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ARCHIVES of FOUNDRY ENGINEERING

ISSN (2299-2944)
Volume 18
Issue 2/2018

215 – 219

DOI: 10.24425/122531

39/2

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

Cracking of Pad-Welded Inconel 713C Precision Castings

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Received 11.04.2018; accepted in revised form 23.06.2018

Abstract

Inconel 713C is a nickel-based casting alloy characterised by improved heat and creep resistance [1]. It is used e.g. in aircraft engine components, mainly in the form of precision castings. Precision casting enables very good reproduction of complex shapes. However, due to major differences in casting wall thickness and the resultant differences in rigidity, defects can form in precision castings. The most common defects in precision castings are shrinkage porosities and microcracks.
Inconel 713C is considered to be a difficult-to-weld or even non-weldable alloy. However, the need to repair precision castings requires attempts to develop technologies for their remelting and pad welding which could be used in industrial practice. This article presents the results of tests consisting in TIG pad welding of defects identified in precision castings intended for the aircraft industry. It was found that the main reason behind failed attempts at repairing precision castings by welding technologies was hot cracking in the fusion zone. Such cracks form as a result of the partial melting of intercrystalline regions along the fusion line. The deformations occurring during the crystallization of the melting-affected zone (fusion zone + partially melted zone + heat affected zone) or pad weld lead to the rupture of the intercrystalline liquid film. Hot cracks form within the so-called high-temperature brittleness range (HTBR) of the alloy. Another type of cracks that was identified were ductility dip cracks (DDC), whose formation is related to the partial melting of carbides.

Keywords: Inconel 713C, Nickel alloy, Cracking, Repairing of casts

1. Introduction

Alloy Inconel 713C is a precipitation hardenable, nickel-based cast alloy containing chromium (approx. 12.50%), molybdenum (approx. 4.20%), niobium and tantalum (in total — up to approx. 2.2%), and aluminium (approx. 6.10%). It is characterised by structural stability up to 980°C and good resistance to oxidation and thermal fatigue [1]. According to AMS 5391, the strength of the alloy in the as-cast condition at room temperature is min. Rm = 760 MPa (Re = 760 MPa); at 980°C, rupture occurs at a stress of 150 MPa and elongation of min. 5% [2]. As-cast Inconel 713C is used for aircraft engine turbine components. However, thermal treatment is also applied in order to increase its creep resistance. The recommended heat treatment is solution treating for 2 hours at 1150°C, in an argon atmosphere or under vacuum [1, 3].
Inconel 713C has a dendritic structure made up of phase γ and a γ-γ' eutectic system in the interdendritic regions, with primary MC carbides and secondary M_6C and $M_{23}C_6$ carbides (Fig. 1) [4].
Aircraft engine components made from Inconel 713C usually have the form of precision castings. Precision casting is a very advanced manufacturing technology. Castings with highly varied wall thickness and thus different rigidity in particular areas are affected by casting defects resulting from stresses and deformations occurring during crystallisation. The most common defects include shrinkage porosity, pores, blowholes, and cracks [5].

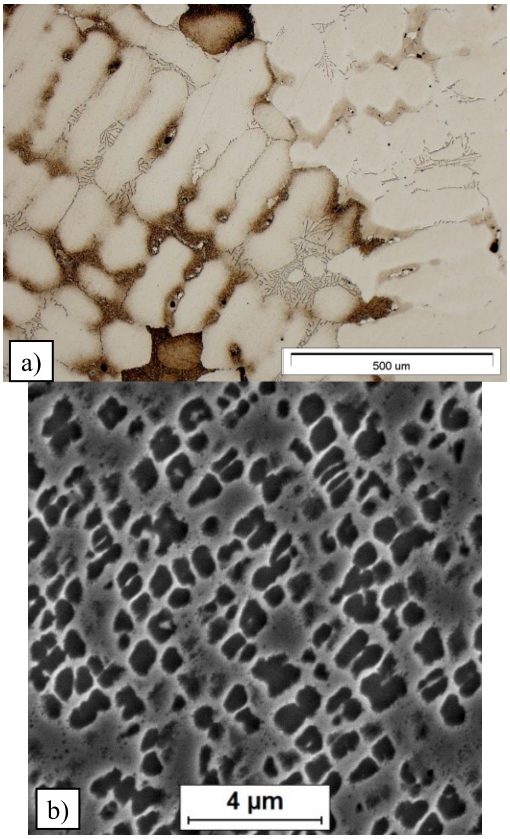

Fig. 1. Inconel 713C structure after precision casting: visible phase γ dendrites and carbides, b) γ–γ' eutectic mixture [3]

Based on the reviewed literature, it was determined that the weldability of this alloy was limited primarily by hot cracks in the weld (5–7). There are no precise data describing the cracks and the mechanism for their formation. Knowledge of such information is one of the main factors determining the possibility of developing a technology for repairing precision castings of Inconel 713C.

