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Measurement of Heat Transfer in a Sand Mould Foundry - Optimisation of Cooling Time for Cast Iron and Ductile Cast Iron Mass Castings

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Cast iron with nodular graphite is one of the most important structural materials that exhibit really good mechanical properties already in the as-cast condition. Nowadays, cast iron with nodular graphite is used in many areas of the manufacturing industry, the most widespread being in the engineering and automotive industries. The applicability of this material for construction purposes is mainly due to its mechanical properties, which are close to those of steel, but the production cost of cast iron is lower. This experiment was aimed at optimizing the production of ductile iron castings in the casting pits so that the foundry could produce ductile iron castings in the casting pits. Therefore, the optimization of the moulding compound database material was carried out in numerical simulation and at the same time, the heat transfer measurement of the foundry sand mould was carried out.

Keywords: Ductile iron, Heat transfer, Measurement

1 Introduction

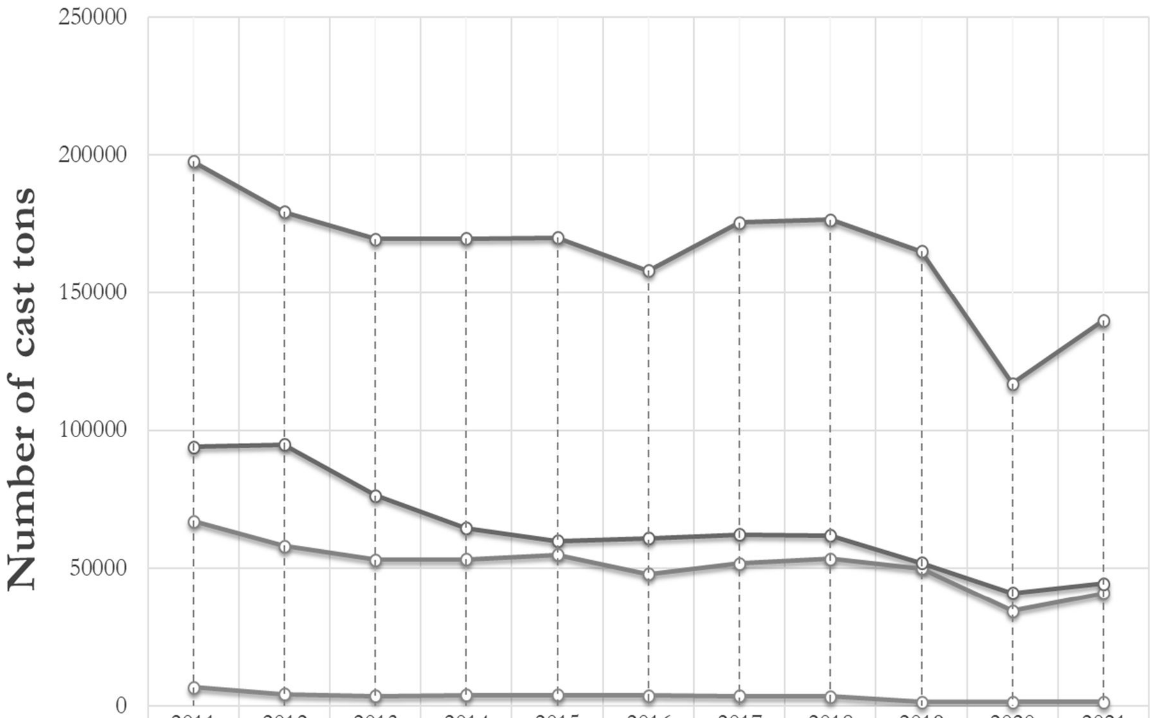
Cast iron with nodular graphite is one of the most important structural materials that exhibit really good mechanical properties already in the as-cast condition. Nowadays, graphite cast iron is used in many areas of the manufacturing industry, the most widespread being in the engineering and automotive industries. The first production of cast iron with nodular graphite dates back to the 1940s, when it was first produced independently at two scientific sites. The British Cast Iron Research Association (BCIRA) laboratory was one of these scientific sites where graphite cast iron was produced. Here, researchers Williams and Henton Morrough attempted to influence the shape of graphite in cast iron International Nickel Co. (INCO) company from the USA was the second site where the graphite bead cast iron was produced. At this company, Keith Millise and his team of workers attempted to replace expensive nickel in the production of abrasion-resistant cast iron with other metals in the 1940s [3]. It was here that magnesium metal was chosen as a replacement. In this way, another possibility of modifying graphite into its spherical form was invented. Not long afterwards, licenses were sold and the production of this new type of cast iron began to be tried in many countries that had sufficiently advanced industries. One of these countries was the Czech Republic.

Just for the record, it should be mentioned that spherical graphite has been found in nature in the eutectic rock pigmetite, as reported by GORSHKOV [2]. It is not known who and how it was possible to produce cast iron with spheroidal graphite, but the clear structure of this cast iron from the casting of a cast iron cannon, which, according to IVANOV [3], is said to date from the 16th century. In addition to these findings, according to publication [4], the method of production of quality cast iron is mentioned, which, according to our current knowledge, gives a prerequisite for the formation of nodular graphite.

