

# Effect of technological parameters on structure of castings made from IN-713C nickel alloy

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Received 22.06.2011; accepted in revised form 27.07.2011

## Abstract

The work includes studies to determine the significance of the effect of selected technological parameters of moulding and casting conditions on the macrostructure of IN-713C cast nickel alloy. Two-level, fractional  $2^{4-1}$  experiment was carried out, requiring eight experiments. The evaluation covered the number of grains per  $1\text{mm}^2$  of the sample surface, the average grain surface area, and the shape index. Macrostructure of test castings indicates a positive effect of combined surface and bulk inoculation treatment, with the effect of surface inoculation prevailing as regards its importance. Statistically significant effect on the number and surface of grains have in descending order: surface modification, bulk modification and temperature of alloy pouring.

**Keywords:** Nickel superalloys, Macrostructure, Inoculation, Grains, Shape index, Pouring temperature,  $\text{CoAl}_2\text{O}_4$  inoculant

## 1. Introduction

Continuous studies on improving aircraft engines make the planes now fly faster and farther than 30 years ago. To ensure better flight safety, components of the hot engine part are subject to quite unique manufacturing and quality requirements. Improving aircraft engines consists, among others, in the use of alloys of improved creep resistance. Currently, the temperature of exhaust gas driving the engine is  $2000 \div 2200^\circ\text{C}$ , while the efficiency of such engines reaches 45%. Increasing the operating temperature of an engine increases its efficiency. On the other hand, the operating temperature of the engine parts depends on the resistance to creep, on thermo-mechanical fatigue, and on the high-temperature erosion and corrosion damage behaviour of creep-resistant superalloys.

Currently, the precision castings for parts of aircraft engines are produced from modern grades of nickel and cobalt alloys such as IN 100 and IN 713C, RENE 77, MAR-M257 [1, 2]. Castings made from these alloys are required to offer tight dimensional tolerances, excellent surface condition in as-cast state and after heat treatment, and minimum gas and shrinkage porosity. Efforts are also made to obtain the structure of equiaxed grains within the entire volume of casting.

The literature, both national and international, gives a lot of valuable information on how to refine the microstructure of nickel superalloys [3] and make inoculation with nanoparticle agents [4-6]. The introduction of inoculants into the surface layer of mould results in the  $\gamma$  and  $\gamma'$  phases homogeneously distributed in the casting structure and reduces the content of MC carbides of a "Chinese script" type, compared with the structure of castings obtained without inoculation [7]. In [8] it was described how the physical and chemical properties of cobalt aluminate powder and

inoculant concentrations in the surface layer of mould affect the grain size refinement and microstructure, and hence the mechanical properties of creep-resistant cobalt base superalloy MAR M 509 and RENE-77 alloy. It was found that the preferred cobalt aluminate content in the inoculating coating is 5%. A significant grain refinement, combined with an increase of mechanical properties and elongation was obtained. The authors of this study also conducted successful research on the structure refinement and improvement of properties in IN-713C, IN-100 and MAR-247 alloys, using a combined inoculation treatment in both surface and bulk variant [9-11].

## 2. Research problem

Nickel alloys are not produced in Poland, neither are the recovery remelting processes carried out. Therefore, an important issue is the management of production waste (scrap, components of gating systems, etc.). Reusing alloys requires making up for the content of certain additives (especially trace elements), and inoculation to refine the alloy structure. From the point of view of the performance properties of the creep-resistant nickel base alloys, it is recommended to obtain an optimum combination of mechanical properties at elevated and high temperatures, i.e. tensile strength, yield strength, elongation and resistance to high temperature creep. A preferred combination of properties can be obtained, among others, by appropriate selection of the grain size, orientation and homogeneity. Grain size can affect the mechanical and plastic properties, as well as toughness. In practice, the grain size is adjusted to the alloy operating conditions. Fine structures with the presence of equiaxial grains are used for operation at low temperatures (up to 700 °C), where higher fatigue resistance and tensile strength are required.