2. Test material

The material used for the tests was Inconel 713C precision castings manufactured at CPP Poland (Consolidated Precision Products Poland Sp. z o.o.). The VIM (Vacuum Induction Melting) method was used to melt the charge material. The chemical composition was verified for compliance with the manufacturer's requirements by the XRF (X-ray fluorescence) method, using a Niton XLt 898W analyser. The results of the analysis are shown in Table 1.

Based on a comparison of the chemical composition and the material specification requirements for Inconel 713C, it was found that the material of the precision castings met the requirements of AMS 5391 with regard to the chemical composition. The microstructure was examined on metallographic sections. Examples of base material structures are shown in Fig. 2. The phase analysis of the material was carried out using the XRD (X-ray diffraction) method (Fig.3).

Table 1.
Results of a quantitative XRF analysis of the chemical composition of the tested castings

Alloy	Ni	Cr	Al	Mo	Nb	Zr	W	Cu	Co + Ta	Fe	Mn	Ti
In 713C (XRF)	70.38	13.29	5.78	4.44	2.13	0.04	0.31	0.47	1.92	0.36	0.08	0.8
AMS 5391	bal	12-14	5.5-6.5	3.8-5.2	<2.5	<5	-	<0.5	1.8-2.8	<2.5	<0.25	0.5-1.0

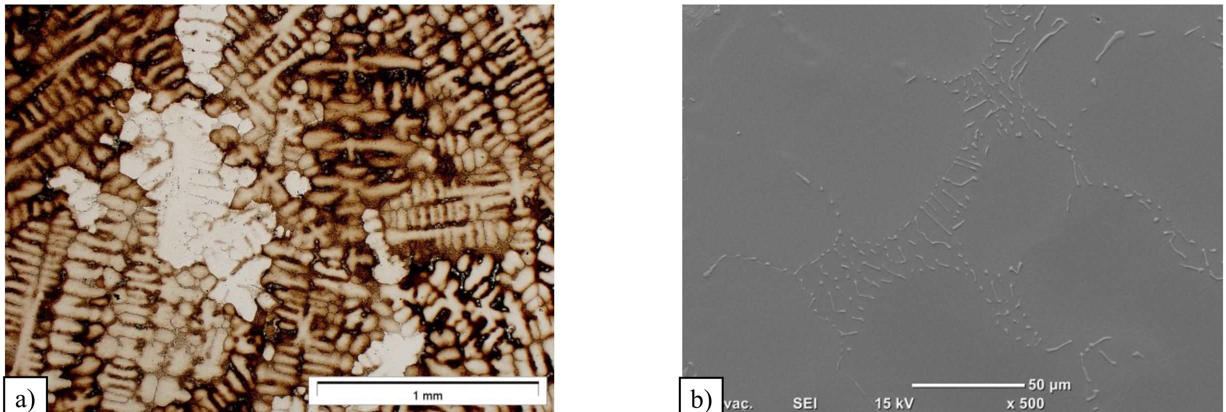

Fig. 2. Structure of the Inconel 713C castings used for the tests: a) casting macrostructure (LM), b) dendritic structure with visible carbides (SEM)

