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Repair of Precision Castings Made of the Inconel 713C Alloy

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Abstract

Inconel 713C precision castings are used as aircraft engine components exposed to high temperatures and the aggressive exhaust gas environment. Industrial experience has shown that precision-cast components of such complexity contain casting defects like microshrinkage, porosity, and cracks. This necessitates the development of repair technologies for castings of this type. This paper presents the results of metallographic examinations of melted areas and clad welds on the Inconel 713C nickel-based superalloy, made by TIG, plasma arc, and laser. The cladding process was carried out on model test plates in order to determine the technological and material-related problems connected with the weldability of Inconel 713C. The studies included analyses of the macro- and microstructure of the clad welds, the base materials, and the heat-affected zones. The results of the structural analyses of the clad welds indicate that Inconel 713C should be classified as a low-weldability material. In the clad welds made by laser, cracks were identified mainly in the heat-affected zone and at the melted zone interface, crystals were formed on partially-melted grains. Cracks of this type were not identified in the clad welds made using the plasma-arc method. It has been concluded that due to the possibility of manual cladding and the absence of welding imperfections, the technology having the greatest potential for application is plasma-arc cladding.

Keywords: Weldability, Inconel 713C, Precision castings, Hot cracks

1. Introduction

Nickel-based casting superalloys used in the aircraft industry contain numerous alloying elements, e.g. Ti, Al, Mo, W, Nb, Zr, B, V, Y, La, and Re [1-2]. One of such superalloys is Inconel 713C, which has been successfully used for crucially important components working in the temperature range of 700÷950 °C, e.g. low pressure turbine blades and guide vane segments (Fig. 1a). Inconel 713C is a polycrystalline, precipitation-strengthened nickel-based superalloy. It is characterised by a close packed, face-centred-cubic structure made up of coherent γ' phase precipitates (Ni_3Al) accounting for min. 50% of the structure, nickel dendrites, and eutectic and primary MC carbides. This enables obtaining a stable γ/γ' bond inhibiting dislocation, which results in increased creep resistance at elevated temperatures [3, 4]. The mechanical properties of the nickel-based alloy depend mainly onthe shape, size, and volume fraction of γ' phase particles, which, however, can change depending on the service parameters and the heat treatment applied [5].

The basic technology used for producing Inconel 713C components is precision casting [6]. It is a complex and costly technology, however, it enables obtaining a complete element, which, after the application of finishing machining and heat treatment, can be used in aircraft engines [6]. However, the process involves the formation of defects. These include mainly cracks, microshrinkage, and porosity (Fig. 1b) [7]. Such defects prevent any further use of affected castings. Currently, attempts are being made at repairing such defects by welding technologies (Fig. 1c).


a)

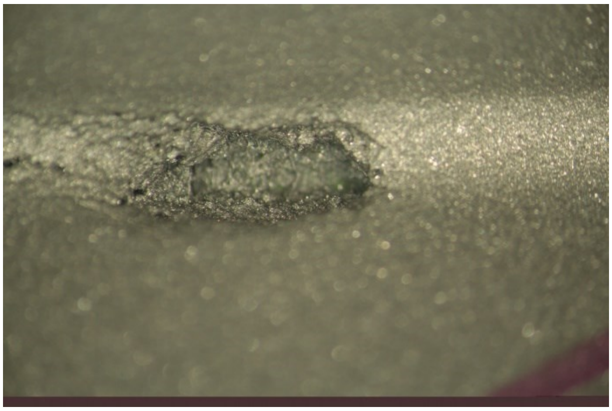

b)

Fig. 1. Repair of an Inconel 713C vane segment: a) a guide vane segment, b) surface defects identified in the casting and classified as requiring repair, c) repairing defects by TIG pad welding

The analysis of the literature indicates that despite attempts at melting and cladding, Inconel 713C should be classified as a low weldability material due to its susceptibility to hot (crystallisation) cracking at the fusion line. This results mainly from its complex casting structure, the large number of carbides, and the fact that precision castings have complex shapes and thin walls.

The development of modern cladding technologies, e.g. plasma technologies and laser cladding enables applying such methods to repairs of defects in precision castings. This paper presents the results of the structural examinations of melted areas and clad welds made by TIG, laser, and plasma arc on precision-cast specimens made of the Inconel 713C alloy.