The industrial production of cast iron with nodular graphite began in 1948, but the first test casting took place at the end of the Second World War and subsequently afterwards. Scientific work at that time mainly investigated the nodulation effect of cerium and magnesium on the excluded graphite. In our country, the first melting of cast iron with nodular graphite was carried out in 1949 and 1950 in several Czech foundries [5]. Between 1951 and 1953, trials of cast iron production in pressure pans, patented by V. Otáhal [5]. After many tests, magnesium was chosen as the more suitable of the two elements for these purposes. Its main advantages were reliability and affordability, for these reasons it appeared to be a suitable candidate for the production of LKG. However, the use of magnesium presented certain pitfalls. These were mainly its violent reaction with the liquid metal, which could be mitigated in two ways [6].

In the early days of production, operational tests and production were carried out using a dipping bell, where pure magnesium was dipped into a melt of suitable chemical composition. This method has since been replaced by pouring methods. Another frequently used method of modification was by means of pressure pans, where the modification with magnesium was carried out at elevated pressure. Another important milestone in the production of LKG was the use of autoclaves, in which an entire pan of liquid metal of a particular chemical composition was placed. This method is not much used nowadays [6]. The second method of reducing the violent reaction between magnesium and melt was based on reducing the magnesium content of the modifying additive by replacing it with other elements such as Ni, Cu, Si. Of these elements, it was silicon that made this modification method the most widespread, resulting in the well-known FeSiMg prealloys, which are not only still used today, but also have the greatest application in the production of LKG [6,8,9].

Although it cannot be stated that the production of cast iron with nodular graphite in the Czech Republic is currently experiencing an increase, on the contrary, in recent years the volume of its production has rather stagnated, it is still a very popular material that has applications in many industries (automotive, food industry, energy, etc.). Fig. 1 shows the production of individual iron alloys in the Czech Republic from 2001 to 2018, [7].



	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
malleable cast iron	6951	4307	3722	4100	4000	3800	3760	3500	1500	1500	1500
spheroidal cast iron	67025	58058	53193	53352	55000	48000	51850	53500	50000	34500	41000
grey cast iron	197666	179394	169456	169654	170000	158000	175450	176500	165000	117000	140000
steel	94013	94929	76380	64606	60000	61000	62260	62000	52000	41000	44500

Fig. 1 *Production volume of selected ferrous alloys in the Czech Republic between 2011 and 2021 [4,5,6]*

The applicability of this material for structural purposes is mainly due to its mechanical properties, which are close to the mechanical properties of steel, but the production cost of cast iron is lower. This means that cast iron with spheroidal graphite has mechanical properties somewhere between cast iron with flake graphite and steel. Unfortunately, this does not only apply to the mechanical properties, but also to the technological ones - specifically foundry properties such as tamping or the tendency to form stagnation and dilution. Cast iron with nodular graphite is more technologically demanding and requires more attention than cast iron with flake graphite. This is even more true for the preparation of large quantities of melt for the production of castings of cast iron with spheroidal graphite [10,11]. The requirements for both metallurgical quality and mechanical properties are continuously becoming more stringent, and therefore simulation programs are nowadays used in many foundries to control the production technology. Thermal analysis, for example, can serve well for controlling the metallurgical quality of the metal [12,13].

At the beginning of 2022, the foundry was facing the same problems as most other foundries; work was beginning to overflow, delivery times were getting longer and it was necessary to produce faster. This problem was most pronounced in the castings that are produced in the casting pits, as these castings have a very long cooling time, which so significantly affects the production time of these castings. According to the foundry's long-standing practice, these mass castings were removed from the casting pits on the basis of a simple rule, namely 1 tonne of casting weight equals 1 day of cooling time.

Another intention of the foundry was to expand the production of mass castings (approx. 8-10 tons) from cast iron with nodular graphite, and since the foundry does not have tall buildings and therefore no high crane runway, this precludes the possibility of using large moulding frames, because the low crane runway would make it impossible to manipulate (turn) the frames during moulding, which is why the production of such castings would also have to be located in the casting pits, where there were already major capacity problems. It was therefore necessary to find a solution to make the existing production in the casting pits as fast and efficient as possible.

Of all the processes of casting production - production of the foundry mould, production of cores, placing cores in the foundry mould, casting, cooling and dressing of the casting, the most time-consuming is the cooling of the casting. In terms of time, the other processes are negligible compared to the cooling of the casting. Therefore, if the intention is to reduce the overall production time of the casting and make it as efficient as possible, it makes sense to focus on the cooling time of the casting and look for reserves there and that is exactly what has been done.

2 Optimization of cooling time for cast iron and ductile cast iron mass castings produced in casting pits

In the foundry there was an old dogma about the cooling of the casting, that one tonne of casting weight is equal to one day of cooling in the sand mould (which is in the casting pit). This dogma first had to be disproved and therefore heat transfer measurements were made in the foundry sand mould.

Fig. 2 shows three different castings which are exactly the same in terms of the technological design, the only difference being their weight and length. Thus, according to the old rule of thumb regarding the cooling of castings, the largest one should be in the casting pit for 14 days, the middle one for 12 days and the smallest one for 11 days. Logically, this is nonsense, the castings must cool in about the same amount of time, the difference in cooling between them may be on the order of hours, but certainly not on the order of days.

But this had to be proven first, so measurements were made, the results of which are presented on the following pages.

The middle variant of the three casts in Fig. 2 was chosen for the experiment. This means 12 tons of mass that should be refrigerated for 12 days. As can be seen in Fig. 3, both the sides and the bottom of the casting are is formed by the cores. A total of 3 K-type thermocouples were used to measure the temperature throughout the cooling period of the casting.

