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Structure of Precision Castings Made of the Inconel 713C Alloy

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Abstract

Inconel 713C alloy belongs to the group of materials with high application potential in the aerospace industry. This nickel alloy has excellent features such as high strength, good surface stability, high creep and corrosion resistance. The paper presents the results of metallographic examinations of a base material and padding welds made by laser beam on the Inconel 713C alloy. The tests were made on precisely cast test plates imitating low - pressure turbine blades dedicated for the aerospace industry. Observations of the macro- and microstructure of the padding welds, heat-affected zone and base material indicate, that the Inconel 713C alloy should be classified as a hard-to-weld material. In the investigated joint, cracking of the material is disclosed mainly in the heat-affected zone and at the melted zone interface, where pad weld crystals formed on partially melted grains. The results show that phases rich with chromium and molybdenum were formed by high temperature during welding process, which was confirmed by EDS analysis of chemical composition.

Keywords: Castings defects, Nickel alloys, Inconel 713C, Precision castings, Pad welds

1. Introduction

The aviation industry requires the development of new materials and improvements of the solutions which are currently in use. For example, a material for low-pressure turbine blades or vane segments (aircraft engine components exposed to aggressive exhaust environment and high temperatures) must exhibit high strength, very good corrosion resistance and low coefficient of thermal expansion. Precision castings made of nickel-based alloy – Inconel 713C meet the mentioned requirements. This material is characterized with a densely packed wall-centred crystallographic structure containing of γ-grains, interdendritic (γ + γ') eutectic, (γ + MC) eutectic, carbides and coherent γ' precipitates distributed uniformly within the γ-matrix [1-3]. This allows to obtain γ/γ' – binding, which inhibits the motion of dislocations and affects the increase in the creep resistance at elevated temperatures [4-9]. The mechanical properties of IN 713C alloy depend mainly on the composition, size, shape and volume fraction of γ' - phase particles, which may change depending on the service parameters and the heat treatment applied. This material has significantly better strength properties at elevated temperatures than iron alloys. The possibility to work in corrosive environment full of gases, nitrogen compounds, carbon and sulphur enable the application of that nickel-based alloy, especially where the reliability is required. As materials from the group of the highest operational risk, there is a need to ensure the highest quality of welding constructions and elements repaired with welding methods. Joining technologies are used in joining of structural elements in turbines and power aviation fittings such as sealing rings, exhaust systems, combustion chambers, fuel nozzles, but also help fill the micro-cracks, which arise during the operation of the engine blades. The main disadvantage of the Inconel 713C alloy is the tendency to form cracks during welding and during reheating to operating temperature and heat treatment. The most frequently occurring crackings are crystallization cracks (hot-crackings) in the weld area, however, there is a greater risk of cracks occurring in HAZ, which are difficult to eliminate due to the lack of exposure by non-destructive methods. It is therefore necessary to understand phenomena and processes occurring in the material and impact on the phenomena arising in the microstructure, which affect the final properties of the finished elements during operation [10-20].

2. Research material and methodology

The cast plates of Inconel 713C alloy were made at Consolidated Precision Products Poland Sp. z o.o. as part of a project financed by the National Center for Research and Development. The charge material was melted by VIM (Vacuum Induction Melting) method. The alloy was cast to the multilayer ceramic mold, composed of SiO_2•ZrO_2 facing layer, $CoAl_2O_4$ modifier and colloidal silicon as a binder. The second construction layer was formed of Al_2O_3 and SiO_2 and silicic acid zol. Samples were welded in the areas of casting defects, such as pores and cracks. Samples were surface-remelted with the plasma arc (PAW - Plasma Arc Welding). The material has been kept in the inert atmosphere of argon with flow rate of 6 l/min using tungsten electrode with diameter of 1.6 mm and a nozzle for plasma gas feeding with a diameter of 1.2 mm. Arc voltage was set to 20 V, with direct current ranging from 5 to 18 A.

The chemical composition of Inconel 713C are shown in Table 1. Samples for metallographic examinations were cut out perpendicular to the welding direction. The samples were ground with sand papers of 120, 320, 500 and 1200 μm and polished with diamond pastes. The metallographic examinations were conducted using the Olympus GX71 light microscope (LM). The structure was also examined under the JEOL JCM-6000 Neoscope II scanning electron microscope (SEM). The examinations were complemented by the EDS microanalysis of the chemical composition in the HAZ and welded joints.

