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A New Laser-Registered View of the Shrinkage Kinetics of Foundry Alloys

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Abstract

This paper presents a new stand for studying the linear shrinkage kinetics of foundry alloys. The stand is equipped with a laser displacement sensor. Thanks to this arrangement, the measurement is of a contactless nature. This solution allows for the elimination of errors which occur in measurements made using intermediary elements (steel rods). The supposition of the expansion (shrinkage) of the sample and the expansion of the heated rod lead to the distortion of the image of the actual dimensional changes of the studied sample. A series of studies of foundry alloys conducted using the new stand allowed a new image of shrinkage kinetics to be obtained, in particular regarding cast iron. The authors introduce in the study methodology a real-time measurement of two linked quantities; shrinkage (the displacement of the free end of the sample) and temperature in the surface layer of the sample casting. This generates not only a classic image of shrinkage (S) understood as S = f (t), but also the view S = f (T). The latter correlation, developed based on results obtained using the contactless method, provide a new, so far poorly known image of the course of shrinkage in foundry alloys, especially cast iron with graphite in the structure. The study made use of hypo- and hypereutectic cast iron in order to generate an image of the differences which occur in the kinetics of shrinkage (as well as in pre-shrinkage expansion - expansion occurs during solidification).

Keywords: Casting shrinkage, Cast iron, Laser measurements

1. Introduction

In the design of foundry technologies, one of the most important parameters essential for the development of project documentation is the amount of shrinkage of the alloy used. Volumetric and dimensional changes in the metal which fills the mould cavity over a range of temperatures: from the temperature at the time of pouring to the temperature after cooling. During the cooling phase while the metal is still molten, volumetric changes can mainly be observed which lead to the shortening of one dimension, the level of the metal throughout the entire system of cavity, pouring and feeding system. In the case of feeding, during release of excess heat volumetric shrinkage occurs as a lowering of the level of metal in the areas which have been fed. For the purpose of establishing the final dimensions of the casting, an important factor is casting shrinkage, which is of a linear nature and leads to changes in the dimensions of the casting during cooling and solidification of the alloy. Naturally, at this time volumetric changes also occur, which for all alloys apart from cast iron, in which the carbon is at least partially precipitates in the form of graphite, remains in proportion to linear shrinkage (bypassing phase transitions - volumetric shrinkage is approximately three times greater than linear).

The linear shrinkage, commonly known as foundry shrinkage, is one of the primary qualities of every alloy, and should be precisely determined. Otherwise , the dimensions of the pattern

will be incorrect, meaning that the castings formed will also be of incorrect dimensions. Casting shrinkage is defined by Equation 1:

$$\varepsilon_{cast} = \frac{l_{patt.} - l_{cast.}}{l_{patt.}} \cdot 100\% \quad (1)$$

where:

ε_{cast} – casting shrinkage [%],

$l_{patt.}$- length of pattern (specifically, length of the cavity in the mould),

l_{cast} - length of casting after cooling.

Study of the course of foundry shrinkage is conducted at testing stands, the typical construction of which is illustrated in Figure 1 [1÷7].

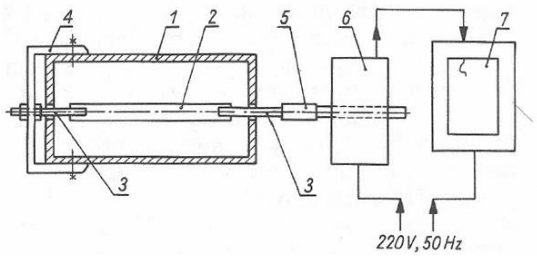

Fig. 1. Diagram of apparatus for determining shrinkage kinetics: (1 – casting mould, 2 – cast bar (ingot), 3 – steel rods, 4 – mounting bracket, 5 – connecting point between steel bar and transducer, 6 – displacement transducer, 7- recorder [1]

Study of the course of shrinkage involves the recording of displacement of the free end of a steel rod (3) shown in Fig.1, embedded in the sample. This solution, making use of intermediary steel rods, is applied in nearly all testing stands, which generally differ from each other in the way in which the rod is mounted, in the measuring equipment fitted to the stand, etc.