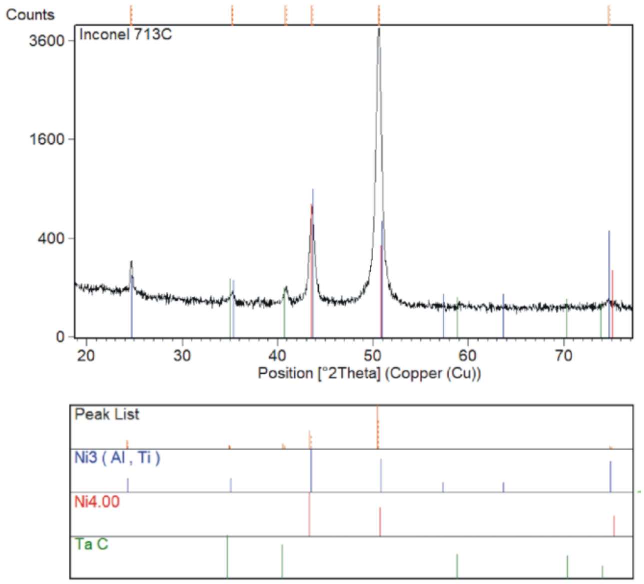

Fig. 3. Results of the XRD phase analysis of an Inconel 713C precision casting

On this basis, it was found that the test material was characterised by the typical dendritic structure with sparse areas of a γ–γ' eutectic mixture and carbide precipitates, mainly in intercrystalline regions.

3. Determination of relevant temperatures in the crystallisation process

Differential thermal analysis (DTA) and a Setaram SETSYS thermal analyser were used to determine the solidus and liquidus temperatures. A TG-DTA head was used for the tests to measure the temperatures of phase transitions and the transition enthalpies related to the melting and solidification of Inconel 713C. A type S thermocouple (Pt-Rh/Pt-Rh 10%) was used for the differential thermal analysis. The material was kept in an inert argon atmosphere (Ar 99.999% with a flow rate of 1.35 l/h). The specimens were heated to 1500°C at a rate of 10°C/min. The temperature of the beginning and end of the transition was measured using the method of two intersecting tangents ("one set point"). The DTA curves are shown in Fig. 4, whereas Table 2 presents the measured temperatures.

4. Technological tests — TIG (141) remelting

Inconel 713C precision castings (thickness - 2 mm) were melted by the TIG method in an inert gas (argon) atmosphere with a flow rate of 12 l/min, using a 1.6 mm thick tungsten electrode, in the flat position, with a direct current of 40 A and an arc voltage of 10 V. These parameters of melting were selected besed on [5]. An example of a melting-affected zone (fusion zone + partially melted zone + heat affected zone) surface is shown in Figure 5a. Figure 5b shows the macrostructure of a melting-affected zone with a visible crack.

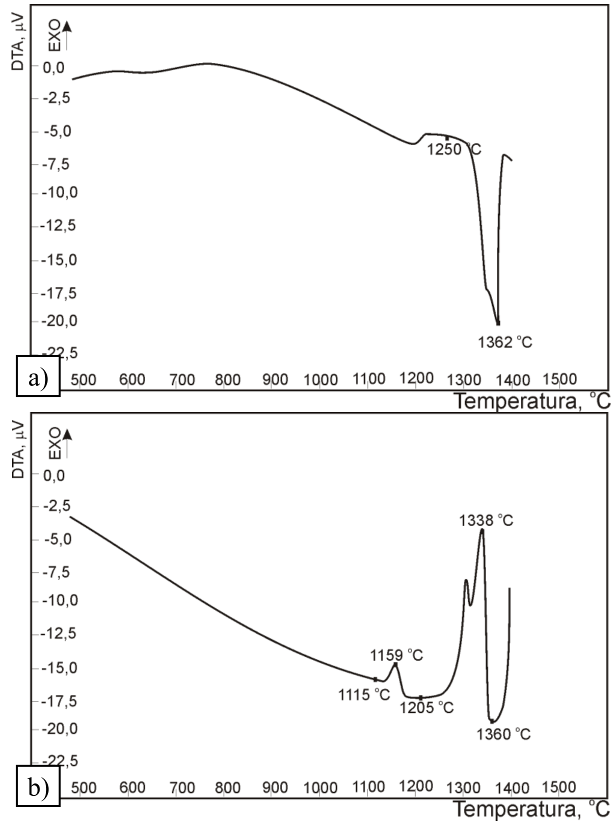

Fig. 4. DTA curves for Inconel 713C: a) on heating, b) on cooling

Table 2.
Temperatures characteristic of the crystallisation process for Inconel 713C

Alloy	Temperature where the liquid phase begins to appear on heating, °C,	Liquidus temperature on heating, °C,	Temperature where the first solid phase crystals begin to appear on cooling, °C,	Solidus temperature on cooling, °C,
INC 713C	1250	1362	1338	1205