Table 1.
Chemical composition of IN 713C alloy

Alloy	Ni	Cr	Al	Mo	Nb	Zr	Cu	Co + Ta	Fe	Mn	Ti
IN 713C	70,38	13,29	5,78	4,44	2,13	0,04	0,31	0,47	1,92	0,36	0,08

3. Result analysis and discussion

The observation of the macrostructure of the precision casting revealed that it has a dendritic structure in a crystal phase of γ and γ'. In the inter-dendritic spaces and along the grain boundaries, precipitation of MC primary carbides can be found. Large segregation and diversified morphology was also observed there (Fig. 1).

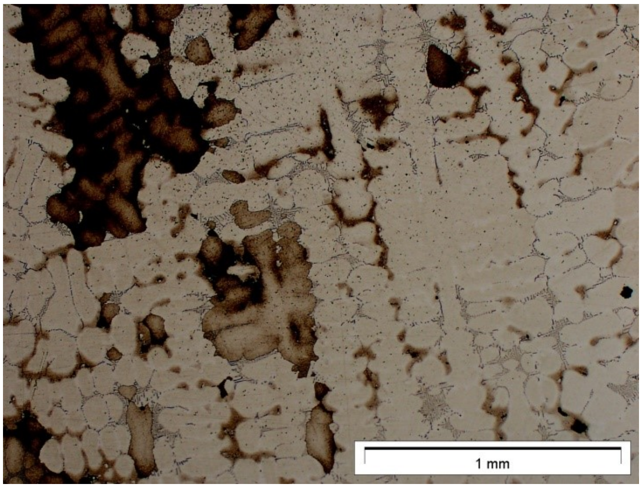


Fig. 1. Microstructure of IN 713C alloy in the as-cast condition; LM

In the inter-dendritic regions there was also an increased amount of Nb, Ti and Mo found which is related to the dendritic crystallization process. As a result of high temperature in the heat affected zone, the start of carbide precipitations dissolution process was observed together with the simultaneous disappearance of the two-phase matrix area. In the HAZ a diffusion transformation occurred between the MC primary carbides and the γ matrix. This transformation involves the diffusion of alloy components (Cr, Mo, Co, Ni, Ti) and also carbon from the matrix towards the carbide. Due to the faster diffusion of carbon, it combines with Cr or Mo, thus forming secondary carbides on the MC - γ boundary. Secondary carbides were found mainly in the inter-dendritic spaces, at the same time creating a characteristic "Chinese script" (Fig. 2). In the areas enriched with the elements Ni, Ti and Al and around the primary and secondary carbides the Ni_3(Al, Ti)(γ’ - phase) was formed. Inside the γ' layer there was the presence of secondary carbide precipitates found ($M_{23}C_6$ or M_6C) in irregular shape. The carbides found were rich in Cr and Mo (Table 2, Fig. 3). Additionally, in the area of the fusion line there was a compact phase observed which created areas without precipitations γ’(PFZ - precipitation-free zones) (Fig. 4). After the padding process, there were also cracks along the grain boundaries, which were mainly in the heat affected zone and on the fusion line. In the cracks area there was increased chromium content found (Table 3), which proves the formation of eutectic-forming carbides with the γ-phase and the γ'-phase. The presence of oxygen on the surface of the crack indicates the possibility of chromium oxide formation on the metal surface, which proves the characteristics of hot cracking.