The imperfection inherent in this type of solution involves the heating of both intermediary steel rods (3). The thermal extension of the heated rods is counted into the overall dimensional changes of the sample itself – the cast bar (ingot) 2. The courses and ranges of dimensional changes of the rods are proportional to the length and the extent to which they are heated. The inclusion of the dimensional changes of the rods embedded in the sample in the total dimensional changes of the sample alloy delivers results marred by measurement error. In many publications, one can observe in the initial phase of measurements hard to explain "increases" in the length of the sample of the alloy in question [1,8]. Only in the case of cast iron with graphite does the phenomenon of so-called pre-shrinkage expansion occur (Fig.2) during eutectic transformation (expansion occurs during solidification). In the case of the remaining alloys, e.g Al-Si [9] and cast steel [10], there is no physical justification for the increase in length of the measured sample during the process of solidification. In the case of these types of alloys, the increase in the length of the measurement system of the ingot-rods us caused solely by the increase in the dimensions of the heated steel rods, the mounting rods and the free rod, Fig.1. Thus, the results of the measurement of linear shrinkage using the methodology described are invariably marred by a certain level of error generated by this phenomenon.

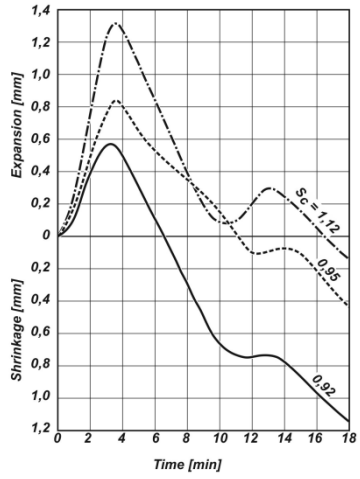

Fig. 2. Impact of eutectic saturation degree Sc of cast iron on shrinkage/expansion kinetics [8]

2. Investigation methodology

The authors propose a modification of the method of studying the kinetics of linear shrinkage in foundry alloys, the idea of which is based on the elimination of the steel rods embedded in the sample ingot. The aim of this modification is obvious – to eliminate (or minimise) the compounding of the lengthening effect of the steel rods on the dimensional changes in the studied alloy ingot. Several changes are introduced into the construction of the measurement stand:

- The new stand is to be equipped with a contactless (laser) system which will measure the displacement of the free end of the measurement sample (ingot).
- During measurement, the temperature of the cooling ingot is recorded, in the surface layer of the sample.
- A steel rod restricting the motion of the other end of the measurement sample is very short (several millimetres) and is attached in a perpendicular plane to the axis of the studied sample.
- To eliminate the impact of dimensional changes of the flask, which becomes heated up in long-term measurements, the measuring system is mounted on an independent frame which hardly gets hot.

Figure 3 presents the concept of the new stand for studying the course of linear shrinkage of foundry alloys. In the new version (Fig. 3), the mould cavity of the ingot to be poured is closed on the measurement side with thin-walled cast-iron spigot (9). During the pouring of the molten metal into the mould, the spigot fuses with the casting of bar (3) at the beginning of the process of solidification in the mould wall region. The countersunk sleeve shape of the stopper on the interior mould walls facilitates its complete fusing with the casting. During measurement of length changes of the sample ingot, the motion of the exterior surface of the stopper is recorded as the ingot cools

using a laser displacement sensor (11). This measurement is of a constant nature, in real time. The course of shrinkage can also be displayed in visual form. The immovable end of the ingot is fixed in place with a short rod (5), which is fused with the flask (1) and frame (2). The laser sensor (11) is attached to the frame (2), remaining separate from the flask. Any changes in the dimensions of the flask do not impact the recorded dimensional changes. Thanks to this solution, the impact of the expansion of elements essential for the operation of the measurement system is restricted to the minimum. The long (several, or even dozens of centimetres) steel rods (5) shown in Fig. 1 have been replaced with elements of several millimetres in length. These, unfortunately, cannot be completely eliminated. The measurement system of the new stand is illustrated in Figure 3.