2. Methodology and test results

The purpose of the tests was to assess the structure in the melted zone, the heat-affected zone (HAZ), and the base material (BM) of melted areas and clad welds made on Inconel 713C precision castings. The specimens used for the melting tests were precision castings in the form of 1 mm, 3 mm, and 5 mm thick plates. The castings were made at Consolidated Precision Products Poland Sp. z o.o. as part of the project financed by the National Centre for Research and Development [9]. The chemical composition of the test material was verified by an XRF analysis performed using a Niton XLt 898W analyser (Table 1, Fig. 2a). Based on the analysis of the chemical element content and the radiographic radiation spectrum, the alloy studied was found to fulfil the material specification requirements. The metallographic examinations revealed that the alloy in the initial condition was characterised by dendritic structure made up of γ phase crystals forming the face centred cubic (A1) lattice, with the alloying elements Cr, Co, and Mo dissolved in the lattice. The interdendritic spaces contained the γ-γ’ eutectic mixture ($Ni_3(Al,Ti)$) and individual carbide precipitates (Fig. 2b).

Table 1.
Chemical composition of IN 713C determined by XRF

Alloy1	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
Material specification	balance	12-14	5.5–6.5	3.8–5.2	<2.5	<0.15	-	<0.5	1.8–2.8	<2.5	<0.25	0.5–1.0

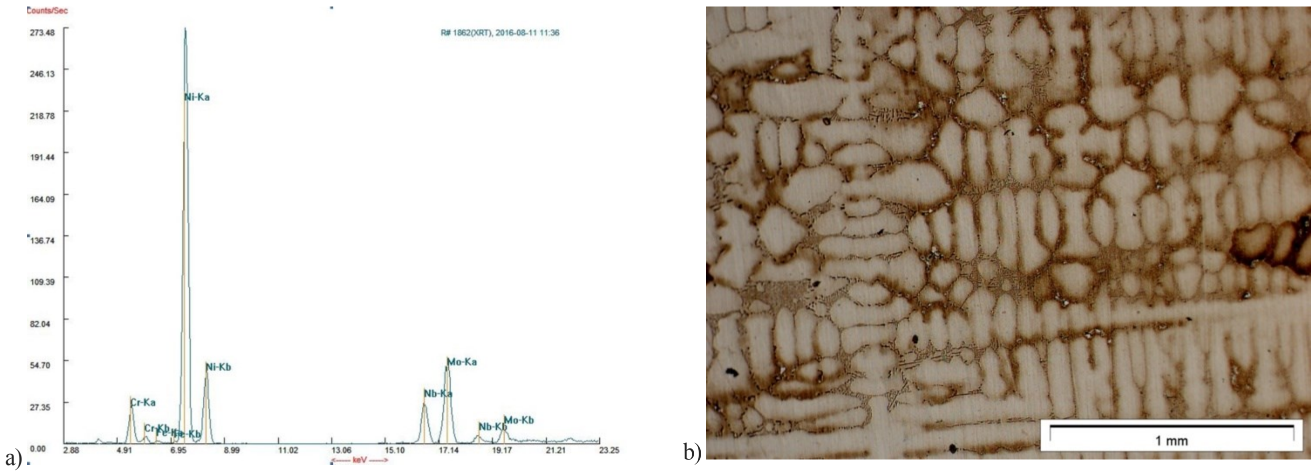


Fig. 2. XRF spectrum showing the chemical composition of the IN713C alloy (a), Microstructure of the alloy in the as-cast condition (b)