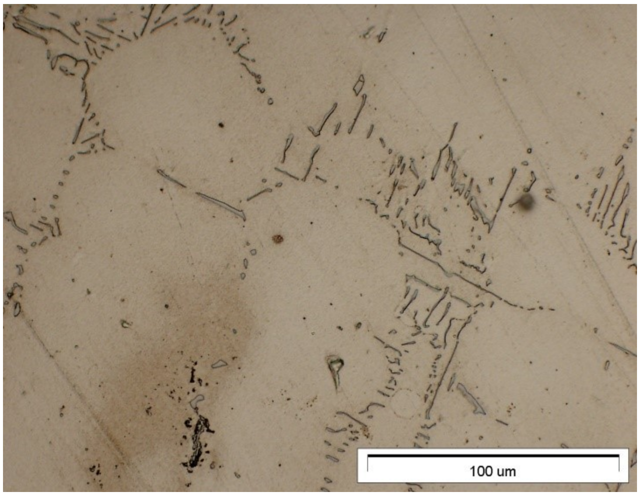
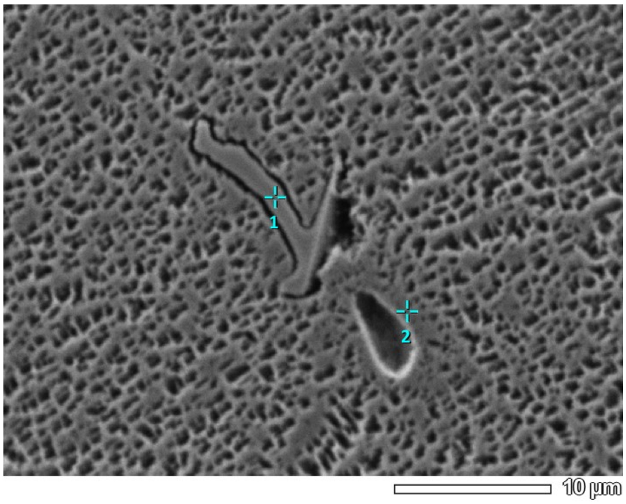


Fig. 2. Structure of IN 713C alloy with „Chinese scripts"

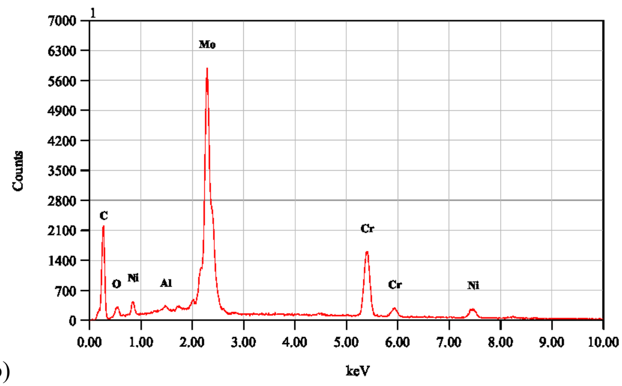
Table 2.
Chemical composition of the crack area of IN 713C

Spot	Al	Ti	Cr	Ni	Mo
1	0.44	0.51	25.23	8.42	65.4
2	3.08	0.47	22.78	64.45	9.22

Inside the γ' - phase precipitation there were spherical particles found, which arranged into characteristic chains crossing the γ'-phase separations (Fig. 5). A structural analysis has revealed that their morphology is similar to the $M_{23}C_6$ carbide precipitates that were formed around the decaying MC type carbides. $M_{23}C_6$ carbides play an important role in the strengthening the alloy by inhibiting the dislocation movements. They usually precipitate at the grain boundaries as irregular and discontinuous particles, which was confirmed by Energy Dispersive X-ray Spectrometer analysis (Table 4).



a)



b)

Fig. 3. a) The Cr and Mo- enriched carbide particles, b) The chemical composition of Cr and Mo- enriched carbide particles

