www.czasopisma.pan.pl PAN www.journals.pan.pl

ARCHIVES of FOUNDRY ENGINEERING

ISSN (2299-2944)
Volume 18
Issue 3/2018

107 – 112

DOI: 10.24425/123611

19/3

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

Dependence of Reoxidation Effect on a Type of Gating System in Investment Casting Technology

A. Herman *, O. Vrátný
Czech Technical University in Prague, Faculty of Mechanical Engineering,
Technicka 4, 16607 Prague, Czech Republic
* Corresponding author e-mail address: ales.herman@fs.cvut.cz

Received 27.04.2018; accepted in revised form 27.07.2018

Abstract

Nowadays, there are growing demands on the accuracy of production. Most of this is reflected in precise manufacturing, such as the investment casting process. Foundries are looking for causes of defects in some cases for a very long time, and it may happen that the source of defects is completely different from what was originally assumed.

During the casting process there exist potential causes of defects as oxygen inclusions. This paper represents a summary of the beginnings of a wider research that will address the problems of gating systems in investment casting technology. In general, the influence of the melt flow is underestimated and the aim of the whole scientific research is to demonstrate the significant influence of laminar or turbulent flow on the resulting casting quality. Specifically, the paper deals with the analysis of the most frequent types of defects found in castings made of expensive types of materials casted in an open atmosphere and demonstration of connection with the design of gating systems in the future.

Keywords: Investment Casting, Gating system, Oxide film, metallography

1. Introduction

The process of investment casting consists of several stages. First producing a wax pattern. These are the same shape and size (with modified dimensions because of different shrinkage) as the final casting. This wax pattern is invested into ceramic slurry and then hardened into the mold. The next step is to melt the wax out of the mould. That is the reason, why investment casting is often referred to as "lost-wax casting". Before pouring the molten metal, the mould must be dry and heated to a temperature as close as possible to the pouring temperature of the metal. After solidification comes breaking the mold, cutting of gating system, scouring, grinding, and finally control of final casting.

The investment casting process is a complex technology in terms of ensuring optimal casting conditions. Considering the casting in the surrounding atmosphere, there are a number of potential causes of defects that need to be eliminated by optimizing the production process. These potencial causes are: perfect cleaning and preparation of the shell, ensuring a clean inflow during the shell preheating process, a suitable furnace crucible with well prepared refractory lining, suitable process of deoxidation during melting, ensuring minimal contact with the melt. At present, for example, many foundries underestimate the influence of gating systems on the resulting casting quality.

Typical precise castings are blades, blade segments, and a number of complex thin-walled castings or, on the contrary, massive castings casted from nickel and cobalt superalloys or high alloyed heat-resistant steels.

In the case of complex thin-walled castings, it is necessary to ensure a laminar filling to achieve a good quality casting. This assumption is generally known, however, the foundries do not every time optimize the gating system properly. [10, 11]

2. Gating system for investment casting technology

The gating system for investment casting technology is different from the sand casting system because the requirement is not only to supply the melt to certain places, but the design must suit the complete removal of the wax pattern from the shell mold. If the gating system is not properly designed, there are problems not only with the assembly of the mould or with the removal of the shell, but the quality of the castings is directly affected by shrinkage, porosity, slag inclusions, cracks etc. [2, 3, 4, 7]

In general, the following steps should be observed when designing a gating system: [1, 2, 3, 4, 7]

- Filling of the ceramic mould with alloys susceptible to oxidation should proceed smoothly to ensure laminar flow. Elimination of the formation of oxide inclusions and trapped air into the mold is an important prerequisite.
- The gating system also acts as a feeder, therefore it is necessary to ensure a directed setting towards the inlet system. This eliminates shrinkage.
- The gating system must have sufficient rigidity. The wax tree must not deform during the applying of investment materials.
- The shell must be constructed so that the casting is easily removable after casting and solidification.
- The gating system should be as simple as possible for production, both in terms of preparation itself and in terms of ensuring a smooth mould filling.
- The design of gating system must ensure the quality of the castings on the one hand, saving the maximum amount of charge on the other hand, since castings produced by investment casting technology are incomparably more expensive than conventional castings.