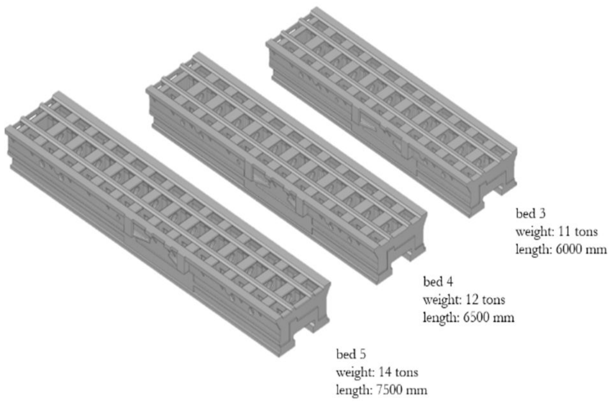


Fig. 2 *Castings of the bearings that were the subject of the experiment, the material of the castings is EN-GJL-300*

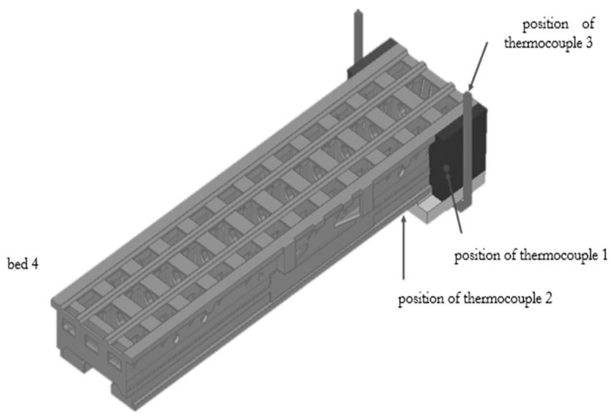


Fig. 3 *Middle variant of casting 4 - locations of individual thermocouples*

The positions of the individual thermocouples can be seen in the section in Fig. 4. The first thermocouple was placed just behind the side core, the second thermocouple was placed at the bottom of the mold also below the core.

In Fig. 2 and 4, the construction of the closed steel section with a square cross-section is also clearly visible. This welded steel structure, which has been named the waste heat removal element-abbreviated as cooling element, was formed in the mould in the casting pit at one point. This cooling element was used to admit pressurised air throughout the cooling period. A third and final thermocouple was therefore placed at the outlet of this profile to allow the temperature coming out of the profile to be sensed.

Individual photographs of the thermocouple or cooling element formation are then also shown in Fig. 4, where the position of thermocouple 2, which was located at the bottom of the casting pit below the core, can be seen in Fig. 4a), b) shows thermocouple 1, which was located on the side of the casting (also behind the core), Fig. 4 c) shows the pressure air inlet to the cooling element and Fig. 4 d) shows the last thermocouple 3 at the cooling element outlet.

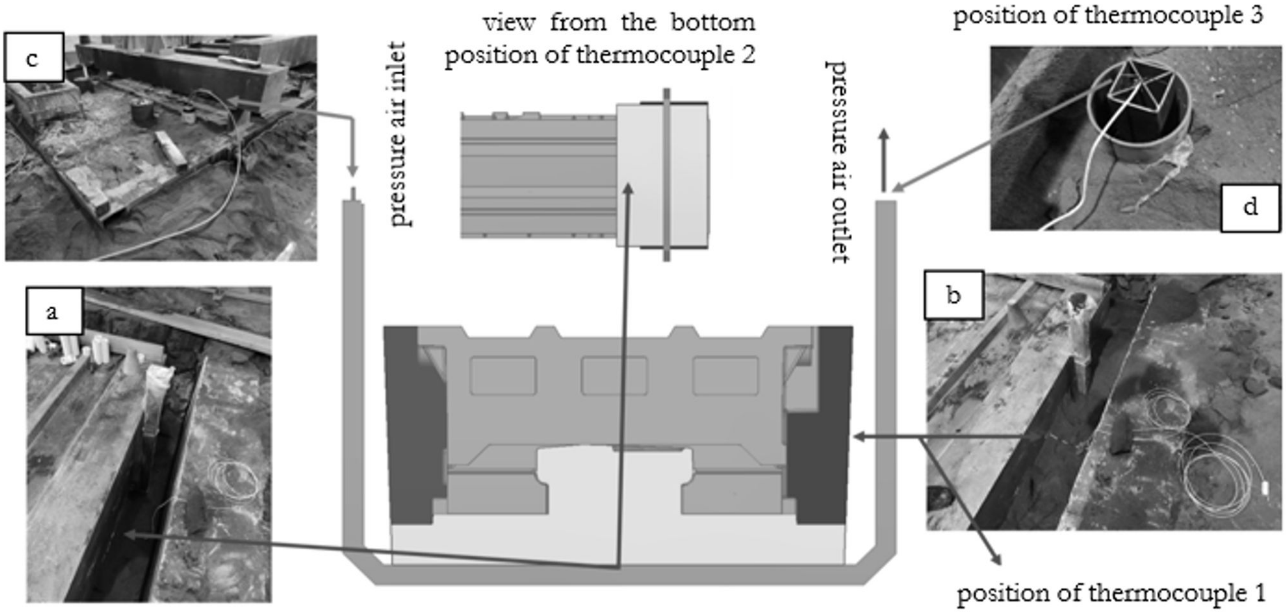


Fig. 4 *Middle variant of casting 4 - locations of individual thermocouples*

The measuring station was very simple. The laptop and the data bus to which the thermocouple wires were connected were enclosed in a paper box and the whole box was then in a metal cabinet next to the casting pit to prevent as much dust as possible from reaching the electronics. The measurements took a total of 8 days during which the temperature from all three thermocouples was recorded every 15 minutes.