In a schematic way, the impact of the nickel alloys cast macrostructure on their properties is shown in Figure 1.

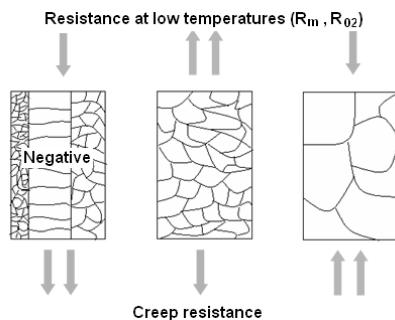


Fig. 1. Schematic representation of microstructure effect on low- and high-temperature properties

At higher temperatures, it is the material creep behaviour that decides about everything. In such cases, attempts are made to produce items with large grains and monocrystalline structure.

Therefore, an important research problem is to determine the intensity and direction of the impact of the basic parameters of casting technology and solidification regime on the formation of morphological features of macro- and microstructure

## 3. Materials and methods of investigation

The aim of the research was to examine the impact of inoculation technique (surface variant only, bulk variant only, combined surface/bulk variant) and casting conditions on the course of solidification, and formation of macrostructure and mechanical properties in test castings. To achieve the preset objective, the research was based on a two-level, fractional  $2^{4-1}$  experiment shown below.

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

The individual variables included:

A: Mould surface, (-) white (without inoculant), (+) blue (with inoculant coating),

B: ceramic filter, (-) white, without modifier, (+) blue, with the inoculant coating,

C: casting temperature, (-) 1420°C, (+) 1480°C,

D: casting cooling conditions, (-) mould without thermal insulation, (+) mould with an insulating material.

The study was conducted on IN-713C nickel superalloy, which besides nickel also contained: 0.03% Co, 13.26% Cr, 5.85% Al, 4.10% Mo, 0.85% Ti, 2.27% (Nb + Ta), and 0.12% C.

Melts were carried out in an induction furnace type VSG-02 (made by Balzers), in an  $Al_2O_3$  crucible. The charge weight was about 1.2 kg. Melting took place under a protective atmosphere of argon. Moulds, before being placed in furnace chamber, were baked in an electric resistance oven heated to a temperature of 1000°C. The temperature of the liquid metal and of the ceramic mould was controlled by a Pt-PtRh10 immersion thermocouple. The casting temperature for individual melts was consistent with the conditions of the experiment (1420 or 1480°C). Because of the small amount of liquid alloy, immediately after turning the furnace off, the temperature of pouring could drop below the required level. For melt No. 8, due to thermocouple failure, the temperature of pouring was exceeded by more than 100°C.

A view of the ceramic mould is shown in Figure 2, while Figure 3 shows a view of the furnace with mould and charge loaded (before closing). From the obtained castings, samples were prepared for the examinations of macro- and microstructure, as shown in Figure 4.