2.1. Issues of the top and bottom filling of the shells

This part will briefly describe how the shell mould is filled with melt from the top and bottom. Both variants have their advantages and disadvantages. The advantage of top filling is, for example, faster filling of the mould, simpler design, easy to achieve a rigid setting of castings to a tree. A very significant disadvantage however is a turbulent flow, which plays an important role in the case of alloys inclinable to oxidation. The flow of the melt traps the air present in the mold, and the formation of oxide inclusions is formed by reacting the elements of the alloy with the affine to the oxygen.

The bottom filling on the other hand ensures a laminar flow, which is required for castings of superalloys and high alloy steels. The disadvantage in terms of production is mainly the more complex and expensive preparation of shells. It is important to design a gating system with sufficient strength to avoid deformation, especially at the time of investigating in ceramic slurries.

A very important example of parts cast by investment casting technology are blades which require special approaches in precise casting technology to obtain high quality products for current gas turbines. Over time, demands for precision and quality are increasingly being applied in every manufacturing technology. In the case of blades, the first important shift in quality was the grain size control. In practice, grain size has begun to be monitored by observing process parameters such as pouring temperature and using nucleating agents on the inside wall of the shell. Nowadays, the most commonly used nucleating elements are alumina, cobalt or nickel silicates beside the previously used nickel, cobalt or iron oxides. These oxides are not used mainly due to their reaction and solubility with the shell components. The nucleation mechanism represents the absorption of considerable heat by the nucleants, which are used as heterogeneous nuclei.

The next step in the development of precise casting of the blades was the ability to create a cast system of formally complex internal channels to improve the thermal properties. The turbines were then exposed to higher temperatures due to the air cooling of the blades. [5, 6, 9]

The mechanical properties of both nickel and cobalt alloys depend on the chemical composition and also on the cooling rates during and after the solidification. To obtain the values of mechanical properties, it is necessary to carry out destructive tests, not only for this reason all the castings cannot be evaluated. The dispersion of mechanical properties is difficult to improve in practice. [1, 7, 8]

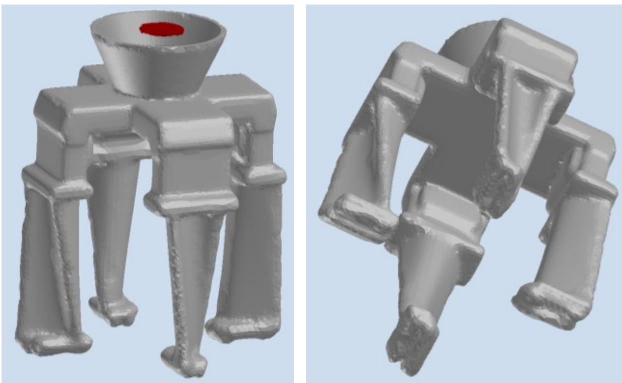

Fig. 1. An example of design of gating system with top filling

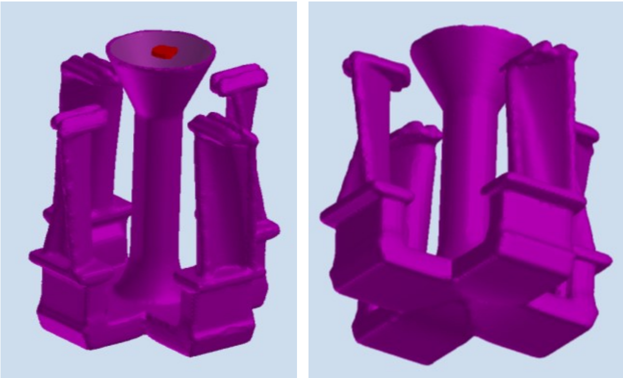

Fig. 2. An example of design of gating system with bottom filling

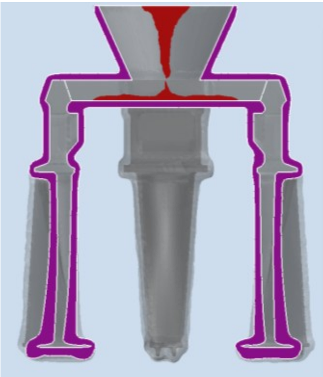

Fig. 3. An example of filling process of gating system with top filling (Step 1)