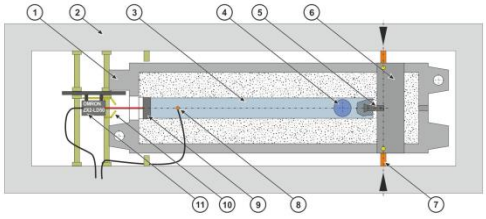

Fig. 3. View from above - diagram of stand for studying the shrinkage kinetics of foundry alloys using laser technology: 1 – flask; 2- frame, 3 – casting of bar; 4 – down sprue; 5 – immovable rod (fixed); 6 – rod block; 7 – connection between immovable end of sample and flask with frame; 8 – thermocouple; 9 – metal spigot at movable end of sample; 10 – laser cover with slot; 11 – laser displacement sensor

3. Results of own investigations

The studies described in this article involved the conduct of a series of measurements, for the purpose of verifying the new conception for the study of shrinkage and the new measuring apparatus. Two types of alloys were selected for testing: an alloy from the Al-Si group and cast iron with both hypo- and hypereutectic compositions. In each test, the course of shrinkage and simultaneous changes in temperature of the sample ingot (bar) were recorded. An attempt was made to generate a precise description of the course of shrinkage as a function of cooling time, but also to obtain an image of the course of dimensional changes of the ingot as a function of the temperature of the alloy.

The measurement stand is pictured in Figures 4 and 5. Laser measurement of shrinkage (of the displacement of the free end of the sample) is a contactless measurement, on the one hand eliminating the problem of heating of the rods joining the sample to the displacement sensor, and on the other hand making the measurement very simple and precise.

Fig. 4. Pouring of the mould for study of linear shrinkage using laser technology

a) b)

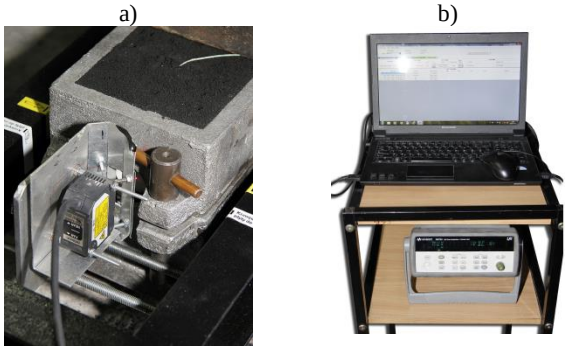

Fig. 5. Mould with laser sensor for study of linear shrinkage of alloys (a) and a set of recorded data (b).

Initial trials of the new method of studying shrinkage kinetics were conducted for an AK11 alloy containing roughly 11% Si (a eutectic alloy). In each measurement, the course of temperature changes in the mould wall region and the course of dimensional changes in the cooling sample. The image thus recorded of both these quantities is shown in Figure 6. At the very beginning of the measurement, it can be seen that there is a slight increase in the dimensions of the sample, which should be attributed to the heating of the cast iron “stopper” which seals the mould cavity. In the described version of the construction of the stand, this stopper was approximately 3.0 mm thick, and when heated to the temperature of the casting sample (nearly 700°C), its dimensions slightly increased. If the temperature of the cooling sample at any given moment is assigned to the displacement of the free end of the sample, then the image shown in Figure 7 is obtained. Based on this correlation, the precise temperature at which the shrinkage process of the sample ingot begins can be determined. In the sample studied, this was a temperature below 570 ÷ 575°C, thus after completion of the solidification of eutectic systems, as can be seen in Figure 6.