Fig. 5 *Measuring station - laptop + data bus*

A drawing of the waste heat removal element used in the experiment is shown in Fig. 6.

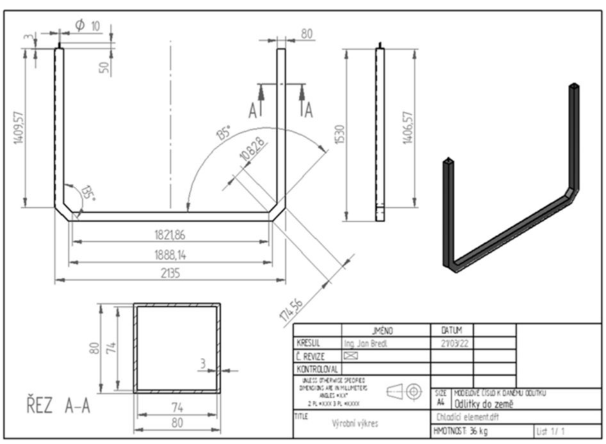


Fig. 6 *Drawing of the waste heat dissipation element*

Fig. 7 shows a graph with the outputs from the individual thermocouples. The blue curve shows the temperature waveform from the thermocouple that was on its side, the orange curve shows the temperature waveform from the thermocouple that was on the bottom of the sand mould. The grey curve thus logically remains on the thermocouple that was at the exit of the cooling element. The temperature coming out of the cooling element was about 60°- 65° C, about in the middle of the grey curve, you can see the temperature rise to about 100°C, this was due to the fact that on Friday afternoon the supply of pressurised air was cut off as the last shift shut down all the compressors. The following Saturday shift then turned the compressors back on and the supply of pressurised air was restored, as shown by the drop in the grey curve, and then the Saturday shift switched all compressors off again on the way out and the temperature rose again. The supply of pressurised air to the heat extraction element was therefore intermittent, hence the temperature fluctuations on the grey curve. As I mentioned, the measurements were taken over 8 days and the temperature was recorded every 15 minutes.

To determine the cooling time of casting 4, a simulation of a very similar part in terms of design and weight was used to save time. Internally, the foundry has set a safe temperature of 300°C for the castings to be hammered out. As can be seen, at a casting temperature of 300°C, the temperature of the area where thermocouple 1 (on the side) was placed during the experiment is 188-206°C, see Fig. 8. These temperatures were reached according to the measurements on day 7 after casting. The casting was not removed for safety until the 8th day after casting and immediately after removal the temperature of the casting was measured using a pyrometer.