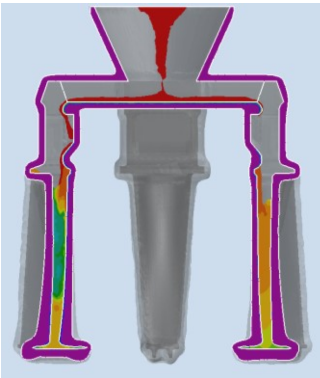

Fig. 4. An example of filling process of gating system with top filling (Step 2)

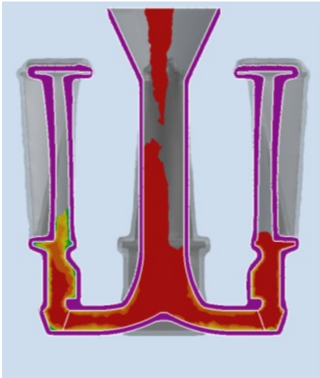

Fig. 5. An example of filling process of gating system with bottom filling (Step 1)

Fig. 6. An example of filling process of gating system with bottom filling (Step 2)

Fig.1 and Fig. 2 are examples of top and bottom filled moulds used for simulations. In Fig. 3 – Fig. 6 there are models and results of simulations made in ProCast software. This is the initial design of the gating system for comparison only, it does not represent realistic results, since the parameters of the casting and the dimensions of the gating systems were designed by estimation. Other variants will have the aim of optimizing the filling process to achieve laminar flow. Once the optimal variant has been obtained, the results will be verified in practice.

3. Metallographic and GDS analysis

First, the cause of the most common defects has to be experimentally detected. Two types of material which are ordinarily cast in the air and have similar defects have been selected. There are some available metallographic samples in the following pictures that show internal defects in castings. In the structure there are a lot of inclusions formed in the shape of membrane. It means, that they must develop as a film on the melt and then infiltrate in the casting. There are also inclusions of another shape. However, the samples show a lot of oxide films and other smaller inclusions around developed probably from destroyed films.

3.1. The analysis of inclusions

AISI 304L

The first chosen material was AISI 304L, it is a commonly used stainless steel with a reduced carbon content (chemical composition in Table 1). Following figures show the most common defects in castings which are casted in open air surroundings (Fig. 7, Fig. 8, Fig. 9).

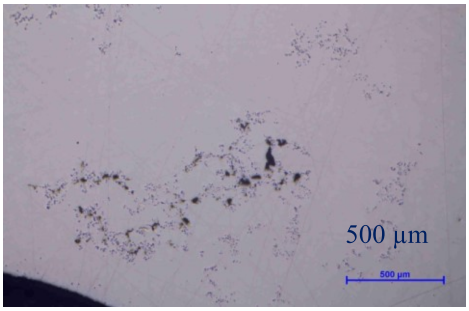

Fig. 7. Metallographic image of the defect

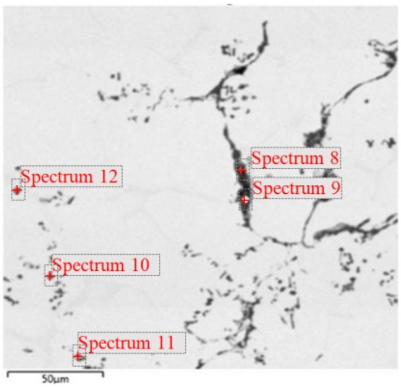

Fig. 8. The analysis of oxide film (AISI 304L)

Table 1.
Chemical composition of the base (AISI 304L)

AISI 304L									
Element		C	Si	Mn	P	S	Cr	Ni	Co
Content [wt. %]	Min						17	8	
	Max	0.03	2	1.5	0.04	0.04	21	12	0.05

In Fig. 8 there are marked areas, which were analyzed on micron microscope.
Table 2 represents a summary of analyzed areas:

- Spectrum 8 – It looks that this analyzed area contains about 30 % of the base. If there is higher content of certain chemical element than in the base, then this element is probably in oxidized state. In this case for example Mn or Al (MnO_2, Al_2O_3).
- Spectrum 9 – This area looks like pure base.
- Spectrum 10 – There is about half of the base and a probably Al_2O_3.
- Spectrum 11 – It consists of mostly pure base and some oxidized inclusions (Al_2O_3).
- Spectrum 12 – There is also only pure base.