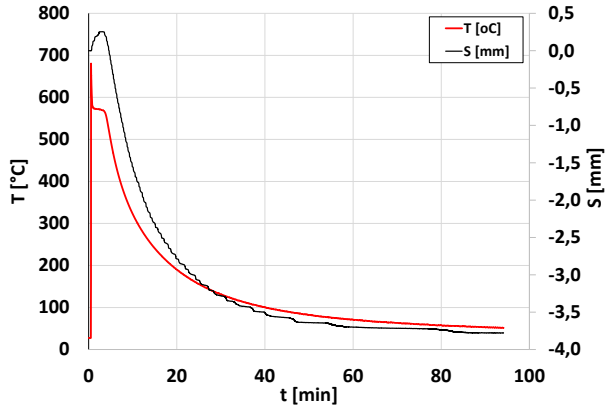

Fig. 6. Course of temperature and size change in cast bar (ingot) during study of shrinkage of the AK11 alloy

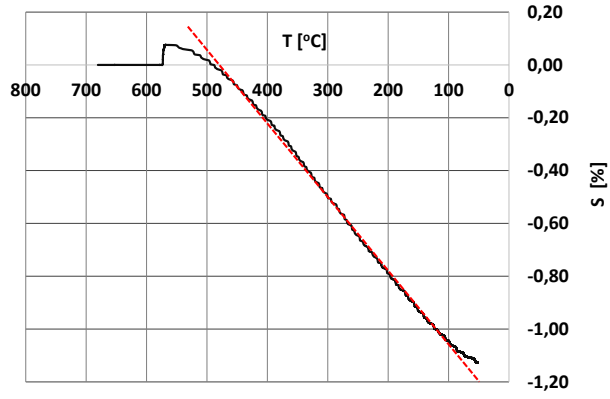

Fig. 7. Course of linear shrinkage of AK11 alloy as a function of temperature

The linear shrinkage of the AK11 alloy as a function of temperature for most of the temperature range displays a course which is nearly linear (Fig.7). In the first phase of cooling (above ~ 470°C), however, there is no proportion between drops in temperature and changes in dimensions (shrinkage) of the sample. The temperature drops fairly quickly, and the dimensional changes are disproportionately smaller. It may be that resistance of shrinkage in the sand mould is at this time greater than the strength of the alloy, which at this temperature range is still highly malleable. In this situation, within the described temperature range the deformation is not entirely elastic, but is of an elastic-plastic nature. In the final phase of cooling, the opposite situation can be observed when compared to the higher temperature range. The sample shrinks disproportionately quickly compared to drops in temperature. These deviations are, however, relatively slight. A problem which remains unsolved is the beginning of the shrinkage of the sample, whether this occurs at the beginning of solidification in the mould wall region (as the authors of this article believe) or perhaps during the formation of the skeleton of the primary structure throughout the entire ingot ?. The development of an answer to this question will require further research work.

In studies of the shrinkage kinetics of cast iron, a series of measurements was conducted of iron compositions which were both clearly hypoeutectic and clearly hypereutectic. For comparison purposes, the two chemical compositions provided in Table 1 were selected for analysis and description. The iron from smelting 5 had a composition with a S_C coefficient of $S_C = 0.799$, while that from smelting 6 was $S_C = 1.075$.

Table 1.
Chemical composition of cast iron from smelting 5 and 6

No	% C	% Si	% Mn	% P	% S	S_C
5	3.01	1.46	0.08	0.06	0.012	0.799
6	3.58	3.35	0.03	0.04	0.001	1.075

Figure 8 shows the recorded courses of changes in the dimensions of the cooling and solidifying cast iron from smelting 5 as well as the courses of temperature changes recorded with two thermocouples. The use of two thermocouples was dictated by the nature of the study, whose aim was to test the new measurement stand. The temperatures recorded vary only slightly. The temperature measurement point was located in the region of the mould walls, taking into consideration the fact that it is in this region in the initial phase of solidification that the forming skin begins to shrink earliest and enters into a solid states, and thus it is this region which should be linked to a description of the course of shrinkage.

