities in the samples

We carried out two methods of filling the ingot mould cavity: First Case (Fig. 4) status I, and Second Case (Fig. 4) status II. The filling port (inlet), which is not used in either method, is plugged with an auxiliary plug during filling the ingot mould cavity. In the actual cavity filling process we attempted to create the conditions for a linear flow of the melt. Observation of the ingot after it solidified confirmed the fact that the cavity filling was carried out under such conditions in terms of the melt flow velocity. The total time of the cavity filling was 42s.

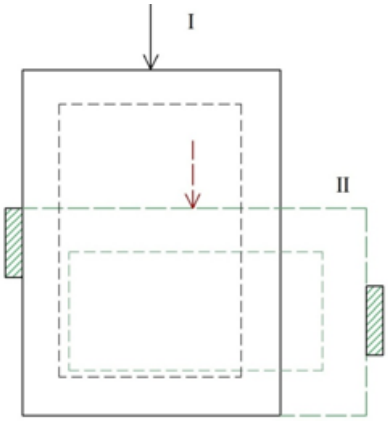

Fig. 4. Two positions for casting ingot

2.3 The course of experimental work

In the course of the model ingot solidification process in laboratory conditions we observed how a layer was gradually forming along the contour of the ingot casting. Cooling of the ingot was gradual, which resulted in reducing the volume of liquid phase in the ingot body, which was observed during the experiment. Shrinkage is readily observable with the naked eye, and this is manifested by formation of a gap between the ingot mould wall and the ingot body. Based on the temperature readings of the thermocouples we plotted a graph – dependance of temperature on time during the ingot cooling. The temperature of the ingot decreased rapidly during the first five minutes, then it stabilised at the same value (Fig. 5).

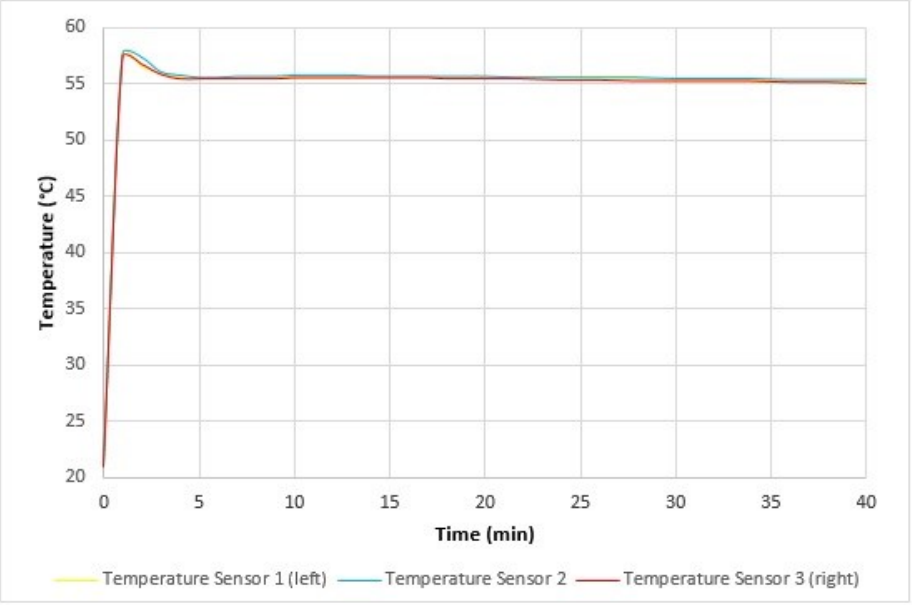

Fig. 5. Graphs showing temperatures over the sample solidification

2.4 Solidification

Regarding solidification it is desirable to continue to determine the effect of chemical composition of steels (high carbon and high alloyed steels) on the liquidus and solidus temperatures. It is also necessary to deal with the determination of the coefficients of heat transfer between the ingot and the mould, and between the ingot and the pad, both for conventional casting as well as for continuous casting. The above-mentioned data are required for a very close approximation of numerical procedures to real-life conditions during cooling of steel ingots. Special attention should be paid to the study of solidification of very heavy ingots of non-alloyed as well as alloyed steels, because other properties of forgings are largely influenced by solidification and primary crystallisation of ingots. The solidification process is directly associated with the development of macro-segregations, segregates and sedimentation cone. Heavy forgings are the basis for the development of mechanical engineering and chemistry. It is also equally important to study solidification of the ingot surface layer in order to comprehensively improve surface quality of raw ingots and prevent cracks resulting from heat stress [10, 11].