Table 2.
Results of chemical composition of different areas

Spectrum 8	Element	Fe	Cr	O	Al	Mn	S	Ni
	[wt. %]	51.1	19.8	7.2	7.2	6.6	3.9	2.9
Spectrum 9	Element	Fe	Cr	Ni	Si	Mn	O	
	[wt. %]	70	19	8.1	1.2	1.1	0.7	
Spectrum 10	Element	Al	Fe	O	Cr	Ni	Si	Mn
	[wt. %]	34.1	32.2	19.9	9.2	3.6	0.5	0.5
Spectrum 11	Element	Fe	Cr	Al	Ni	O	Si	Mn
	[wt. %]	61	16.1	7.9	7.5	5.7	1	0.8
Spectrum 12	Element	Fe	Cr	Ni	Si	Mn	O	
	[wt. %]	70.8	19.6	7	1.1	0.8	0.8	

Table 3.
The oxygen distribution

		Molar weight [g/mole]	Content [wt. %]
element	Al	27	37
	Si	28	12.5
	O	16	47
Al_2O_3	2xAl	54	37
	3xO	48	33
SiO_2	1xSi	28	12.5
	2xO	32	14

Table 3 shows, that 47 % of O is divided to Al and Si according to the molar weight of elements represented in compound. Total of oxygen represented in Al_2O_3 and SiO_2 makes 47 % (33 % + 14 %), so we can probably say, that the whole amount of oxygen is divided just between Al and Si.

The analysis of membrane shows that in two analyzed areas there was found only the pure base (Spectrum 9, Spectrum 12). In the others areas there is for sure at least a portion of pure base and surprisingly quite a lot of Al probably occurring in oxidized state as Al_2O_3.

AISI 661

In this case there the chemical analysis of AISI 661 follows. This kind of material may be referred to as an iron based superalloy (chemical composition in Table 4).

Table 4.
Chemical composition of the base (AISI 661)

AISI 661									
Element		C	Si	Mn	P	S	Cr	Ni	Co
Content [wt. %]	Min	0.10		1.50			21.0	19.0	19.0
	Max	0.20	1.00	2.00	0.04	0.03	22.5	21.0	21.0

Fig. 9 and Fig. 10 show the analysis of AISI 661. Also increased content of aluminium and oxygen. The type of defect is comparable to material AISI 304L defects.

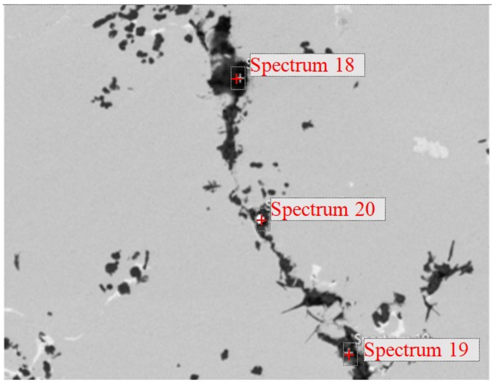

Fig. 9. The analysis of oxide film (AISI 661)

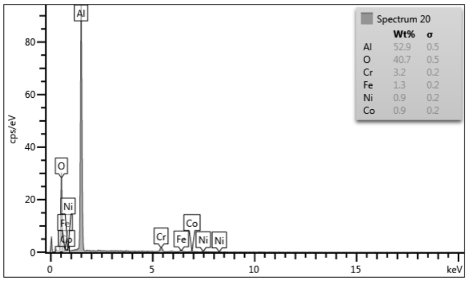

Fig. 10. The chemical composition results of Spectrum 20

3.2. The analysis of oxygen content in certain castings

The analysis of three certain casting was done by Department of Material Engineering based in Prague. In Table 5 there is those three samples compared with Standard by Alpha resources. The experiment was performed on device called G8 Galileo ON/H (product of company Bruker) known as high performance oxygen, nitrogen and hydrogen content analyzer.