The technological tests of TIG melting were conducted at the Silesian University of Technology and the processes of plasma arc melting and cladding and laser melting were carried out at the Welding Institute in Gliwice. The TIG melting was carried out using a Lincoln Invertec V205-T power source, with the direct current of 50 A and argon as the shielding gas, at the gas flow rate of 12 l/min.
The plasma arc melting was carried out in an inert shielding gas (argon), the gas flow rate being 6 l/min, using a 1.6 mm thick tungsten electrode and plasma gas nozzle having a diameter of 1.2 mm, with a direct current of 5–18 A and an arc voltage of 20 V. A filler material complying with the material specification for Inconel 625 was used for the cladding.
A 12 kW Trumpf LaserDisk 12002 disk laser with a D70 Hybrid head and a 0.3 mm optical fibre was used for the laser melting. The focal length was 400 mm and the focus diameter was 0.6 mm. Beam power of 1 kW to 2.5 kW and the melting rate of 1–2 m/min were applied in the melting process. Argon was used as the shielding gas.
The specimens for the metallographic examinations were cut out perpendicularly to the melting direction so that all the zones would be revealed. The specimens were subsequently ground and polished using abrasive paper and diamond polishing paste. In order to reveal the structure, the material was etched in an etchant having the following chemical composition: $FeCl_3$, $CuCl_2 \cdot 2NH_4Cl \cdot 2H_2O$, HNO_3, HCl, and H_20. The metallographic examinations were conducted using the SZX9 stereoscopic microscope (SM) at magnifications of up to 50x (Fig. 3–5) and the Olympus GX71 light microscope (LM) at magnifications of up to 500x, in the bright field mode (Fig. 6–7). The structure was also examined under the JEOL JCM-6000 Neoscope II scanning electron microscope (SEM). Images were recorded in the secondary electron mode, at a magnification of up to 1000x and at a voltage accelerating the electron beam to 15keV. The examinations were complemented by the EDS microanalysis of the chemical composition in the crack area. Examples of results of those examinations are shown in Fig. 8 (for plasma arc melting) and in Fig. 9 (for laser melting).

3. Summary

Melting and cladding tests were conducted on precision-cast Inconel 713C test plates. The melting was carried out using the TIG method (I=50A), a plasma arc with an electric current of up to 18 A (in the inert gas atmosphere), and a disc laser, with a beam power of up to 2.5 kW. The purpose of the tests was an initial determination of the weldability of Inconel 713C precision castings characterised by varied wall thickness and the formulation of initial guidelines for the development of repair technologies for this type of castings.
The examination of the macrostructure of the TIG melted areas revealed three typical zones, i.e.: the base material, having a dendritic structure, the heat affected zone, in which crystals were observed to grow on partially melted dendrites along the fusion line (Fig. 3), and the melted zone. The microstructural analysis led to the identification of cracks along crystal boundaries in the HAZ (Fig. 6a,b).