2.5 Steel shrinkage during cooling and solidification

Shrinkage in ingots is formed due to steel shrinking during its cooling and solidification. The size of shrinkage can be calculated using the equation by [12]:

$$V_S = \alpha_V + \alpha_{\Delta t}(t_1 - t_S) - \frac{1}{2}\beta(t_S - t_2) \quad (1)$$

where V_S is the volume of shrinkage; α_V - the coefficient of volumetric shrinkage during solidification (dimensionless); β - the coefficient of volumetric shrinkage in the solid state; t_1 - the mean temperature of liquid steel at the beginning of solidification; t_2 - the mean

temperature of solidified steel at the end of solidification; t_s – temperature of solidification; $\alpha_{\Delta t}$ - the coefficient of volumetric shrinkage in the liquid state.

Shrinkage size when casting steel into an ingot mould and if it is $\alpha_{\Delta t} = 0.9.10^{-4}K^{-1}$, $\alpha_V = 0.0034$, $\beta = 0.64.10^{-4}K^{-1}$, $t_1 = 1525\,°C$, $t_2 = 1275\,°C$, $t_S = 1500\,°C$ can be written as :

$$V_S = 0.034 + 0.9.10^{-4}(1525 - 1500) - \frac{1}{2}.0.64.10^{-4}(1500 - 1275)$$
$$V_S = 0.034 + 2.25.10^{-3} - 7.2.10^{-3}$$
$$V_S = 0.029$$

The shrinkage volume is 2.9 % of the ingot volume. The equation does not include metal solidification during casting, which of particular importance in ingot casting. The shrinkage size is governed by the relation by [13]:

$$V_S = \alpha_{4t}(t_1 - t_S) + \alpha_V\eta - \beta(t_1 - t_2)\varphi - \beta(t_S - t_2)\eta \quad (2)$$

where: φ – is the coefficient of deformation of solidified crust due to ferro-static pressure, t_1 – is the ingot surface temperature at the end of casting, t_2 – is the temperature of the ingot at the end of solidification.

The above-mentioned relationship not only includes steel solidification during casting, but it also notes the solidified crust deformation. Differences in the shrinkage volumes can be explained in case of ingots of different sizes by the solidified crust deformation. However, accurate representation of the third member of the equation is difficult. According to [14] the equation was modified by taking into account the proportion of steel solidified during casting, leading to the following equation:

$$V_S = \alpha_V + \alpha_{\Delta t}(t_1 - t_S) - 0.5\beta(t_S - t_2)\frac{V_{i+h} - \vartheta_1}{V_{i+h}} \quad (3)$$

2.6 Vertical solidification of the ingot

Solidification of the ingot from the bottom in the vertical direction affects the central uniformity of the steel is shown on Fig.6. A theoretical calculation of the course of vertical solidification of a cylindrical ingot according to equation (4) [15]:

$$h = \frac{r}{2} ln \frac{r}{r - 2k\sqrt{\tau}} \quad (4)$$

Derivation of equation (4) is based on the following simplifying assumption:
- the ingot pad is a flat plate,
- the heat removed in vertical and horizontal directions is calculated according to a parabolic relationship, $\xi = k\sqrt{\tau}$; $Q = \frac{k}{n}\sqrt{(\tau)}\pi r^2$ where n is an empirical coefficient (m^3J^{-1}),
- the volume of solidified metal for the time period $d\tau$ is directly proportional to the amount of heat removed for the same time period:

$$\frac{dV}{d\tau} = n\frac{dQ}{d\tau} \quad (5)$$

$$dV = (\pi r^2 - 2\pi r\xi)dH \quad (6)$$

$$\frac{dV}{d\tau} = (\pi r^2 - 2\pi r\xi)\frac{dH}{d\tau} \quad (7)$$

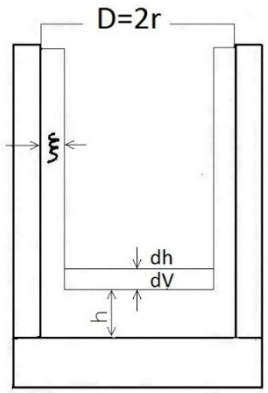

Fig. 6. Scheme of solidifying ingot with designated individual parameters used in the equation

The resulting equation is as follows:

$$\frac{dQ}{d\tau} = \frac{1}{2}\frac{k}{\sqrt{\tau}}\frac{\pi r^2}{n} \tag{8}$$

$$\frac{dh}{d\tau} = \frac{kr^2}{2(r^2\sqrt{(\tau)}-2rk\tau)} \tag{9}$$

After integration and determination of the integration constant from the condition ($t = 0$ is $h = 0$), the resulting equation will be:

$$h = \frac{r}{2}\ln\frac{r}{r-2k\sqrt{\tau}} \tag{10}$$

Difference between the predefined course of vertical solidification according to the probe measurements and the theoretical calculation using equation (10) is determined by sedimentation of equiaxic crystals, which is not taken into account in equation (10).

