Materials Science-Poland, *Vol. 27*, *No. 4/1*, *2009*

Surface defects of investment castings of turbofan engine components made of IN713C nickel superalloy

H. MATYSIAK[1*], J. MICHALSKI[2], A. BALKOWIEC[3],
K. SIKORSKI[3], K. J. KURZYDŁOWSKI[3]

[1]Functional Materials Research Center, Warsaw University of Technology,
02-507 Warsaw, Wołoska 141, Poland

[2]Materials Engineers Group Sp. z o.o., 02-507 Warsaw, Wołoska 141, Poland

[3]Faculty of Materials Science and Engineering, Warsaw University of Technology,
02-507 Warsaw, Wołoska 141, Poland

The purpose of this study was to investigate typical casting defects occurring in investment cast turbofan engine parts made of IN713 C superalloy. SEM and EDS examinations were used to reveal that dross and non-metallic inclusions of a shell mould and crucible material are the most frequently occurring defects. A hypothesis is put forward with regard to the mechanisms of dross formation. EBSD studies were also carried out to reveal grain structure of the elements in question.

Key words: *IN713C; nickel based superalloy; investment casting; turbine blades*

1. Introduction

Investment casting of critical aircraft engine parts is a complex process [1] during which surface defects of castings of various origins may emerge. The surface defects of precision castings are important, particularly with regard to the high scale industrial production of airplane engine parts such as turbine blades, gas flow guide segments, blade outer air seals, etc. [2].

As these components are of crucial importance to flight safety, their functional reliability cannot be compromised by surface defects measuring no more than a few hundred of a millimeter (the critical, maximally-allowed defect size is 0.05 mm). In industrial practice, surface defects are detected via the fluorescent penetrant inspection (FPI). Detected defects are assessed with the naked eye, a magnifying glass or with a microscope. Defects are identified in accordance with the instructions given by customers. Those instructions are confidential, and may be different for each customer.

---

*Corresponding author, e-mail: hmatysia@inmat.pw.edu.pl

Defects are formed in the processes occurring at the interface between the liquid metal and the ceramic, as is evident from the locations where defects are found. As a result, reactions between liquid metal and a ceramic crucible shell may be of vital importance. In particular, this applies to the erosion of the crucible and the inner walls of the casting shell mould. An alloy charge may also be a source of impurities which are later "frozen" in the surface layer of the casting [1–5].

In order to ensure that the cast is of adequate quality, each stage of the casting process must be strictly monitored, taking into account the alloy chemistry , the shape of the cast, the configuration of the pouring-lip, as well as additional quality checks specific to particular products [2].

Thus efficient ways of improving the quality of the investment castings of airplane parts need to be identified, by systematic investigations into the formation of defects. The purpose of these investigations is to enhance technical guidelines for the manufacture of precision castings of critical airplane engine components.

2. Experimental

5-th and 7-th stage jet engine turbines were investigated. The turbines were made from IN 713C alloy. The chemical composition of the alloy was determined using an Arc-Met 930 arc spectrometer. Results are shown in Table 1.

Table 1. Chemical composition of IN713C [wt. %]

Material	C	Mn	Si	S	Cr	Mo	Nb+Ta	Ti	Al	Fe	Cu	Co	Ni
IN 713C	0.16	0.28	0.30	0.008	14.11	4.25	2.27	1.18	4.73	0.63	0.19	0.12	71.77
Norm PWA	max 0.2	max 0.35	max 0.35	max 0.015	13.00-15.00	3.50 5.50	1.00 3.00	0.75 1.25	5.50 6.50	Mac 1.00	Max 0.50	Max 1.00	Rest

During casting processes, typical ceramic shell moulds were used. The primary coat was based on Zircon (filler) and Ludox SK (binder). Casting processes were carried out under vacuum of 1.33 mbar at 1500 °C. The crucible was made from zirconia stabilized with magnesia. To determine melting time dependence of the gas content in the casting, three samples were taken. The microscope investigations were performed on the ingot material (sample marked as 0), on a sample with the cast material prepared in accordance with currently used technology (sample 1), and on the sample of the materials that had been kept in the melting chamber for 10 min longer (sample 2) than sample 1. The measurements of the gas content (O, N and H) in the castings were performed with the use of an ON-mat 8500nHmat 2500 made by Strohlein.