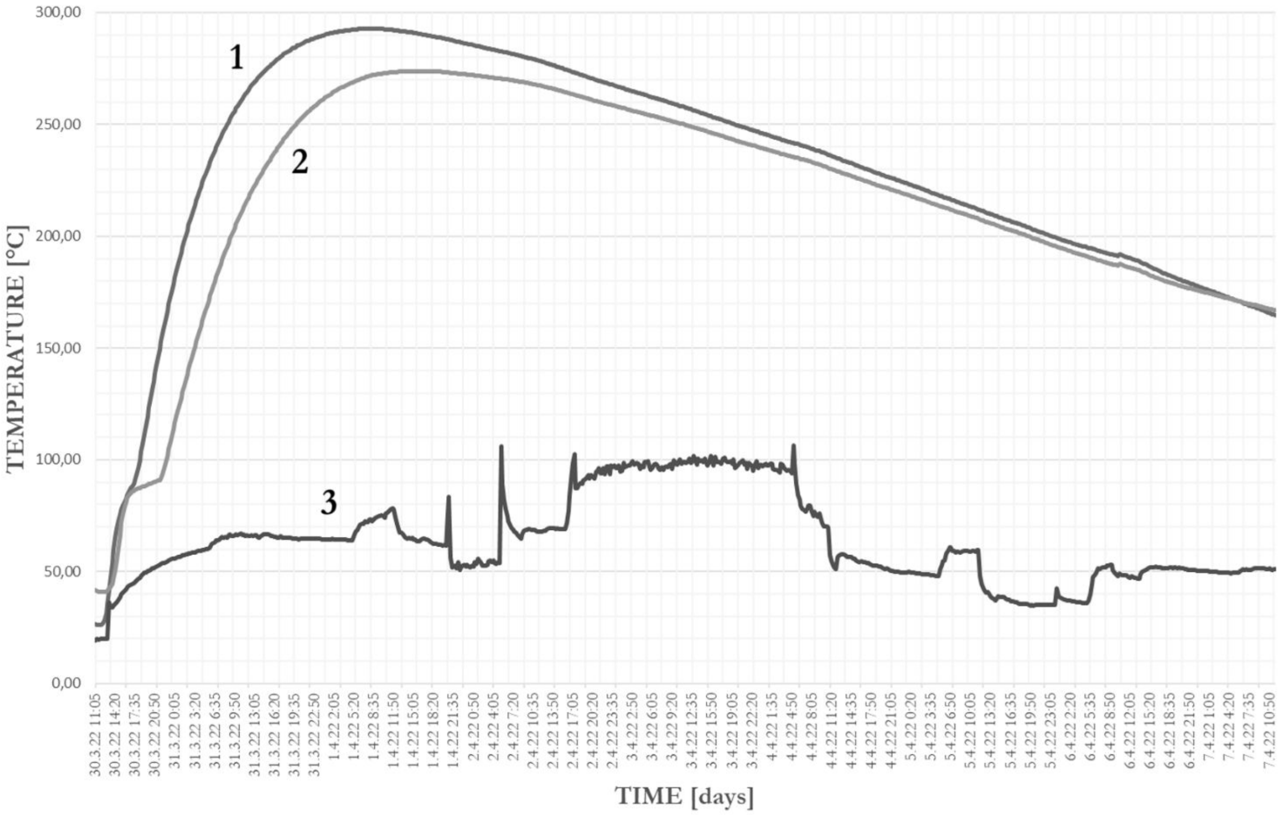


Fig. 7 *Temperature record from thermocouples 1, 2, 3 (1 – termocouple 1; 2 – termocouple 2; 3 – termocouple 3)*

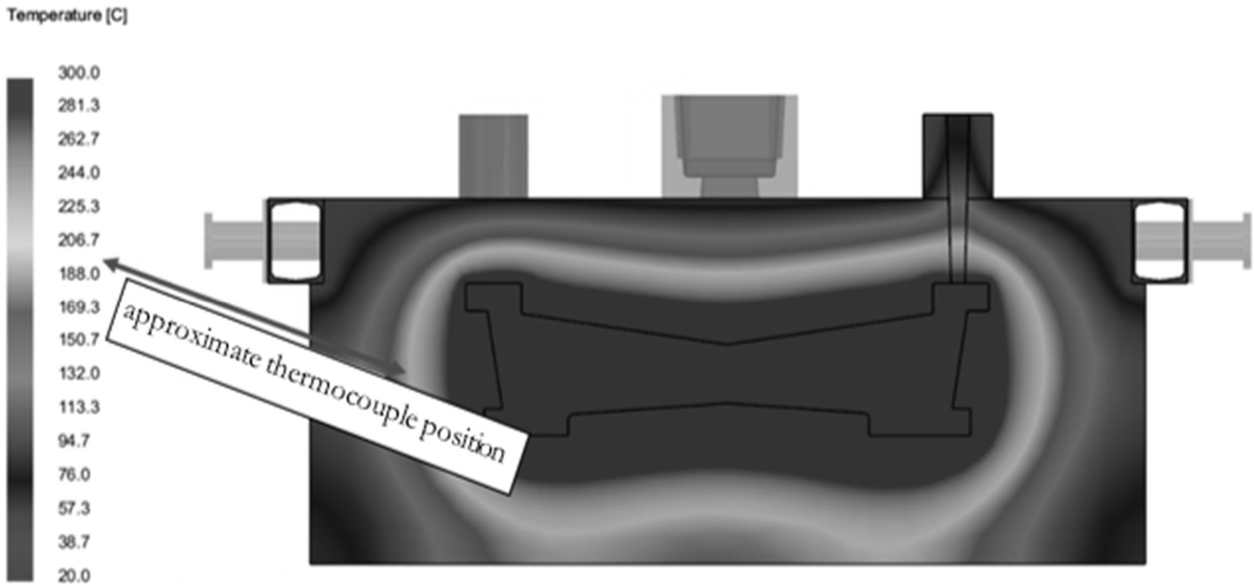


Fig. 8 *Comparison of the simulation with the approximate position of thermocouple 1 in the experiment*

The temperature of the casting was measured using a pyrometer at about 10 places - mainly on the sides and bottom of the casting. The measured values ranged between 145-180°C. This measurement therefore confirmed the accuracy of the simulation. The measurement of the casting temperature using the pyrometer is then shown in Fig. 9.

The original assumption regarding the cooling time was confirmed by this experiment. However, it is not realistic to make such measurements for every other casting. Therefore, in order to effectively use the simulation to calculate the cooling time of material castings in general, it was first necessary to optimize the database material of the furan molding compound. The measured data was used and compared with the cooling times of selected points from the simulation. Gradually, the parameters of the forming mixture in the simulation were adjusted so that the cooling time evolution was as close as possible to the reality measured in the experiment. In Fig. 10, the results of all the test simulations that were performed to obtain the optimized furan molding compound material are shown. Thus, each curve represents one simulation.

Fig. 9 *Temperature measurement of the casting using a pyrometer immediately after its removal from the sand mould (pit face)*