Conclusion

Some authors [11] utilised model experiments on ingots with sodium thiosulphate, cast into ingot moulds made of Plexiglas, to observe the effect of the ingot mould conicity and slenderness on the course of vertical solidification. An increase in conicity for 45 t forging ingots very significantly improved homogeneity in the axial part, as well as a reduction in the H/D ratio, because vertical solidification significantly slowed. When we look at the curve depicting the vertical solidification process with respect to time, we can conclude that the smaller the curve slope, the better ingot homogeneity in the axial part. Acceleration of vertical solidification in the later stages of the ingot solidification can be explained by the horizontal solidification fronts getting closer to the ingot axis. Efficient and long-term heating of the ingot top (by electric arc or induction) may affect the central part of the ingot by slowing down vertical solidification. Input power must be regulated so that, at the time of the ingot solidification, too intense heating does not result in the creation of a wide two-phase zone of solidification in the ingot axis. This paper described the process of ingot solidification in a model ingot mould when placing the given mould in two positions. The graph show the course of temperatures recorded by three sensors during 40 minutes. At the stearin casting temperature of 58 °C we can observe that inner shrinkage is smaller. Shrinkage could be completely eliminated using a raiser. Material to forming (forging)

processes is supplied in the form of castings, i.e. this is what forming inherently affects. Therefore, it is necessary to deal with this phenomenon that, as soon as at its initial input (first entry), affects the resulting quality of shaped parts.

Research presented in this paper was partially financially supported through realization of projects KEGA 015ŽU-4/2017 and of the project implementation: „Centrum for industrial research and development in the field of light metals and composites“ (ITMS 26220220154) supported by the Operational Programme Research and development funded by the ERDF. The authors gratefully acknowledge this support.

References

1. W. Piekarska, M. Kubiak, M. Vasko, *Numerical estimation of the shape of weld and heat affected zone in laser-arc hybrid welded joints*. Procedia Engineering **177**, 114-120, (2017)
2. L. Jakubovicova, B. Ftorek, V. Baniari, A. Sapietova, T. Potocek, M. Vasko, *Engineering design of a test device.* Procedia Engineering **177**, 520-525, (2017)
3. A. Vasko, M. Vasko, J. Belan, E. Tillova, *Comparison of fatigue properties of nodular cast iron at low and high frequency cyclic loading*. Procedia Engineering **177**, 576-581, (2017)
4. J. Zapoměl, V. Dekýš, P. Ferfecki, A. Sapietová, M. Sága, M. Žmindák, *Identification of material damping of a carbon composite bar and study of its effect on attenuation of its transient lateral vibrations.* International journal of applied mechanics **7** (6), (2015)
5. L. Šmrha, *Crystalization and Solidification of Steel Ingots.* (Praha, STNL, 1983)
6. L. Šmrha, J. Chvojka, *Foundry Letters.* **63 (**9), (1991)
7. L. Šmrha, *Foundry.* **10**, 245-249 (1962)
8. W. James, R. Middleton, *British Foundryman*. January **58**, 36-46 (1987)
9. J. Přibil, *Controlled solidification of steel castings*. (Praha, STNL, 1986)
10. N. Chvorinov, *Giesserei.* **10**, 177-186 (1975)
11. L. Kiesel, K. Smuin, W. Pabst, *Freiberger Forschungshefte.* **6** (B137), 79-92 (1967)
12. N. Chvorinov, *Giesserei.* **11**, 201-208 (1975)
13. J. Nechenedzi, *Litejnoje proizvodstvo.* Moskva, **3**, 14-19 (1982)
14. B. B. Guljajev, *Zatverdevanije i neodrodnost stali*. (Metallurgizdat, Moskva, 1986)
15. L. Kiesel, K. Smuin, W. Pabst, *Freiberger Forschungshefte*. **5** (B137), 81-93 (1985)