The surface defects were determined by FPI. Statistical tests were performed on the emergence of various types of defects (inclusions, dross, post cast, X-rays, hot tears). The statistics were compiled after defects had been identified in 250 turbines and van clusters (Fig. 1). The most common defects were inclusions.

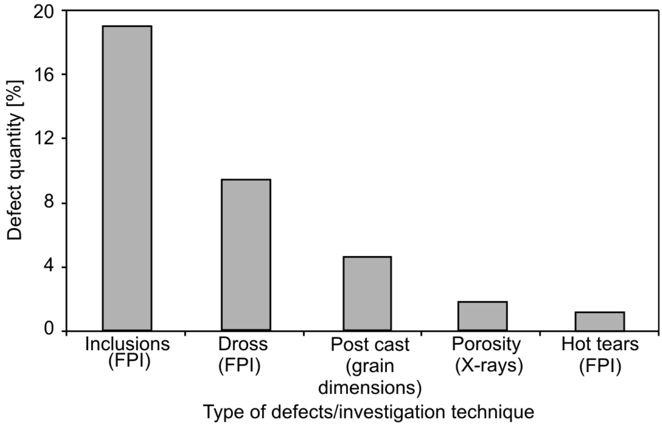

Fig. 1. Statistics of defect occurrences, compiled according to defect type and the method of testing

The cross-sections were prepared in the places were defects occurred. The cross sections were polished to 1 μm with diamond. Observations were performed with a Hitachi model S-3500 L SEM at an accelerating voltage of 15 kV. Samples were observed under secondary electron (SE) contrast in high vacuum mode. Examinations of chemical compositions in micro-regions were performed using a NORAN add-on for EDS analysis (energy-dispersive spectrometry). The grain size was quantitatively measured via the EBSD technique (by the HKL system).

3. Results and discussion

SEM and EDS investigations showed that few kinds of surface defects were present in the material: flow marks and non-metallic inclusions which are ceramic particles from the mould and crucible material and dross. Flow marks were investigated in two places, which are marked in Fig. 2 as imperfect and reference areas (grain size is a technical requirement). The results are shown in Figs. 3 and 4. The comparison of these two areas shows a difference in the grain size. In the flow marks area, the grain size is smaller than in the reference area.

EBSD images of the faulty and perfect sample were prepared using the concept of orientation maps. In the areas qualifying as reference areas, and in the imperfect areas, one observes the polycrystalline character of the microstructure. The results showed, however, a considerable difference in the grain sizes between these two areas. The grain size analysis (Table 2) reveals that areas qualifying as imperfect ones show three times smaller average grain sizes, measured in the directions perpendicular and parallel to the axes of the investigated turbine blades. EDS analysis of dross showed the presence of Mg and the main constituents of 713C. Mg is not present in the 713C alloy or in the shell mould (Fig. 5). The only source of magnesium is a crucible and it comes from ZrO_2 powder stabilized with 3% MgO.

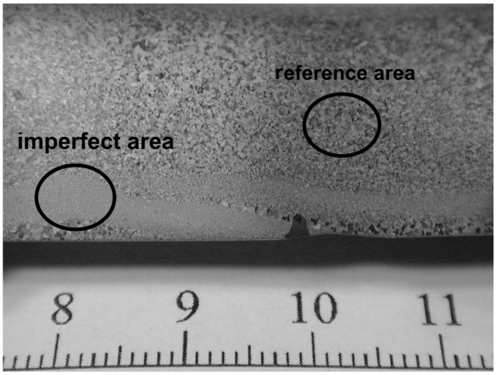

Fig. 2. Surface of a turbine blade after polishing and deep etching, revealed flow marks (imperfect area)

