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Influence of Modification and Casting Technology on Structure of IN-713C Superalloy Castings

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Abstract

The paper presents the results concerning impact of modification (volume and surface techniques), pouring temperature and mould temperature on stereological parameters of macrostructure in IN713C castings made using post-production scrap. The ability to adjust the grain size is one of the main issues in the manufacturing of different nickel superalloy castings used in aircraft engines. By increasing the grain size one can increase the mechanical properties, like diffusion creep resistance, in higher temperatures. The fine grained castings. on the other hand, have higher mechanical properties in lower temperatures and higher resistance to thermal fatigue. The test moulds used in this study, supplied by Pratt and Whitney Rzeszow, are ordinarily used to cast the samples for tensile stress testing. Volume modification was carried out using the patented filter containing cobalt aluminate. The macrostructure was described using the number of grains per mm^2, mean grain surface area and shape index. Obtained results show strong relationship between the modification technique, pouring temperature and grain size. There was no significant impact of mould temperature on macrostructure.

Keywords: Innovative casting materials and technologies, Nickel alloy IN-713C, Surface and volume modification, Cobalt aluminate, Macrostructure

1. Introduction

The ability to adjust the grain size is one of the main issues in the manufacturing of different nickel superalloy castings used in aircraft engines. By increasing the grain size one can increase the mechanical properties, like diffusion creep resistance, in higher temperatures so coarse grained castings are often used for first stage blades in the turbine of turbojet engine. The fine grained castings. on the other hand, have higher mechanical properties in lower temperatures and higher resistance to thermal fatigue and could be used in later stages of the turbine. There are many methods of influencing the grain size of nickel superalloys but the modification using nanoscale inoculants is especially strongly represented in recent Polish and international literature [1-4].

The influence of $CoAl_2O_4$ inoculant concentration in the inner coating of the investment mould was described in the paper [5]. We also carried out the in-depth study on inoculation techniques for refinement of nickel superalloys (IN-713C, IN-100 and MAR-247) using combined, surface and volume modification [6-10].

2. Research problem

Ability to re-use post production scrap (defective castings, gating system parts etc.) is important problem in casting technology of nickel superalloys for aircraft engine parts. It has been proved that the re-melting of nickel superalloy scrap does not result in significant changes to chemical composition [11]. For best functional properties, castings made from heat-resistant nickel superalloys should have optimal combination of mechanical properties (tensile strength, yield strength, elongation, creep resistance) in elevated and high temperature. This optimal combination of properties can be obtained by influencing size, orientation and homogeneity of grains. In case of high temperature components like turbine blades (about 900 to 1000°C) the decisive factor in mechanical strength is creep. Creep resistance increases with grain size, so for turbine blades it may be best to obtain coarse grained or monocrystalline structure, but the lower temperature properties should not be overlooked because of the "cold" cycles of turbojet engine operation. The macrostructure – mechanical properties relationship and the ability to influence the grain shape and size are very important for casting technology of nickel superalloys.

3. Materials and methods of investigation

The aim of the research was to evaluate the influence of modification technique (only volume modification and complex, volume and surface modification), pouring temperature and mould temperature during pouring on stereological parameters of macrostructure in sample castings.

Complex modification technique involves installation of the ceramic filter, coated with cobalt aluminate and hafnium powder, into the pouring cup of the ceramic mould. Ceramic filters were manufactured according to the patented method described in papers [11, 12].

Research was carried out in 2^{4-1} fractional experiment system that required 8 trials to be performed. The experiment plan is shown in Table 1. The following independent variables were set:

A. Mould surface: (-) unmodified, (+)modified by inoculant
B. Ceramic filter: (-) unmodified, (+) modified
C. Pouring temperature: (-) 1420°C, (+) 1480°C,
D. Cooling conditions: (-) mould without thermal insulation, (+) insulated mould.

In all cases the post-production scrap of nickel superalloy IN-713C was used as test alloy. Melting was carried out in single-chamber, vacuum induction furnace Balzers VSG-02 in Al_2O_3 crucible under a protective atmosphere of argon. Investment moulds for teansile strength test specimkenmade by Pratt and Whitney Rzeszów were altered to fit the furnace. The resulting mould consisted of two conical canals and a pouring cup with filter installed in it. In trials 1, 2, 5, and 6 the filter was unmodified and in trials 3, 4, 7 and 8 it was modified with 10% of cobalt aluminate. Inside surface of one of the mould canals was coated with modifying layer of zirconium silicate and 10% cobalt aluminate while the second canal stayed unmodified. In this manner 8 combinations of modifying conditions were obtained.