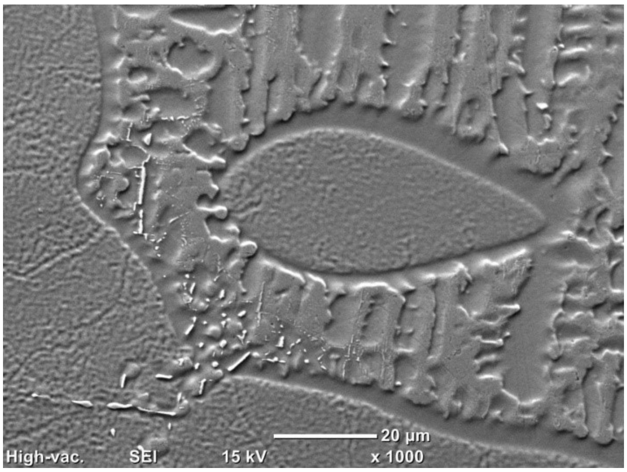


Fig. 4. The fusion line with the PFZ area

Table 3.
Chemical composition of the IN 713C with the (γ + γ') eutectic islands

Spot	Al	Si	Ti	Cr	Ni	Zr	Nb	Mo	Ta
011	1.74	0.34	0.79	17.58	75.27	0.14	0.99	2.90	0.24
012	4.70	0.21	0.89	14.70	72.62	-	1.87	4.55	0.47
013	3.31	0.16	3.69	10.66	46.90	-	25.05	9.89	0.34
014	0.47	0.20	9.63	3.31	10.99	-	66.97	8.06	0.36
015	1.12	0.37	0.45	18.83	60.90	3.18	3.02	11.77	0.36

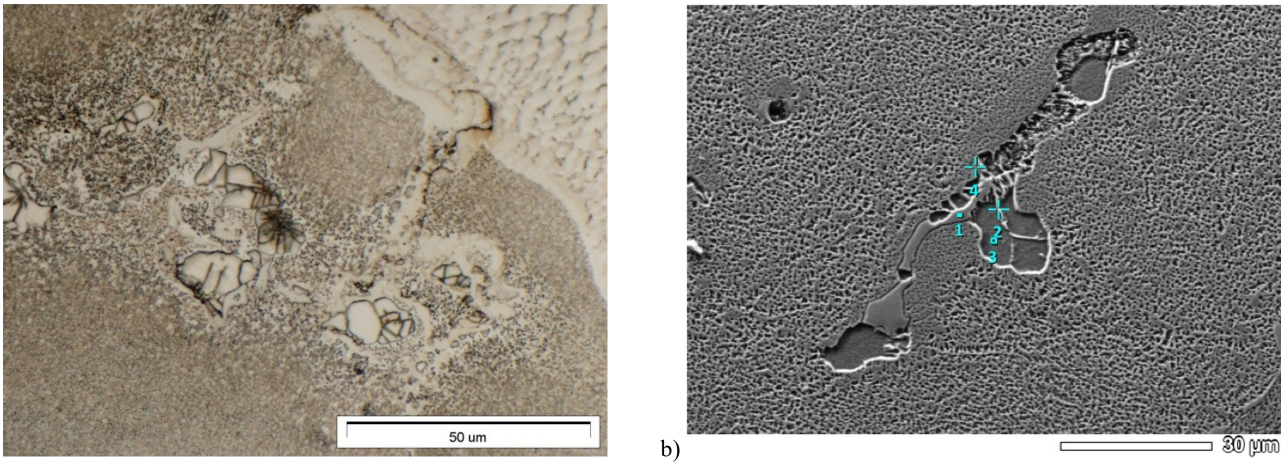


Fig. 5. The microstructure of the IN 713C with the (γ + γ') eutectic islands: a) LM, b) SEM

Table 4.
Results of the chemical composition microanalysis of the carbide particle

Spot	Al	Si	Ti	Cr	Ni	Nb	Mo
1	0.36	0.22	-	26.82	5.65	4.5	62.46
2	0.26	0.28	-	28.4	4.69	5.84	60.53
3	7.55	0.55	2.02	4.69	79.56	3.81	1.82
4	5.2	0.43	0.54	21.57	61.75	2.03	8.48

Cracks in the joint and the heat-affected zone HAZ arise as a result of the liquid layer rupture in the areas on the γ-phase dendrite surface and in the areas of γ-γ' eutectic crystallization (Fig. 6). The microanalysis of chemical composition in these areas showed an increased content of chromium and oxygen, which indicates the presence of chromium oxide on the surface and confirms that these are hot cracks.