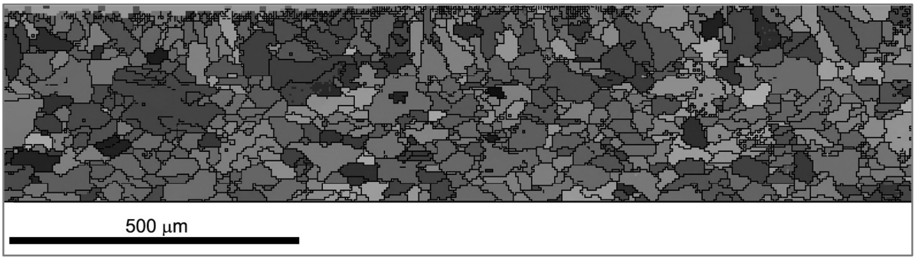

Fig. 3. Grain orientation map in the imperfect area. Turbine blade cross-section cut-out perpendicular to the blade axis – EBSD picture

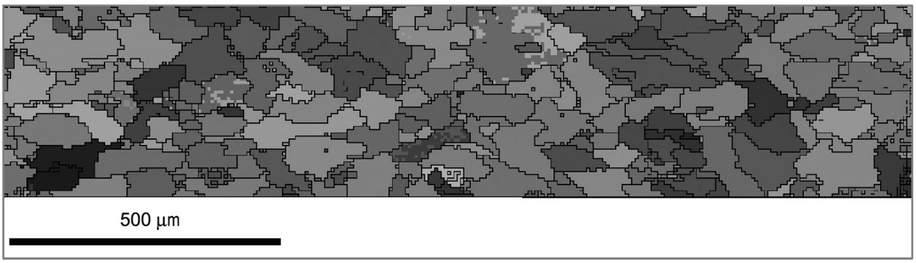

Fig. 4. Grain orientation map in the reference area. Turbine blade cross-section cut-out perpendicular to the blade axis – EBSD picture

Table 2. Average grain size *d* [μm] in the imperfect and reference area

Correct area on the cross-section perpendicular to the turbine blade axis	Defect area on the cross-section perpendicular to the turbine blade axis	Defect area on the cross-section parallel to the turbine blade axis
230	80	70

This suggests that during induction melting of the ingot and casting, Mg migrates into the alloy due to the chemical reaction or due to dissolution at the liquid alloy–crucible interface. Confirmation of this thesis was found in the analysis of skull formatted on the