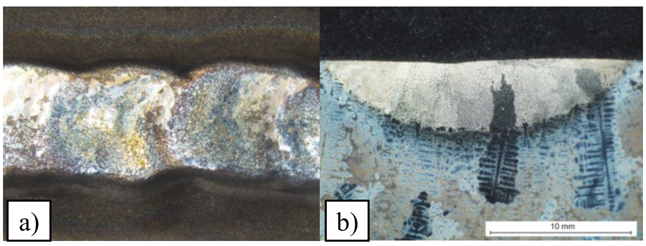

Fig. 5. Melting-affected zone surface ("face") of an Inconel 713C precision casting (a), macrostructure of the melting-affected zone with a visible crack in the fusion zone (b)

5. Examinations of the structure of the melting-affected zones

The specimens for the structural examinations were cut out perpendicularly to the melting direction. The metallographic sections obtained were etched chemically in Marble's reagent (10g, $CuSO_4$ + 50 cm3 HCl + 50 cm3 H_2O).

The metallographic examinations were carried out under an SZX9 stereoscopic microscope (SM), in the dark field mode, at magnifications of up to 50x, and under an OLYMPUS GX71 light microscope (LM), in the bright field mode, at magnifications of up to 500x. The images obtained enabled a qualitative evaluation of the structure of all melting-affected zones on the Inconel 713C precision castings. The structural examinations were complemented by observations under a JEOL JCM-6000 Neoscope II scanning electron microscope (SEM). The examinations were carried out in the secondary electron (SE) imaging mode and in the back-scattered electron (BSE) mode, at magnifications of up to 10000x. The SE images reflect the topography of the specimen surfaces, whereas the BSE images make it possible to evaluate the differences in the chemical composition of particular areas. The results of the examinations are shown in Fig. 6 and 7.

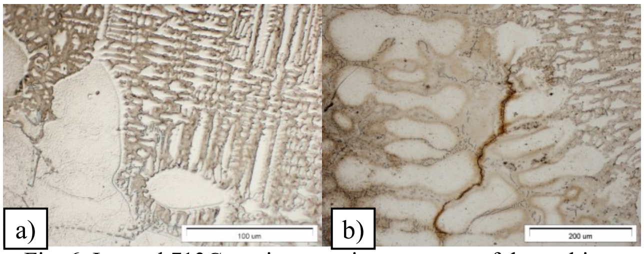

Fig. 6. Inconel 713C casting — microstructure of the melting-affected zone: a) fusion zone — partially melted zone (PMZ), b) crack along dendrite boundaries in the PMZ

6. Result analysis and conclusions

The tests on Inconel 713C revealed that the precision castings were characterised by a dendritic structure of phase γ, areas of a carbide eutectic mixture in interdendritic regions, and carbide (mainly niobium and tantalum carbide) precipitates (Fig. 2, 3).

The surfaces of the precision castings were remelted using the TIG method in order to determine preliminary guidelines for the development of a repair technology (Fig. 5a). The need to repair Inconel 713C castings made in ceramic moulds is related to the possibility of casting defects (misruns, pores, microcracks) forming on the surface. At present, such defects are not repaired.

The analysis of the structure of the melting-affected zones revealed areas typical of local material melting (Fig. 5b), i.e. the base material, the partially melted zone, where the base material is partially melted along dendrite boundaries, in eutectic mixture regions (Fig. 6a), and the fusion zone, made up of fine-sized directional dendrites growing on the partially melted grains of the base material (Fig. 5b).