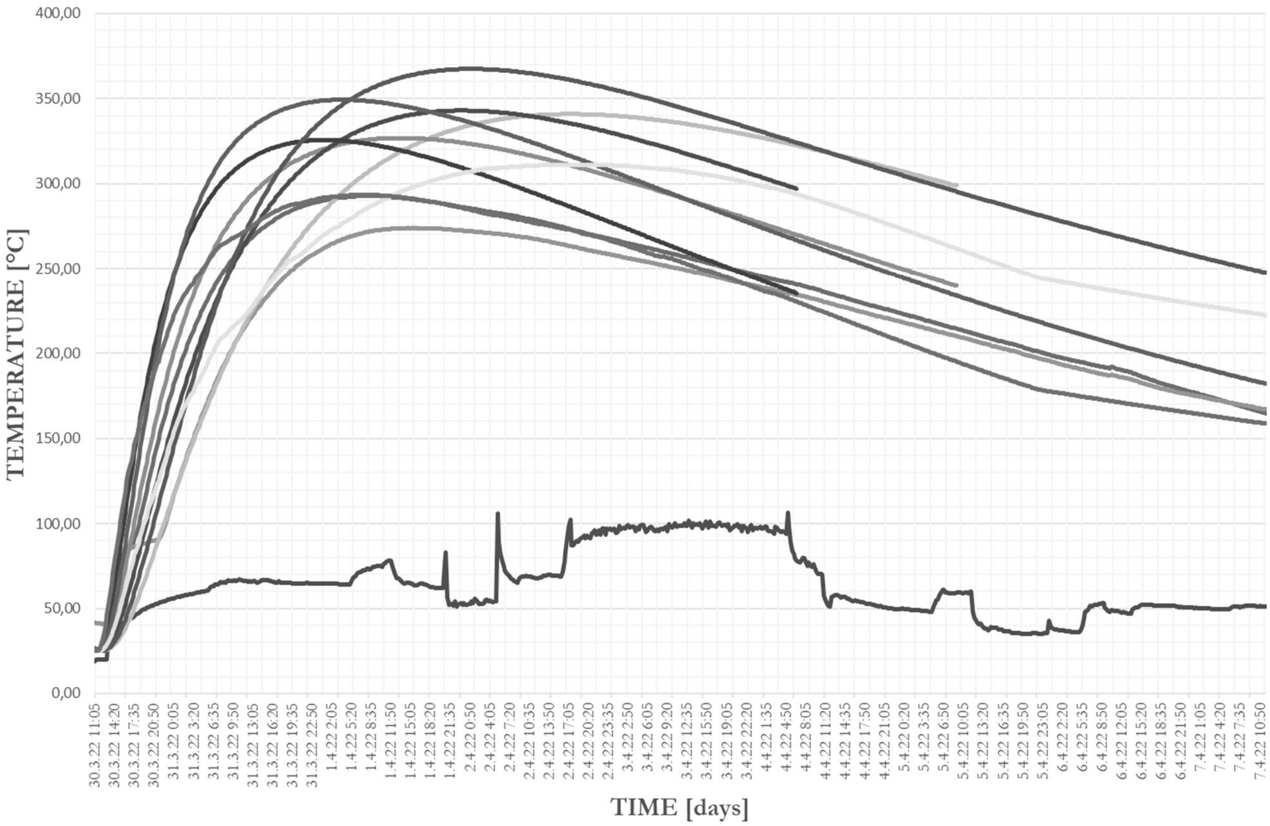


Fig. 10 *Material optimization of the sand furan mixture in the ProCAST simulation program*

The result can then be seen in Fig. 11, where a graph is shown already with the resulting curve after the final optimization of the sand molding mixture. The blue curve in the graph shows the temperature waveform from the thermocouple that was placed on its side in the experiment. The green curve then represents the temperature waveform from the same location from the simulation with only the modified molding compound material. As can be seen, both curves have very similar waveforms. An optimised moulding compound material is now available to obtain the most accurate values for the cooling time of the solid castings.

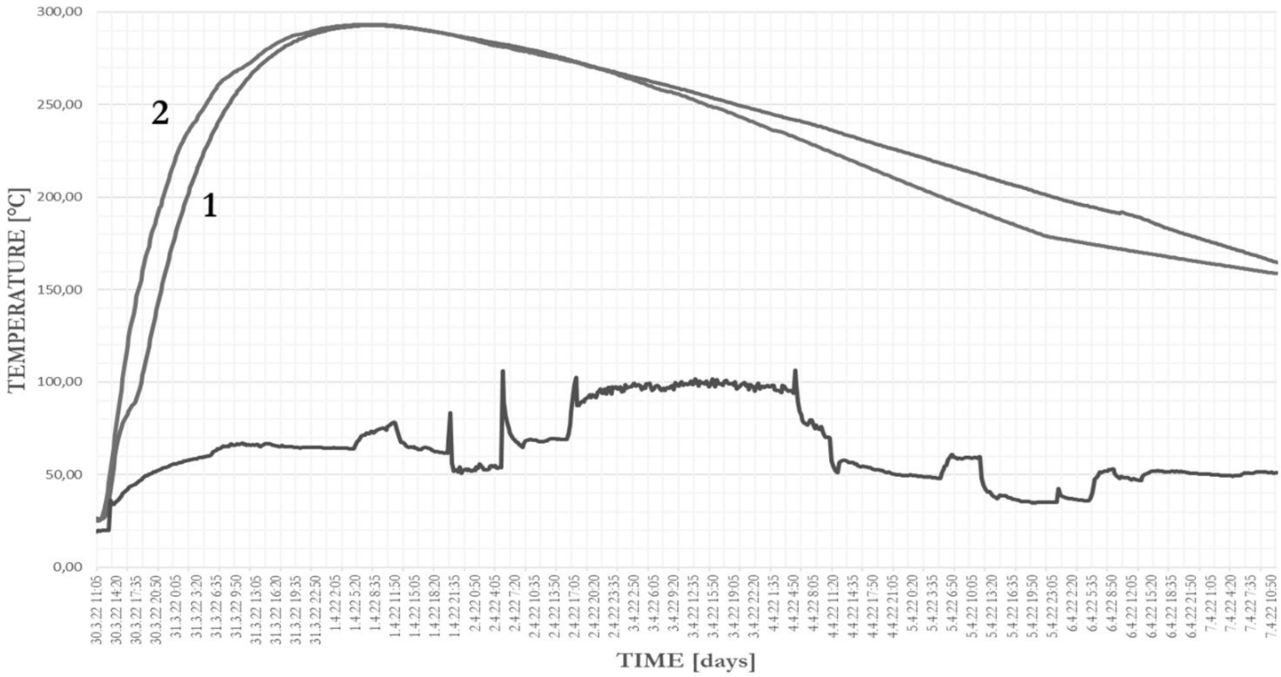


Fig. 11 *Comparison of the temperature waveform from thermocouple 1 (1) with the optimized material from the ProCAST simulation (2)*