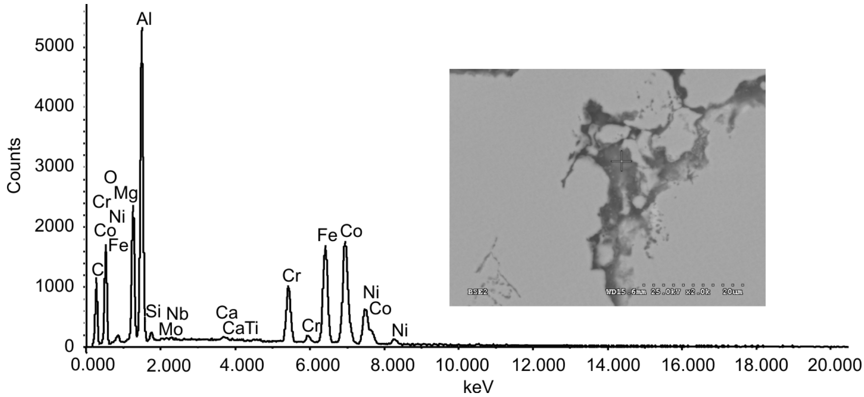

Fig. 5. EDS spectrum and the microstructure of the analysed dross type defect

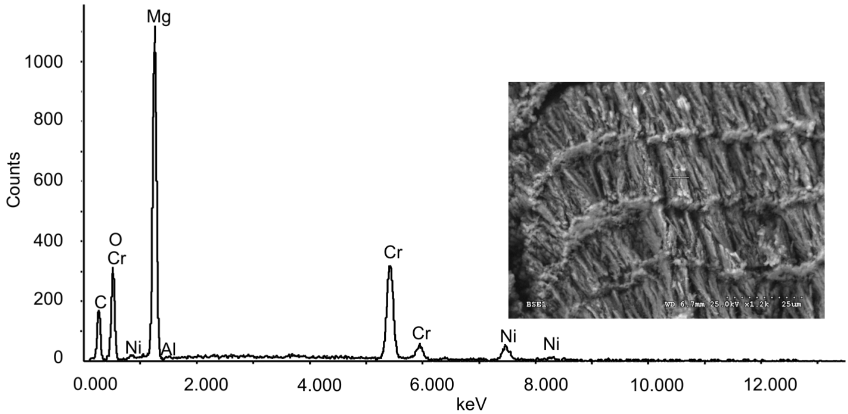

Fig. 6. EDS spectrum and the microstructure with marked spot analysis
– skull formed on the surface of the crucible

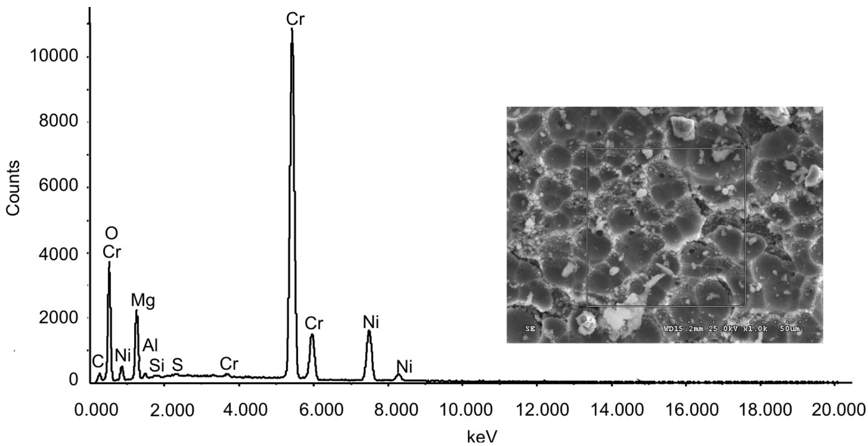

Fig. 7. EDS spectrum and the microstructure with marked spot analysis
– contaminated layer removed from the wall of the casting furnace

surface of the crucible (Fig. 6) in which magnesium is the main component. There is a possibility that Mg gets into the liquid as the result of contact of the liquid surface with the gaseous atmosphere in the furnace. This is confirmed by the fact that magnesium is found in the contamination layer on the inner side of the furnace chamber walls (Fig. 7).