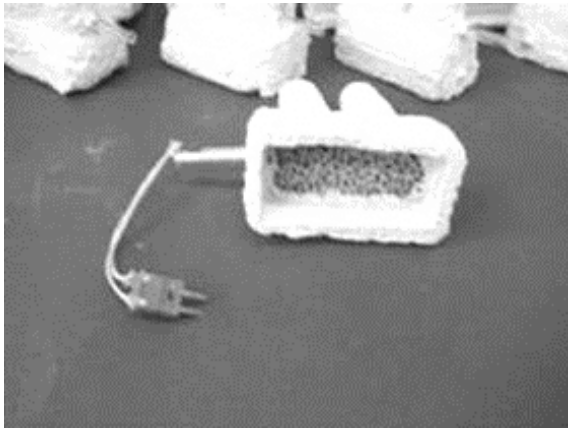


Fig. 2. Ceramic mould ready for tests

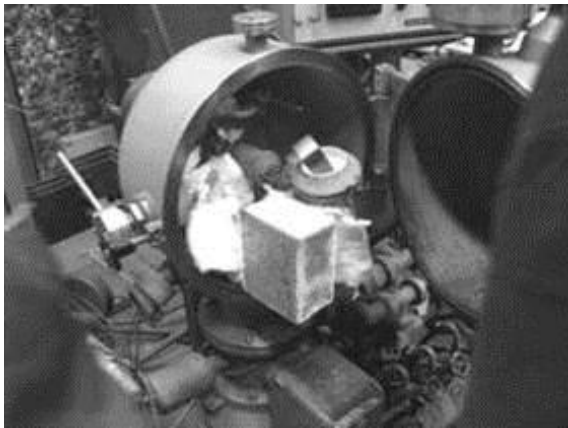


Fig. 3. Mould in the chamber of induction furnace before closing the lid

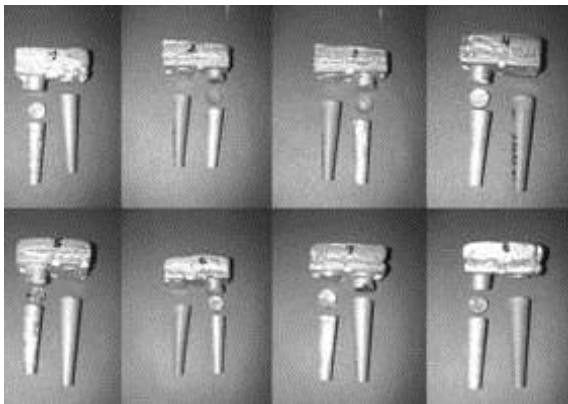


Fig. 4. Ready castings prepared for tests

## 4. The results of investigations and discussion of results

Samples for macrostructural examinations were etched with Marble reagent. The results of these observations are shown in Figure 5.

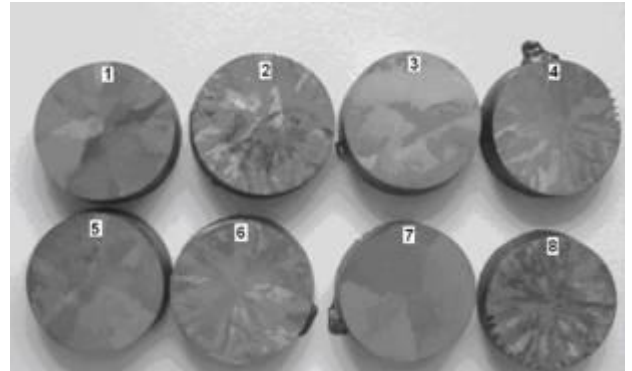


Fig. 5. Macrostructure on cross-sections of castings

Basic parameters of the macrostructure were evaluated with Met-Ilo software [12]. The results of calculations for the number of grains, average surface area and shape index are shown in Figures 6 to 8.