3 Element with waste heat dissipation

The measurement results from this experiment have great potential and therefore there is a possibility to use the measured data and further develop the waste heat removal element. In the experiment, the heat sink element was placed in only one part of the casting. Now, in the simulation, the heat sink element is extended over the whole mould to check whether such an element will not have a negative thermal effect on the casting, which can be seen very clearly in Fig. 12, where Fig. 12 a) is the result of the simulation using the heat sink element and Fig. 12 b) is the result of the simulation without the heat sink element. As can be seen in the figures, the bottom of the mould receives the highest heat load, but more importantly, when the heat dissipation element is used, the casting is not negatively affected thermally and has a uniform temperature. The lower heat load goes to the bottom of the mould and this is where further potential for improvement can be seen, namely less thermal stress on the concrete bottom of the casting pit, leading to faster reuse - simply put, the casting pit will cool down sooner as the accumulated waste heat at the bottom of the mould will be dissipated away. In the winter months, this waste heat can then help heat the foundry hall.

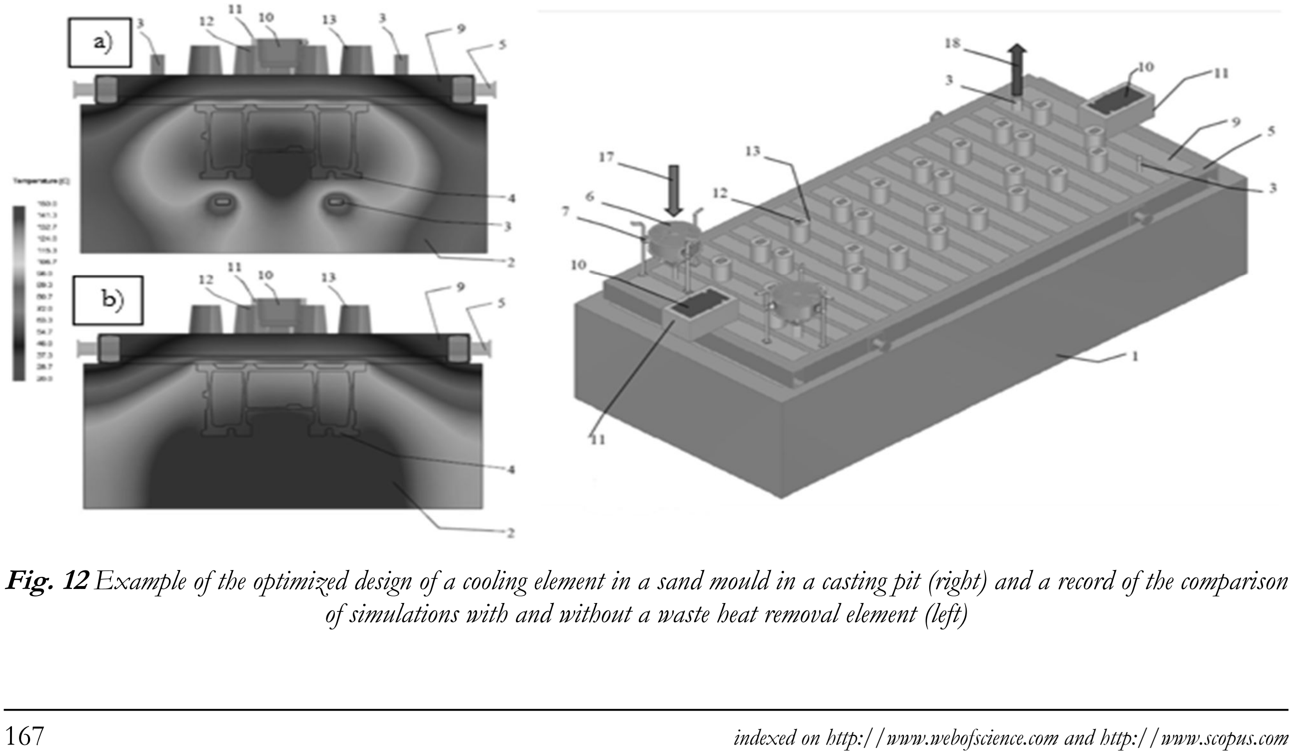


Fig. 12 *Example of the optimized design of a cooling element in a sand mould in a casting pit (right) and a record of the comparison of simulations with and without a waste heat removal element (left)*

Where:
1…Concrete casting caisson,
2…Foundry sand mould - bottom part,
3…Steel profile heat dissipation system,
4…Casting,
5…Top moulding frame,
6…Industrial fan,
7…Extensible fan stabilisers,
8…Funnel for airflow direction,
9…Foundry mould - top part,
10…Casting well,
11…Casting well frame,
12…Exhaust,
13…Exhaust outlet,
14…Allen screw M12,
15…Washer M12,
16…Nut M12,
17…Air inlet,
18…Waste heat outlet,
19…Sand core,
20…Threaded locking pin,
21…Stabilizer base.