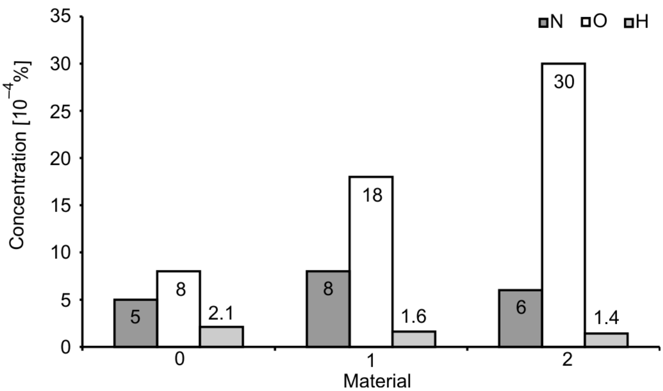

Fig. 8. Gas contents in the castings

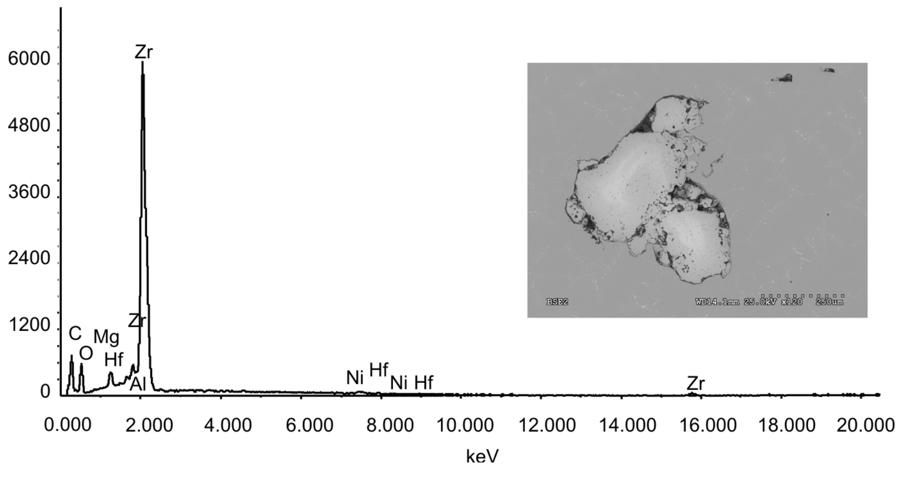

Fig. 9. Microstructure of the inclusion from the crucible material

During vacuum melting in zirconium oxide crucibles, the oxygen content in the castings increases considerably (Fig. 8). Alloy melting, according to theoretical predictions, results in at least a two-fold increase in the oxygen content of the casting. By extending the remelting time by 10 minutes, the oxygen content in the product was observed to be higher by a factor of almost four. At the same time the hydrogen and the nitrogen contents remained constant. The increase in the oxygen content of the castings, compared with the input material, proves evaporation, decomposition and erosion of the crucible material, into the liquid alloy. This is the result of the decomposition of MgO (s) to Mg (g) and O_2 existing in furnace under special conditions (temperature and pressure). Calculations of thermodynamical stability will be published in a separate paper. A study of the reactivity of the alloy and the ceramic material of the crucible and mould in the sessile drop test is currently in progress.

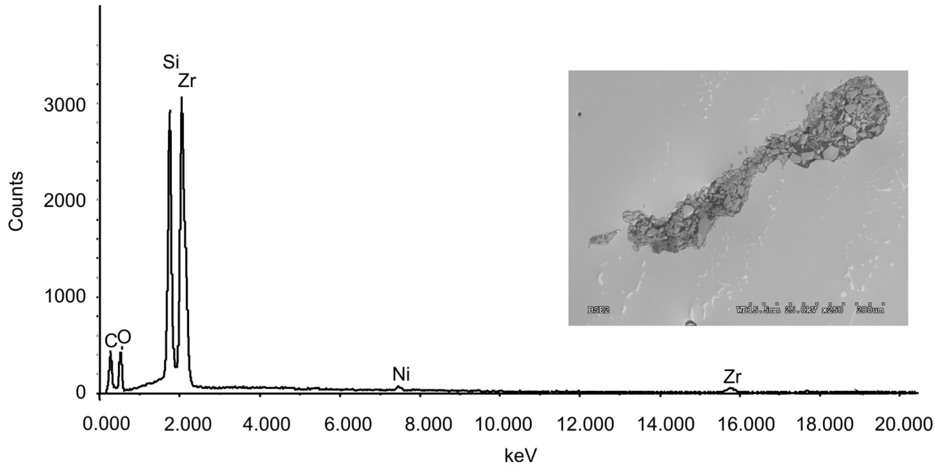

Fig. 10. Microstructure of the inclusion from the shell mould material – primary coat