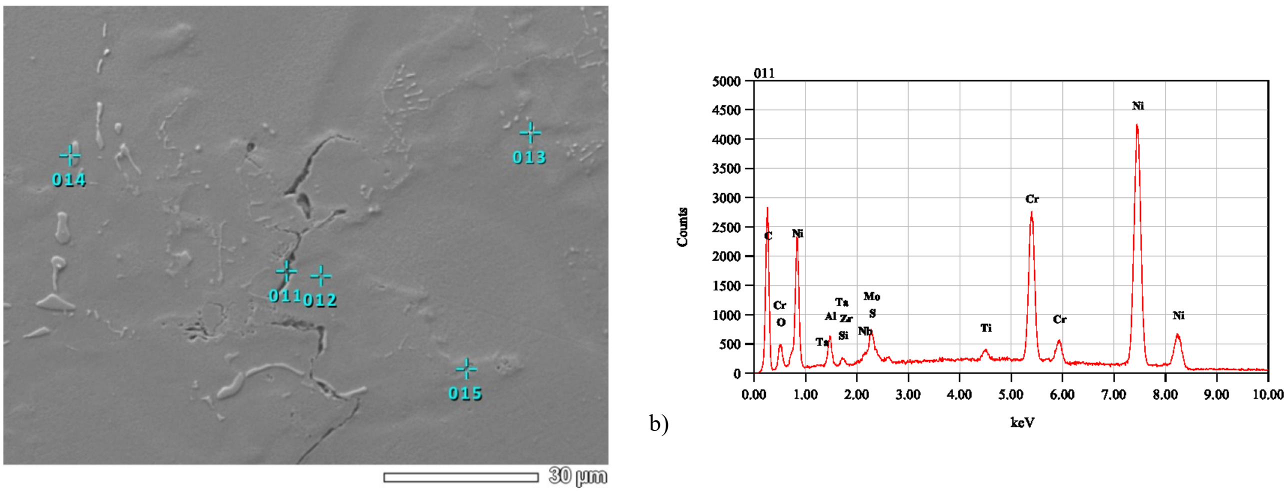


Fig. 6. a) The crack identified in the structure of the pad weld, b) The chemical composition of the crack

4. Conclusions

The structure of Inconel 713C was characterized by a dendritic structure consisting of the γ and γ' phases. In the grain boundaries and inter-dendritic areas there were precipitates of MC type primary carbides found. The temperature increase associated with the pad welding process had a significant influence on the change of Inconel 713C structure. In the weld structure, the carbide precipitations were dissolved and the two-phase matrix regions around these precipitates disappeared. It has also been observed that the direction of orientation and morphology changed depending on the observed weld area. In the HAZ in the interdendritic areas and on the grain boundaries there was a breakdown of MC carbides detected together with formation of secondary carbides in irregular shapes. The found secondary carbides were rich in Cr and Mo. In the inter-dendritic areas there was also eutectic γ - γ' present, close to the area where MC type carbides were observed. There was a continuous layer of γ'-phase found together with the carbides, which were located at the grain boundaries and on the boundaries of crackings.

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References

[1] Cieśla, M., Binczyk, F. & Mańka, M. (2012). Impact of Surface and Volume Modification of Nickel Superalloys IN-713C and MAR-247 on High Temperature Creep Resistance. *Archives of Foundry Engineering*. 12(4), 17-24. DOI: 10.2478/v10266-012-0101-2.

[2] Hernas, A. (2000). *Creep-resistance of steels and alloys*. Gliwice: Silesian University of Technology.

[3] Mastromatteo, F., Mammoliti, F., Giannozzi, M., Romanelli, M., Ficorilli, D. (2006). Metal temperature map determination of a serviced gas turbine bucket and comparision with FEM temperature distribution. Proceedings of ASME Turbo Expo 2006 Power of Land, Sea and Air; 8-11 May 2006 (pp. 913-918). Spain, Barcelona: The American Society of Mechanical Engineers Journal.

[4] Zupanîc, F., Bonĉina, T., Kiržman, A. & Tichelaar, F.D. (2001). Structure of continuously cast Ni-based superalloy Inconel 713C. *Journal of Alloys and Compounds*. 329, 290-297. DOI: 10.1016/S09258388(01)016760.

[5] Zagula-Yavorska, M. & Sieniawski, J. (2018). Cyclic oxidation of palladium modified and nonmodified aluminide coatings deposited on nickel base superalloys. *Archives of Civil and Mechanical Engineering*. 18(1), 130-139. DOI: 10.1016/j.acme.2017.05.004.

[6] Agnoli, A., Bernacki, M., Logé, R., Franchet, J., Laigo, J., Bozzolo, N. (2012). Understanding and Modeling of Grain Boundary Pinning in Inconel 718, 12th International Symposium on Superalloys 9-13 September 2012 (pp. 73-82). Pensylwania, United States: John Wiley and Sons.