Fig. 13 shows the mould with the waste heat removal element in the casting pit in section. The blowing out of the element is no longer based on compressed air, but on an industrial fan. Further development of the waste heat extraction is only in the simulation phase.

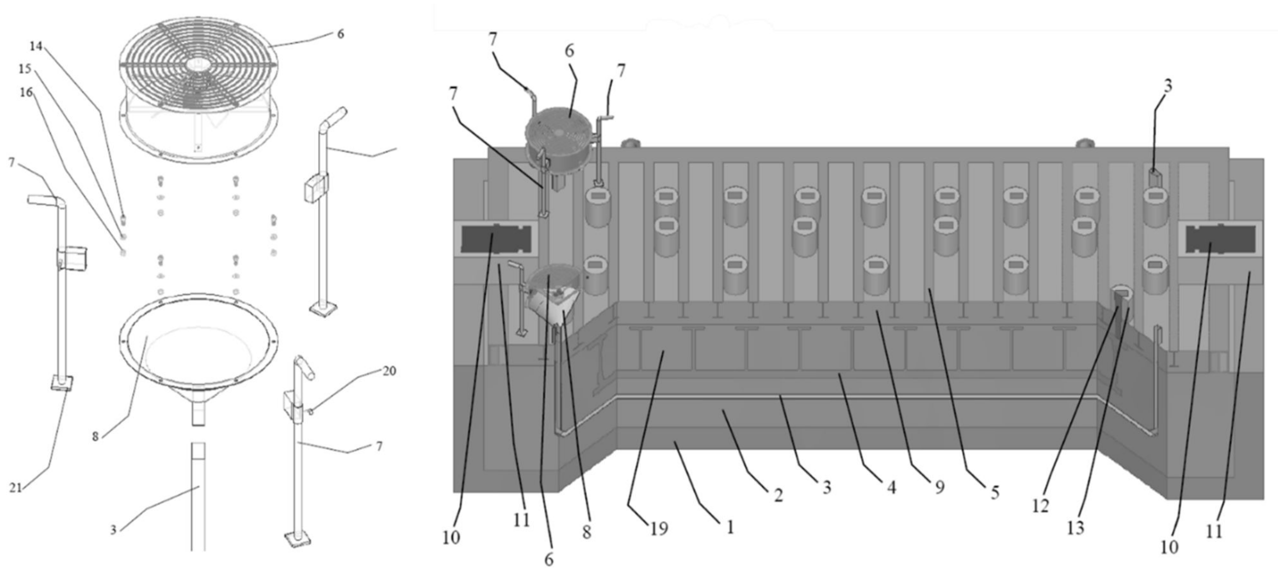


Fig. 13 *Sand mould cut in the casting pit using an optimised waste heat removal element (right), industrial fan connection system (left)*

Where:
1…Concrete casting caisson,
2…Foundry sand mould - bottom part,
3…Steel profile heat dissipation system,
4…Casting,
5…Top moulding frame,
6…Industrial fan,
7…Extensible fan stabilisers,
8…Funnel for airflow direction,
9…Foundry mould - top part,
10…Casting well,
11…Casting well frame,
12…Exhaust,
13…Exhaust outlet,
14…Allen screw M12,
15…Washer M12,
16…Nut M12,
17…Air inlet,
18…Waste heat outlet,
19…Sand core,
20…Threaded locking pin,
21…Stabilizer base.

4 Conclusion

The aim of the experiment was to optimize the cooling time for cast iron castings with flake and nodular graphite. The measurements were carried out on a cast iron casting with flake graphite and a completely analogous procedure would be followed if the object of the measurements was a cast iron casting with nodular graphite. On the basis of the measured data and comparison with the original simulation, the casting could be removed from the casting pit as early as 7 days after casting, the removal did not occur until 8 days after casting and the temperature of the casting was immediately measured using a pyrometer. The temperature was measured at approximately 10 randomly selected locations (sides and bottom of the casting), with a temperature range of 145 - 180 °C. The safe temperature for removal of the casting was set internally at 300 °C, so this measurement suggests that removal of the casting from the casting pit could have taken place as early as day 7 after casting. The temperature fluctuation in thermocouple 3 was always caused by the pressure air being switched off (despite all warnings from the operator), after switching the pressure air back on the output temperature stabilised at about 65°C. The original cooling time of the measured casting was 12 days according to the old foundry practice, based on my experiment the casting can now be removed from the casting pit on the seventh day after casting, which is a time saving of 40% (5 days). This freed up capacity can then be used for the planned production of cast iron bullet graphite castings to be placed in the casting pits. Based on the measured data, it was possible to optimise the material of the furan moulding mixture in the simulation program ProCAST. As a result, it will now be possible to optimise the cooling times of all existing castings produced in the casting pits, including future ones.The effect of the waste heat dissipation element is now being tested at simulation level and based on the output data it is clear that in the case of this particular casting there would be an additional saving of approximately one day, so that the casting could be removed from the casting pit as early as day six. In addition, the concrete casting pit would have less heat load and the waste heat removed could help to heat the foundry hall during the winter months.

The experiment was therefore successful, confirming the accuracy of the ProCAST numerical simulation calculations and at the same time disproved the long-standing dogma about the cooling of castings when 1 tonne = 1 day of cooling, which has been valid in the foundry for decades. Instead of the original 12 days, this experiment has reduced the cooling time of this casting to 7 days, a saving of 5 days, and for this casting, a 40% saving in production time.

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