Type S (Pt-PtRh10) thermocouple in quartz tube was installed in unmodified mould canal for the purpose of temperature control during the solidification process. Due to low volume of the crucible used to melt the superalloy (limited by the furnace dimensions) the pouring temperature in some cases was lower than planned. The actual pouring and mould temperature readings are included in Table 2. During trial no 7 the pouring temperature exceeded the planned value by 100°C because of the failure of furnace temperature controls.

Macrostructure of the samples was revealed using Marble etchant. Images for structural evaluation were obtained using Nikon Ephiphot 200 optical microscope. Further analysis of structural parameters was carried out using digital image analysis of binary images using Met-Ilo 12.1 software package.

Table 1.
Plan of the 2^{4-1} fractional experiment

Trial	Independent variable			
	A	B	C	D
1	-	-	-	-
2	+	-	-	+
3	-	+	-	+
4	+	+	-	-
5	-	-	+	+
6	+	-	+	-
7	-	+	+	-
8	+	+	+	+

Where: - lower level, + higher level

Table 2.
Measured pouring and mould temperature

Trial	Pouring temperature, °C	Mould temperature, °C
1	1390	714
2	1400	836
3	1410	828
4	1420	728
5	1480	824
6	1450	694
7	1560	727
8	1460	821

Fig. 1 Shows the mould prepared to be inserted into the furnace chamber complete with the clipped thermocouple and the iron casing. Casting prepared for etching to reveal macrostructure are shown in Fig. 2. Cross section specimens after etching with Marble solution are presented in Fig. 3.

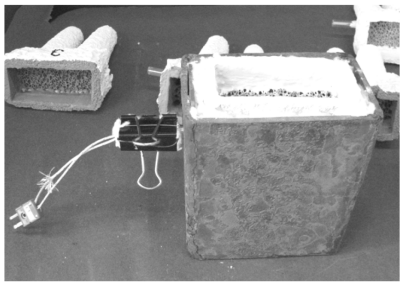

Fig. 1. Mould prepared for an experiment

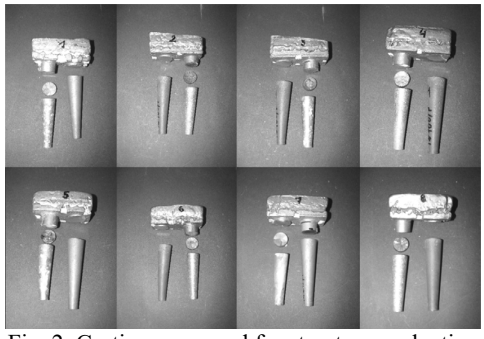

Fig. 2. Castings prepared for structure evaluation

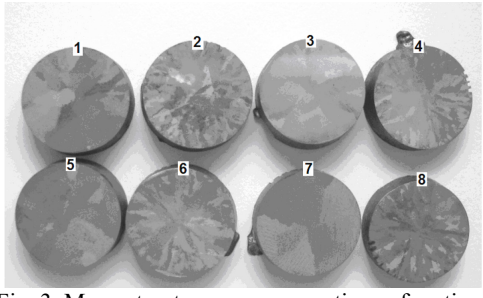

Fig. 3. Macrostructure on cross-sections of castings

4. The results of investigations and discussion of results

Digital image analysis of macrostructure on cross-sections of the test castings, as shown in Fig. 3, was used to determine the number of grains per mm^2 of the sample, mean grain surface area and mean grain shape index. Results of this evaluation are presented in Figs. 4-6.

The multiple regression statistical analysis method was used in the assessment of influence of independent variables A, B, C and D on the selected macrostructure descriptors. The level of significance α, probability of type I error, was set to 0.1. When the calculated probability is lower than 0.1 then the selected parameter have significant influence on macrostructure. The calculations were carried out using StatSoft Statistica 7.1.