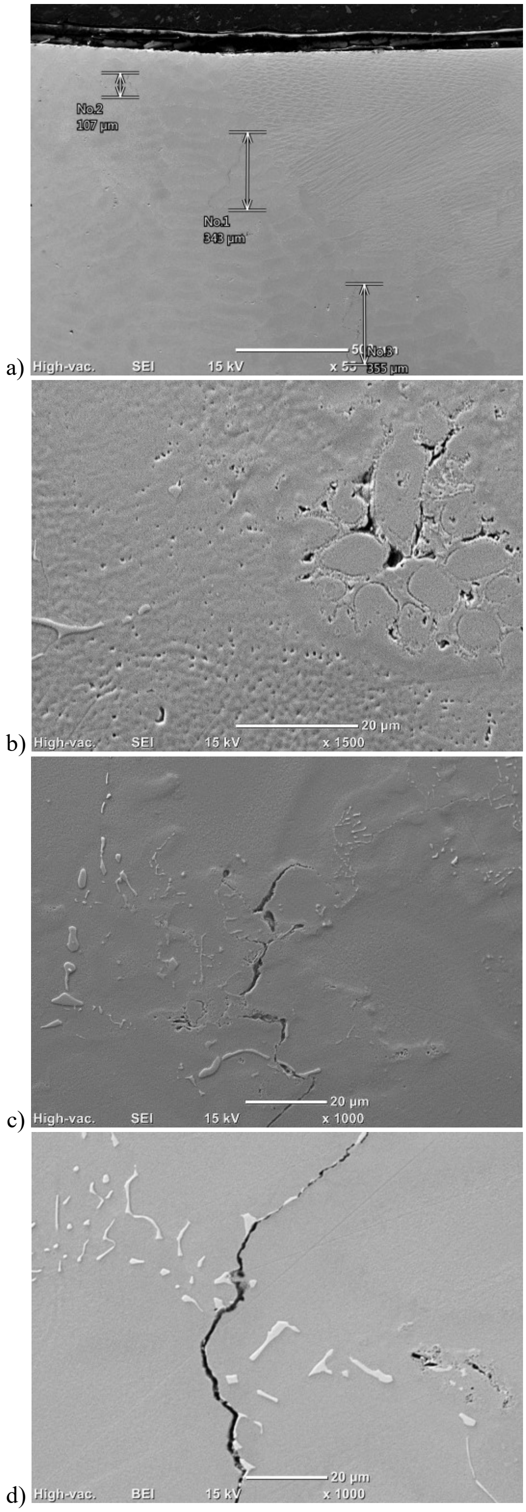

Fig. 7. Inconel 713C — cracks in the partially melted zone in the melting-affected zone: a) cracks identified in the PMZ, b) area of the partially melted eutectic mixture in the PMZ with visible discontinuities, c) interdendritic crack in the PMZ, d) crack along a phase γ dendrite boundary and along niobium carbides

Detailed structural examinations of the melting-affected zone revealed numerous 300–400 m long microcracks in the partially melted zone (Fig. 6b, 7a). The microcracks initiate in interdendritic regions as a result of the partial melting of carbide eutectic mixtures (Fig. 7b) and grain boundaries in segregation areas (Fig. 6b). A similar mechanism of partial melting of eutectic mixtures and segregation areas was described in paper [8]. Due to deformations occurring during the crystallisation of the melting-affected zone, the intercrystalline liquid film ruptures within the high temperature brittleness range (HTBR) and a crack initiates. The high-temperature brittleness range of Inconel 713C was described in detail in paper [7]. Based on tests conducted on a Gleeble 3500 thermal-mechanical simulator, the authors determined that the high temperature brittleness range within which Inconel 713C was susceptible to hot cracking covered temperatures from 1250 to 1290°C. The results conform to the solidus-liquidus temperature range determined on the basis of the DTA analysis for the alloy (Fig. 4). However, it needs to be noted that the high temperature brittleness range determined based on the thermal-mechanical simulations performed using the Gleeble simulator is characteristic of the base material and does not take into account any welding or pad-welding conditions. An analysis of the literature with regard to comparing the high temperature brittleness range determined using a Gleeble simulator and under conditions typical of a welding process (Transvarestraint test) for various materials, including magnesium-based alloys, nickel-based alloys , and austenitic steels, clearly indicates that the HTBR under remelting or pad welding conditions is several times wider [8].

7. Summary

Based on the tests and examinations conducted, it was found that when Inconel 713C was remelted, cracks appeared in the partially melted zone, which limited the alloy's weldability. Such cracks initiate in interdendritic regions as a result of the partial melting of eutectic mixtures or areas characterised by an increased level of element segregation and subsequently propagate along dendrite boundaries due to deformations related to the crystallisation of the melting-affected zone.

Acknowledgements

The study was funded as part of the Applied Research Programme financed by the National Centre for Research and Development, project title: “Advanced Casting Technologies – INNOCAST”, contract No.: INNOLOT/I/8/NCBR/2013.

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