Table 5.
The first analysis of oxygen and nitrogen level

Sample	Content [ppm]	
	Oxygen	Nitrogen
1	-	769.6
2	-	573.3
3	936.2	614.9
average	936.2	652.6

The problem appeared immediately. The results show that there was no problem to measure the content of nitrogen in samples but oxygen levels were outside sensitivity of the device (Fig. 11, Fig. 12). Only in one case (Sample number 3) there was a possibility to find out the amount of oxygen content. Especially this Sample was poured under lower pressure (15 mbar). It was only an experiment how to reduce the problem with inclusions, however other technological problems occurred.

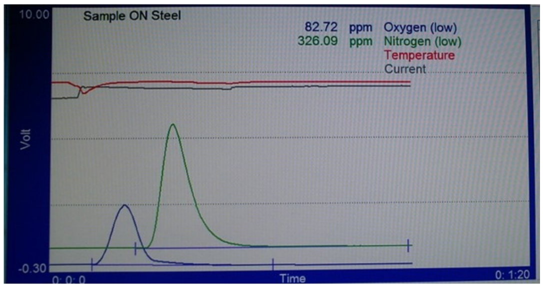

Fig. 11. Signal from detectors for Standard: blue line – Oxygen content, green line – Nitrogen content

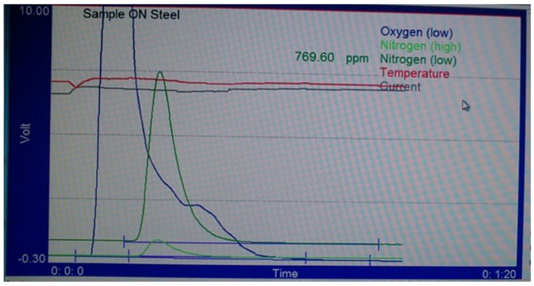

Fig. 12. Signal from detectors for Sample number 1: blue line – Oxygen content, green line – Nitrogen content

The second analysis was done by a Center of Laboratories ENVIFORM a.s. to confirm or disprove the first results. Some other samples were investigated in Table 6.

Table 6.
The second analysis of oxygen and nitrogen level

	Content [ppm]	
Sample	Oxygen	Nitrogen
Number 2	81 - 750	499
Number 3	147 - 162	369
Number 4	92 - 304	349
average	-	406

The analysis of nitrogen content was again without any problems. However the values were lower than in the previous analysis. Approximately the content of nitrogen was 406 ppm, which is ca. 250 ppm lower. The oxygen content was a problem again. The surface of samples was not pretreated appropriately. That means results could be influenced by another factors, for example by corundum (Al_2O_3) using to clean the surface of casting or any other oxide inclusions. Although the analysis was not done according to standards, the oxygen level is still quite high.

5. Conclusion

The investment casting technology is a complicated and long process where at the end should be a high quality casting without defects. There are a number of potential causes of defects from the production of the wax model, through the assembling of the wax trees, dipping of the patterns in several ceramic slurries, the drying of the shells, the melting out of wax from the shells, the preparation of the shells before the casting, the preheating, the casting, the casting removing, finishing, the inspecting and the possible repairing of some pieces. The influence of the design of the gating system on the quality of castings is a neglected topic especially because of the attribution of causes of defects to other influences. Many of authors deal specifically with this issue for a particular casting. The result of studies is mainly the following:

- A simple design of the gating system is connected with ensuring that the melt is introduced into the thin casting walls even at lower casting temperatures.
- The mold design must eliminate the turbulent flow and allow for a laminar flow of the melt.
- The simulation results are verified with real casting results.

The aim of the future work would be the development of the gating system for a particular type of casting and verification of virtual data with reality. The knowledge gained could be applied in general to similar types of castings with regard to minor modifications, especially in dimensions.