Parallel and simultaneous (real time) recording of the changes in temperature and course of shrinkage allow for the assignment of characteristic points along a shrinkage curve for specific temperature values. This can be achieved by analysing the chart in Figure 8 or by simply constructing an equation: changes in the dimensions of the sample as a function of (S = f (T), as is shown in Figure 9. The increases in dimensions of the sample begin at a temperature of about 1050°C. This is the range of solidification of graphite eutectics in unbalanced conditions, and the changes in the structure of the metal are associated with the speed of cooling. The temperature at which the greatest increase in length of the sample occurs can be determined during pre-shrinkage expansion on the loop of dimensional changes of the sample. This is a temperature of roughly 1070°C, as can be seen in Figure 9.

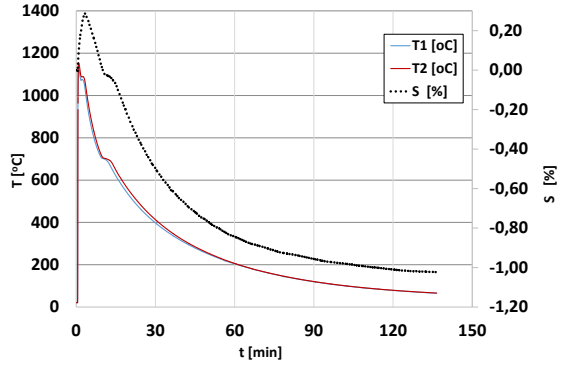

Fig. 8. Smelting 5 (S_C =0.799) – source data for measurement of course of shrinkage (laser measurement) and measurement of temperature

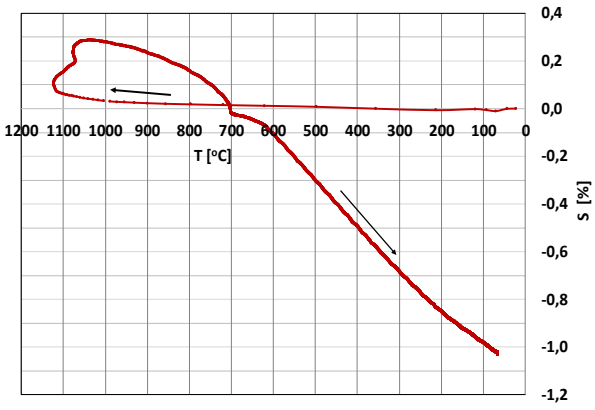

Fig. 9. Course of size changes of sample of free shrinkage as a function of temperature, smelting 5

The course of shrinkage in the temperature range of eutectic and eutectoid transformation has a clearly non-linear nature. At the temperature of the eutectoid transformation for this type of low S_C cast iron, a waypoint can be identified at which the sample "without changing" its temperature additionally shrinks. At such low S_C, the iron has a perlitic structure. Thus, the precipitation of perlite is accompanied by an additional shrinkage of the iron.

Another image of the course of linear shrinkage can be observed in the case of hypereutectic cast iron, Figures 10 and 11. Although in the range of eutectic transformation the changes are similar to the changes in hypoeutectic cast iron, there is nonetheless a decidedly different course of shrinkage in the range of eutectoid transformation, Figure 10. It can be seen that, as during eutectic transformation, at a stable temperature (in this case ~1145°C) the sample's length increases. This phenomenon has been recorded by other authors studying iron alloy shrinkage [1, 8]. Similarly, at the nearly constant temperature of eutectoid transformation, a clear increase in the length of the sample can be observed. The structure of the ferritic matrix is forming; therefore the carbon from austenite diffuses to the previously formed graphite nodules, leading to an increase in the volume and linear dimensions of the sample.