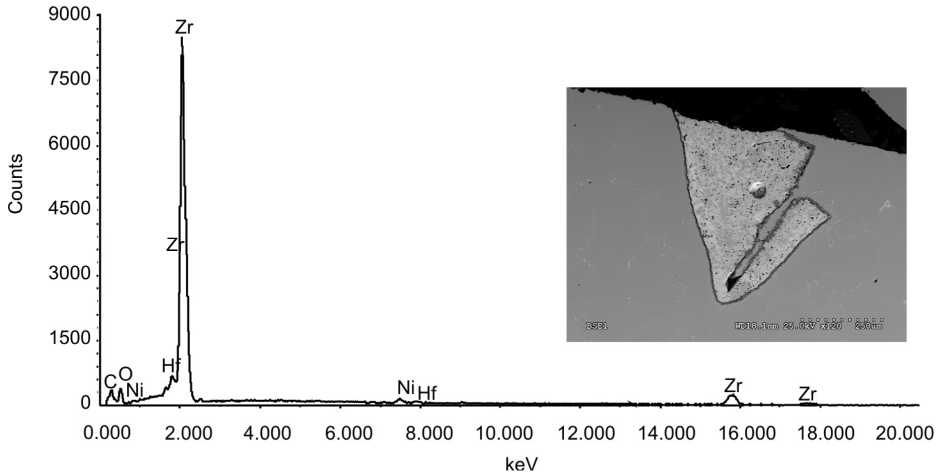

Fig. 11. Microstructure of the inclusion from the filter material

The morphology of the non-metallic inclusions originating from the materials of the shell mould and the casting crucible is presented in Figs. 9–11. The EDS investigations showed that the chemical composition of inclusions is the same as the chemical composition of crucible (Fig. 9), shell mould (Fig. 10) and filter (Fig. 11). The structure of inclusions explicitly shows that the direct cause of their occurrence are the phenomena of erosion and washing out of crucible inner walls, mould and filter by liquid alloy. Having this in mind, it is proposed that any modifications to the casting process should address the following aspects: (i) crucible wedging and filling with charge material; (ii) the melting of ingot material; (iii) the dynamics of mould pouring; (iv) filtering and setting of the filter. Specific knowledge about these modifications is protected by WSK PZL Rzeszów S.A, and therefore will not be discussed in detail.

4. Conclusion

The examination of surface defects of precision castings of airplane parts was performed using FPI and lead to the conclusion that three types of defects occur: flow marks, non-metallic inclusions and drosses. Dross and nonmetallic inclusions, originating from mould and crucible material, are the most common faults. Non-metallic inclusions appear as a result of washing out the crucible mould and filter material. Dross formation is connected with MgO (which is a crucible ingredient) decomposition. MgO is not stable under the parameters of the casting process. The crucible material should be replaced with a different one, which would be stable under casting conditions. Mg diffusion into the melted alloy causes dross formation.

In the flow marks investigation, an immense difference in the grain size was revealed. These defects appear as a result of turbulent flow of liquid materials during pouring into the mould.

Acknowledgement

This work was done as a part of the commissioned research projects - PBZ/KBN/114/T08/2004 and PBZ-MNiSW-03/I/2007 financed by the Ministry of Science and Higher Education.

References

[1] BEELEY P.R., SMART R.F., CHAKRABORTY P.N., PANIGRAHI S.C., *Investment Casting*, The Institute of Materials, Cambridge, UK, 1995.
[2] THORNTON T., SIGH N.P., JAKSON J., *Inclusions And Dross During Alloy Melting For Investment Casting*, 52 Technical Conference and Equipment Expo 2004, Covington, KY USA, 14:1–14:7.
[3] SIMS C.T., STOLOFF N.S., HAGEL W.C., *Superalloys II*, Wiley, Canada, 1997.
[4] MIKUŁOWSKI B., *Stopy żaroodporne i żarowytrzymałe*, Wydawnictwo AGH, Kraków 1997.
[5] KURZ W., FISHER D.J., *Fundamentals of Solidification*, Trans Tech Publications Ltd., Switzerland, 2005.

Received 7 September 2008
Revised 6 January 2009