The analysis of inclusions especially of their chemical composition show that they are oxidized. Higher presence of aluminium which is used by deoxidation appeared. The main problem is probably higher amount of oxygen which show analyzes. The results are not exact but according to higher percentage of nitrogen what is probably caused by contact of the melt with the air, the oxygen level should be also higher. The differences between the analyses of oxygen and nitrogen content can be also explained. The first samples (1, 2, 3) analyzed in Department of Material Engineering in Prague were prepared of a part of castings which were filled in the mold as last part. It means that a lot of inclusions are involved. On the other hand the second samples (Number 2, Number 3 and Number 4) were casted as separated castings and the testing samples were prepared from the body of the casting. Anyway the main problem is the contact between the melt and the surroundings, which is in this case an air. As a proof there can be the analysis of one sample casted under lower pressure (15 mbar) which was the only one from another two casted in normal pressure that was over limits of the device. The next step in research will be suggesting different designs of gating systems on certain type of casting and trying to eliminate the oxide defects.

Acknowledgements

This publication is under the Center advanced aerospace technologies, reg. No. CZ.02.1.01 / 0.0 / 0.0 / 16_019 / 0000826, which is co-financed by the European Regional Development Fund through the Operational Program Research, development and education.

References

[1] Kubelkova, I., Herman, A., Vratny, O. (2017). Evaluation of Critical Places on Wax Patterns of Blades, Proceedings of the 28th DAAAM International Symposium (pp.1126-1135), B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-11-2, ISSN 1726-9679, Vienna, Austria. DOI: 10.2507/28th.daaam.proceedings.157.

[2] Herman, A., Česal, M.A. & Píša, V. (2014). Measuring Wax Properties as Input Data to Simulation Software Database. *Strojírenská Technologie.* XIX(1), 8-12. ISSN 1211-4162. (in Czech).

[3] Ed. and Sci. Elab. Beneš, L., Ulewicz, R. (2012). *New trends in the field of materials and technologies engineering: monography*. Częstochowa: Oficyna Wydawnicza Stowarzyszenia Menedżerów Jakości i Produkcji. ISBN 9788393422524.

[4] Herman, A., Vrátný, O., Kubelková, I. (2016). *Assessment of critical sites on wax models of blades*. Velká Bíteš: PBS Velká Bíteš. (in Czech).

[5] Bonollo, F., Odorizzi, S. (2001). Numerical simulation of foundry processes. Padova: Servizi grafici editoriali. ISBN 9788886281638.

[6] Reduce Turnaround Times with ESI ProCAST (2016). ESItalk: Preparing for the Factory of the Future. Computer optimization of vertical gating system designs. (48), 1, (10).

[7] Huang, P-H & Lin, C-J. (2015). Computer-aided modeling and experimental verification of optimal gating system design for investment casting of precision rotor. *The International Journal of Advanced Manufacturing Technology*. 79(5-8), 997-1006. DOI: 10.1007/s00170-015-6897-5. ISSN 0268-3768. Available from: http://link.springer.com/10.1007/s00170-015-6897-5.

[8] Thammachot, N., Dulyapraphant, P. & BOHEZ, E.L.J. (2013). Optimal gating system design for investment casting of sterling silver by computer-assisted simulation. *The International Journal of Advanced Manufacturing Technology*. 67(1-4), 797-810. DOI: 10.1007/s00170-012-4523-3. ISSN 0268-3768. Available from: http://link.springer.com/10.1007/s00170-012-4523-3.

[9] Zhang, Xi-e, Li, S-Q., Luo, H-l., Cao X., Feng, D. &. Li, S-P (2007). Simulation of Ni 3 Al-based Alloy and Investment Casting Process of its Thin Wall Castings. *Israel Journal of Chemistry*. 47(3-4), 363-368. DOI: 10.1560/IJC.47.3-4.363. ISSN 00212148. Available from: http://doi.wiley.com/ 10.1560 /IJC.47.3-4.363.

[10] Smirnov, V.V., Pavlinich, S.P., Bakerin, S.V. & Khairullina, A.M. (2014). Use of ProCAST Software to Model Casting Systems for the Centrifugal Casting of GTE Blades Made of Intermetallic Alloys. *Metallurgist*. 57(11-12), 961-964. DOI: 10.1007/s11015-014-9829-y. ISSN 0026-0894. Available from: http://link.springer.com/10.1007/s11015-014-9829-y.

[11] Campbell, J. (2011). *Complete casting handbook: metal casting processes, metallurgy, techniques and design*. Waltham, MA: Elsevier Butterworth-Heinemann,. ISBN 978-1-85617-809-9.