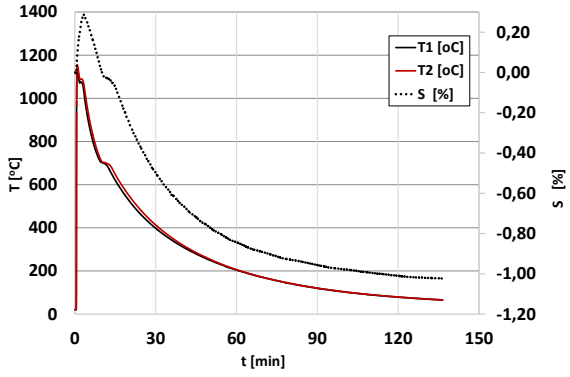

Fig. 10. Smelting 6 (S_C = 1.075) – source data for measurement of course of shrinkage (laser measurement) and measurement of temperature

Carbon, occurring as a free phase in cast iron, in the form of graphite occupies a greater volume than carbon in austenite or ferrite. It is for this reason that the observed increase in the length of the sample, as well as its volume, occurs.

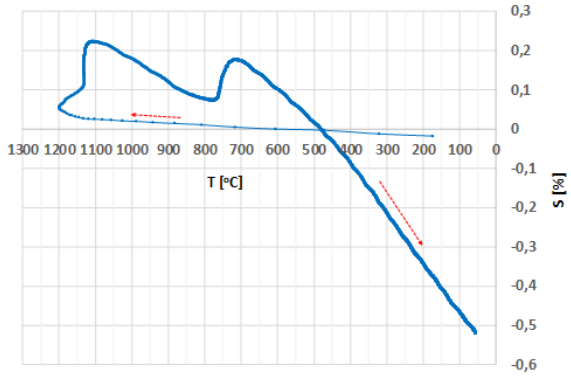

Fig. 11. Course of size changes of cast iron sample of free shrinkage as a function of temperature, smelting 6

The study of two types of cast iron, hypo- and hypereutectic, which was conducted demonstrates that eutectoid transformation plays an important role in the course of foundry shrinkage, Fig. 12. Cast iron with a ferritic structure (S_C = 1.075) increases. First of all, the final shrinkage is visibly less (S = 0.50% instead of roughly 1.0%), Figures 8 and 10. In terms of the tendency to the formation of shrinkage-related defects, including mainly micro porosity, ferritic iron has a greater capacity for self-feeding and lesser tendency for the formation of porosity. This relation is known to practitioners, but the observed variation is more generally attributed to greater pre-shrinkage expansion (eutectic transformation) than to expansion during eutectic transformation. This new image of kinetics introduces new elements to the state of knowledge on shrinkage phenomena in foundry alloys, in particular cast iron.

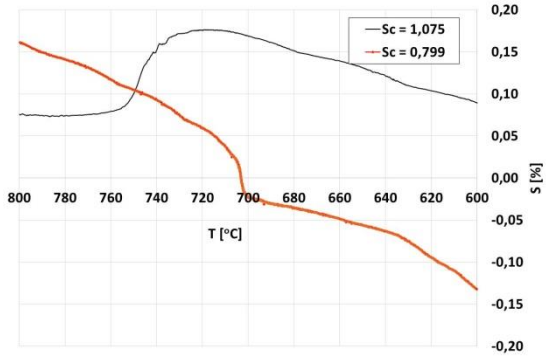

Fig. 12. Courses of free shrinkage of two types of cast iron in terms of eutectoid transformation

4. Summary

The results of the study presented here are the first results obtained with the new research stand for the study of the kinetics of solidification and solid shrinkage of foundry alloys, designed and developed by the authors. The laser (contactless) measurement is more precise than measurements made with the use of intermediary rods; one stabilising the immovable end of the sample and the other transmitting to the displacement meter the movement of the free end of the sample. The authors are aware that the first measurements are imperfect, but the results obtained are interesting enough that they have been used as the topic for this article.

Measurement with the use of a laser displacement sensor is very convenient to use, and as the results show, the record of displacement generated is continuous and the record of displacements is continuous and is not burdened with errors resulting from the thermal expansion of intermediate elements.