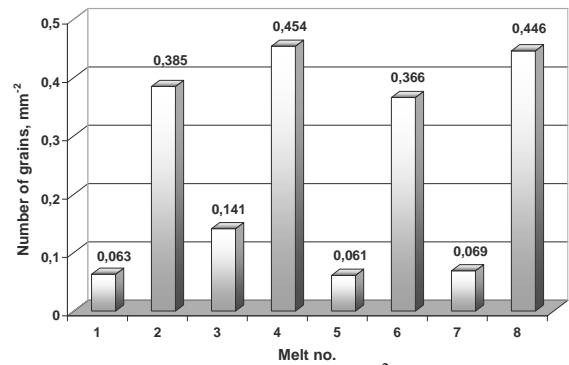


Fig. 6. Number of grains per 1mm<sup>2</sup> vs surface area

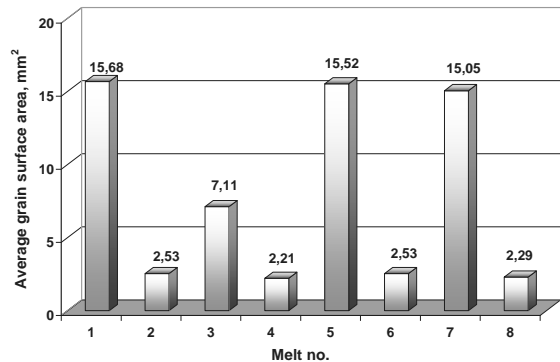


Fig. 7. A comparison of the average grain surface areas

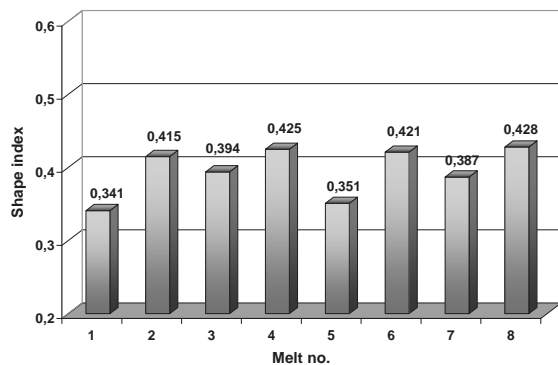


Fig. 8. A comparison of the grain shape index

The effect of dependent variables (variables A, B, C and D) on selected properties of the filters was evaluated by multiple regression analysis. The level of significance  $\alpha = 0.1$  was adopted. How strong the impact of the examined technological parameter will be depends on the value of probability  $p$ , while the direction of influence (decrease or increase) depends on the sign preceding the coefficient  $b_0$  (- or +). Calculations were carried out using a licensed StatSoft V.7.1 Pl. Statistica software. The regression summary of dependent variables is presented below.

Parameter	Results of calculations					
	Number of grains		Average surface area		Shape index	
	$b_0$	$p$	$b_0$	$p$	$b_0$	$p$
Absolute term B	0,6527	0,0280	-20,88	0,098	0,298	0,0860
<b>A</b>	0,1601	0,0001	-5,138	0,015	0,028	0,0157
<b>B</b>	0,0344	0,0054	-1,571	0,087	0,01229	0,0907
<b>C</b>	-0,0003	0,0374	0,026	0,302	0,00005	0,6922
<b>D</b>	0,0001	0,2368	-0,011	0,561	0,00003	0,7627
<b>R<sup>2</sup></b>	0,9951		0,3343		0,7990	

The values in the grey boxes indicate that the examined independent variable significantly affects the feature under consideration because the resulting probability  $p < \alpha$ .

## 5. Conclusions

To conclude, the following should be stated:

1. The value of the adjusted coefficient of determination  $R^2 = 0,9951$  indicates that approximately 99% of the results can be explained with a model described by the following relationship:

$$\text{Number of grains} = 0,6527 -/+ (0,1601) \cdot A -/+ (0,0344) \cdot B - 0,00034 \cdot C, [\text{mm}^{-2}]$$

2. The value of the adjusted coefficient of determination  $R^2 = 0,3343$  indicates that only approximately 33% of the results can be explained with a model described by the following relationship:

$$\text{Surface area of grains} = -20,8801 -/+ (-5,138) \cdot A -/+ (-1,5705) \cdot B, [\text{mm}^2]$$

3. The value of the adjusted coefficient of determination  $R^2 = 0.7990$  indicates that approximately 80% of the results can be explained with a model described by the following relationship:

$$\text{Grain shape index} = 0,298 -/+ (0,028) \cdot A -/+ (0,0123) \cdot B, [-]$$

## Acknowledgements

Research done under Project No. POIG.0101.02-00-015/08 in the Operational Programme Innovative Economy (OPIE). Project co-financed by the European Union through the European Zonal Development Fund

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