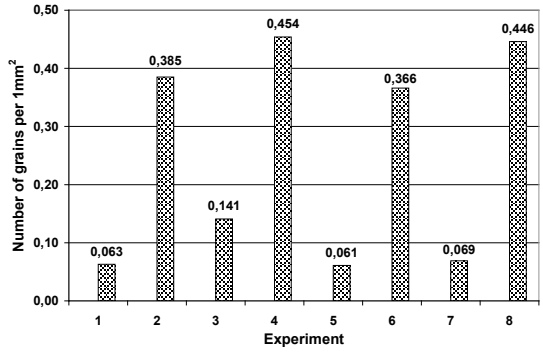

Fig. 4. Number of grains per 1mm^2 vs surface area

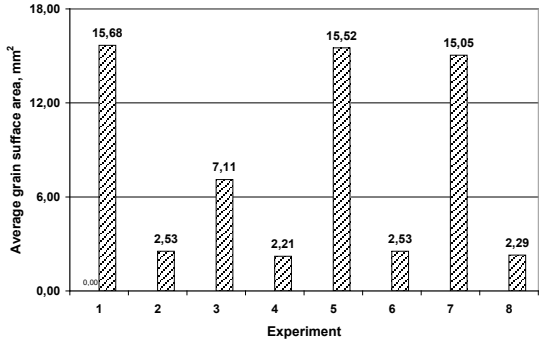

Fig. 5. A comparison of the mean grain surface area values

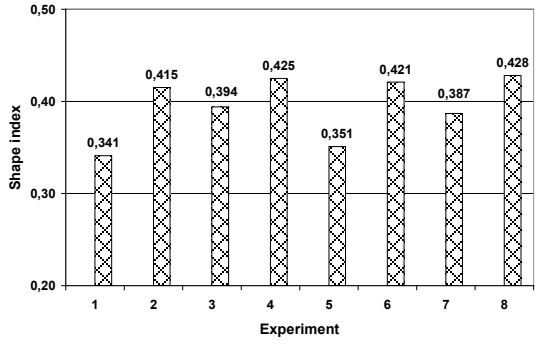

Fig. 6. A comparison of the mean grain shape index

Strength of influence for selected variable (technological parameter) is described by the probability p and the direction of influence (increase or decrease) is described by the sign (+ or -) of b_o coefficient. Results of the calculations are presented in Table 3.

Table 3.
The results of calculations

Variable	Number of grains per mm^2 Ng [mm^{-2}]		Mean surface area of grain Ag [mm^2]		Shape index S	
	B	p	B	p	B	p
Free term	0.653	**0.028**	-20.9	**0,098**	0,298	**0,086**
A	0.16	**0.001**	-5.14	**0,015**	0,028	**0,016**
B	0.034	**0.005**	-1.57	**0,086**	0,012	**0,09**
C	-0.0003	**0.037**	0.02	0,302	0,001	0,692
D	0.0001	0.237	-0.01	0,561	0,001	0,763
R^2	0.9951		0.6343		0.7990	

1. Number of grains (Ng) – value of adjusted correlation coefficient $R^2 = 0.9951$ mean that about 99% of results can be described by following model:
$Ng = 0{,}653 + 0{,}16 \cdot A + 0{,}034 \cdot B - 0{,}0003 \cdot C$, [mm^{-2}]

2. Average of grains (Ag) – value of adjusted correlation coefficient $R^2 = 0.3343$ mean that only about 63% of results can be described by following model:
$Ag = -20{,}9 - 5{,}14 \cdot A - 1{,}57 \cdot B$, [mm^2]

3. Shape idex (S) – value of adjusted correlation coefficient $R^2 = 0.7990$ mean that about 80% of results can be described by following model:
$S = 0{,}298 + 0{,}028 \cdot A + 0{,}0123 \cdot B$, [-]

Macrostructure analysis show that complex, volume and surface modification technique have a vary strong influence on grain size and shape. Unmodified samples (trial 1 and 5) have coarse, slightly columnar grains. Sample from trail 7 have very similar structure due to higher then planned pouring temperature (furnace failure) which disabled the modification effect (cobalt aluminate is ineffective in temperature above 1500°C). Very strong influence of surface modification can be observed in samples from trials 2, 4, 6 and 8, they have much smaller grains than samples cast without modifying mould surface.

Statistical analysis show that the temperature and complex modification technique should have strong influence on number of grains per mm^2. Mean surface area of grains and shape index should be influenced only by modification technique and hardness is not dependant on any technological parameters. Mould temperature in case these trial castings should not influence material properties.

Analysis of pouring and mould temperature measurements in case of trial castings is difficult because the spread of temperature values is very large. This is due to a small amount of furnace load (about 1.2 kg) which temperature dropped very fast in time between turning off the induction heater and pouring into the mould and the variable time needed to transport the mould from the preheating furnace to the vacuum chamber.

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