Feeding of cast iron castings requires precise knowledge of the courses of linear (solid) and volumetric shrinkage [1, 11, 12]. These vary depending not only on the composition, but also as has been mentioned before, on the structure of the cast iron. The structure of cast iron is associated with its chemical composition, but also depends on the speed of cooling. The tests conducted concerned the measurement of samples with a standardised diameter. If, however, the casting (or sample of a different diameter) involves a cooling process which is slower or quicker than in the standardised ingot, then its total shrinkage as well as the course (kinetics) of this shrinkage will display different values.

The interesting results obtained and the repeatability of these results using the new version of the stand for contactless (laser) study inclines the authors to continue these studies.

5. Conclusions

The performed investigations allow several conclusions to be drawn:

- Measurements of the courses of foundry alloy shrinkage and the kinetics of this shrinkage can be conducted using laser displacement sensors.
- Laser (contactless) measurement of the displacement of the free end of the sample for testing of the kinetics of shrinkage eliminates errors committed in previous works as well as the thermal expansion of elements of the measuring system (such as displacement transmission rods) and the supposition of such changes with the shrinking of the tested sample.
- A new image of the kinetics of shrinkage (S = f (T) is obtained with real-time measurements of two linked quantities, i.e. the temperature of the sample and the changed in dimensions resulting from a decrease in temperature and phase transformations.
- Hypereutectic cast iron, which solidifies in a bar of ø 30mm as a ferrite, displays substantial capacity to expand in solid form with the temperature range of eutectoid transformation. This phenomenon (expansion) does not occur in the case of cast iron with perlitic structure.

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References

[1] Jankowski, W. (1976). Pre-shrinkage expansion and total casting shrinkage of ductile iron. *Foundry Review.* 26(1), 7-10, (in Polish).
[2] Pucka, G. (1993). The strain gauge device for continuous measurement of free linear contraction with computer data analysis. II Conference „Computer Methods in Foundry". Bytom-Gliwice, (in Polish).
[3] Pucka, G. (1994). Influence of cooling rate on the free linear contraction of selected metals and alloys. *Material Engineering*. 15(3-4), 91, (in Polish).
[4] Mutwil, J. (2000). Device for the investigation of casting stresses. *Solidification of Metals and Alloys*. 2(44), 503-508.
[5] Mutwil, J. (2000). Linear contraction of aluminium and aluminium-silicon binary alloys in the metal mould. *Archives of Machine Technology and Automation*. 20(1), 107-116, (in Polish).
[6] Mutwil, J. (2003). Stand for investigation of linear contraction and shrinkage stresses in castings. *Archives of Foundry.* 3(8), 287-292.
[7] Alonso G., Stefanescu D. M., Suarez R., Loizaga A. & Zarrabeitia G. (2014). Kinetics of graphite expansion during eutectic solidification of cast iron. *International Journal of Cast Metals Research.* 27(2), 87-100.
[8] Nandori G., Bako K. (1972). Untersuchungen uber die eutektische Ausdehnung und die Ausdehnungkrafte von Gusseisen mit Kugelgraphit. *Giesserei Praxis.* 23(22), 389-396, (in German).
[9] Pucka, G., Śleziona, J. & Żak, W. (2000). Solidification and linear shrinkage of composite in the AK12 aluminum alloy matrix reinforced with Al_2O_3 and SiC particles. *Solidification of Metals and Alloys*, 2(44), 311-316.
[10] Kniaginin, G. (1977). *Cast steel, metallurgy and foundry*. Katowice: Wyd. Śląsk, (in Polish).
[11] Karsay, S.J. (1980). Risering methods for gray and ductile casting. *AFS International Cast Metals Journal*. 5(4), 45-51.
[12] Zych, J. (2019). *Ductile iron - risering of castings, mould pouring*. Krakow: Akapit, (in Polish).