[7] DuPont, N., Lippold, C., Kiser, D.S. (2009). *Welding metallurgy and weldability of nickel based alloys*. New Jersey: John Wiley & Sons.

[8] Szczotok, A. & Matysiak, H. (2014). Influence of constituents of shell mold on the morphology and chemical composition of carbides occurring in IN 713C superalloy castings. *Journal of Materials Engineering and Performance*. 23(8), 2748-2759. DOI: 10.1007/s11665-014-1035-3.

[9] Jia, Q. & Gu, D. (2014). Selective laser melting additive manufacturing of Inconel 718 superalloy parts: Densification, microstructure and properties. *Journal of Alloys and Compounds*. 585(2014), 713-721. DOI: 10.1016/j.jallcom.2013.09.171.

[10] Yuan, H. & Liu, W. (2005). Effect of the δ phase on the hot deformation behavior of Inconel 718. *Materials Science and Engineering*. 408(1-2), 281-289. DOI: 10.1016/j.msea.2005.08.126.

[11] Ges, A., Palacio, H. & Versaci, R. (1994). IN-713C characteristic properties optimized through different heat treatments. *Journal of Material Science*. 29(13), 3572-3576. DOI:10.1007/BF00352065.

[12] Pirowski, Z., Uhl, W., Wodnicki, J., Gwiżdż, A. & Jaśkowiec, K. (2011). Effect of heat treatment on structure of the Inconel 740 type alloy. *Prace Instytutu Odlewnictwa*. 51(2), 5-22. DOI: 10.7356/iod.2011.7.

[13] Pyczak, F., Devrient, B., Neuner, F.C. & Mughrabi, H. (2005). The influence of different alloying elements on the development of the γ/γ'microstructure of nickel- base superalloys during high-temperature annealing and deformation. *Acta Materialia*. 53(14), 3879-3891. DOI: 10.1016/j.actamat.2005.04.041.

[14] Łyczkowska, K., Adamiec, J., Jachym, R. & Kwieciński, K. (2017). Properties of the Inconel 713 Alloy Within the High Temperature Brittleness Range. *Archives of Foundry Engineering*. 17(4),103-108. DOI: 10.1515/afe-2017-0138.

[15] Binczyk, F., Gradoń, P. & Mańka, M. (2012). Mechanical Properties And Creep Resistance Of Nickel Alloys After Complex Modification And Double Filtration. *Archives of Foundry Engineering*. 12(2), 5-8. DOI: 10.2478/v10266-012-0026-9.

[16] Azadi, M., Marbout, A., Safarloo, S., Azadi, M., Shariat, M., & Rizi, M.H. (2018). Effects of solutioning and ageing treatments on properties of Inconel-713C nickel-based superalloy under creep loading. *Materials Science and Engineering A*. *711*, 195-204. DOI: 10.1016/j.msea.2017.11.038.

[17] Sufiiarov, V.S., Popovich, A.A., Borisov, E.V. & Polozov, I.A. (2015). Selective laser melting of heat-resistant Ni-based alloy. *Non-Ferrous Metals*. 1, 32-35. DOI: 10.17580/nfm.2015.01.08.

[18] Kang, D.S., Koizumi, Y., Yamanaka, K., Aoyagi, K., Bian, H., & Chiba, A. (2018). Significant impact of yttrium microaddition on high temperature tensile properties of Inconel 713C superalloy. *Materials Letters*. 227, 40-43. DOI: 10.1016/j.matlet.2018.03.106.

[19] Bahmanabadi, H., Rezanezhad, S., Azadi, M., & Azadi, M. (2018). Characterization of creep damage and lifetime in Inconel-713C nickel-based superalloy by stress-based, strain/strain rate-based and continuum damage mechanics models. *Materials Research Express*. *5*(2). DOI: 10.1088/2053-1591/aaab04.

[20] Szczotok, A., Pietraszek, J., & Radek, N. (2017). Metallographic Study and Repeatability Analysis of γ' Phase Precipitates in Cored, Thin-Walled Castings Made from IN713C Superalloy. *Archives of Metallurgy and Materials. 62*(2), 595-601. https://doi.org/10.1515/amm-2017-0088.