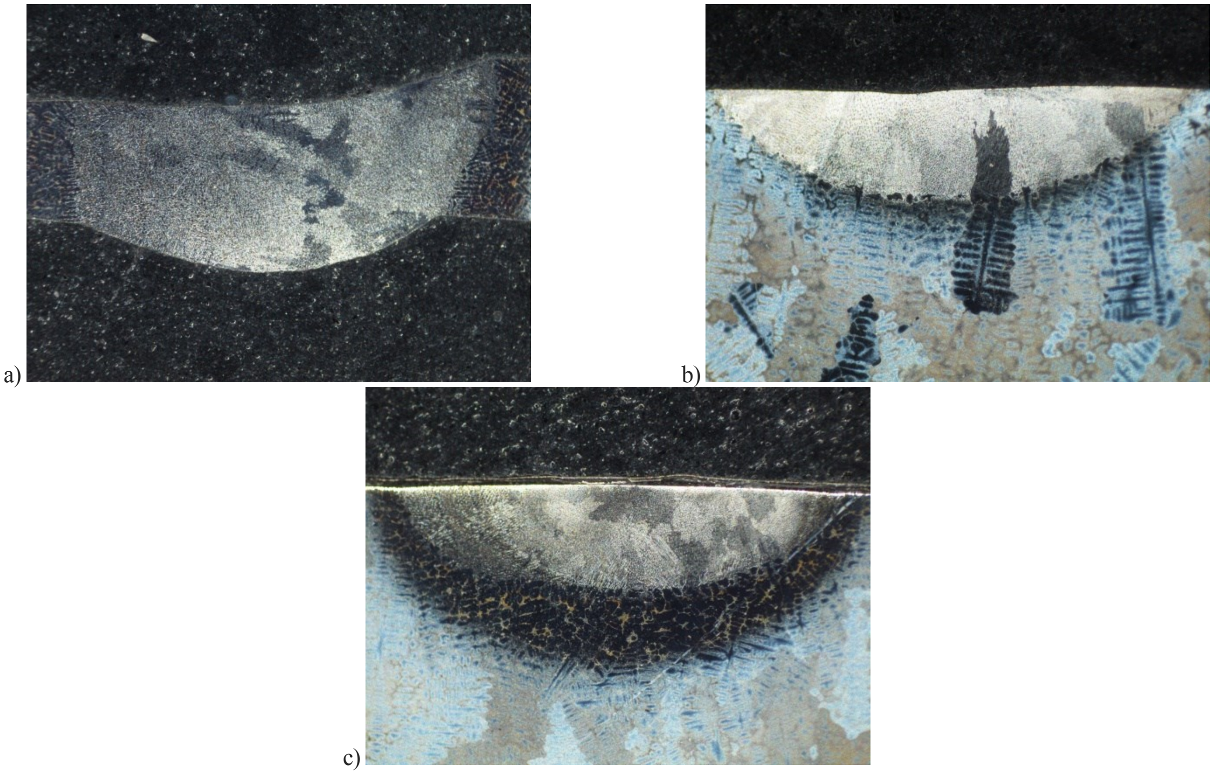


Fig. 3. Macrostructure of the melted areas and pad welds made by TIG: a) melted area on the 1 mm thick plate b) melted area on the 3 mm thick plate c) melted area on the 5 mm thick plate

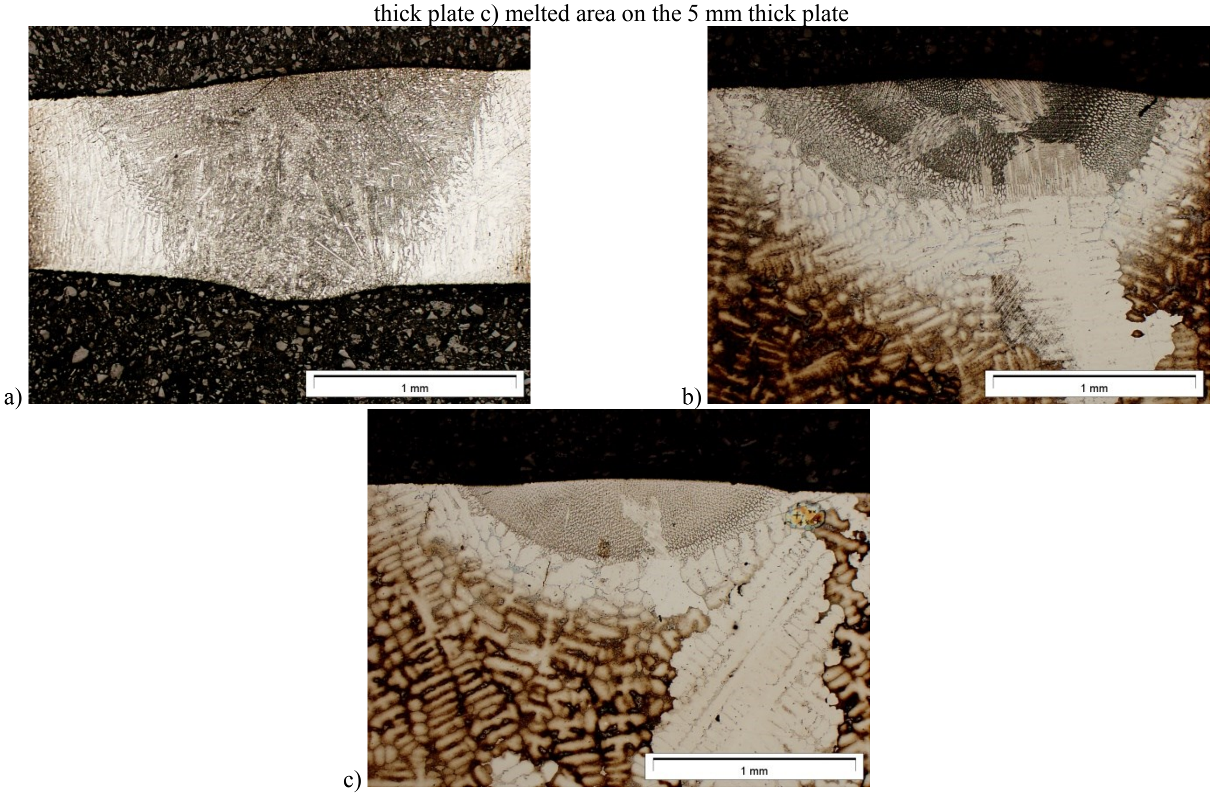
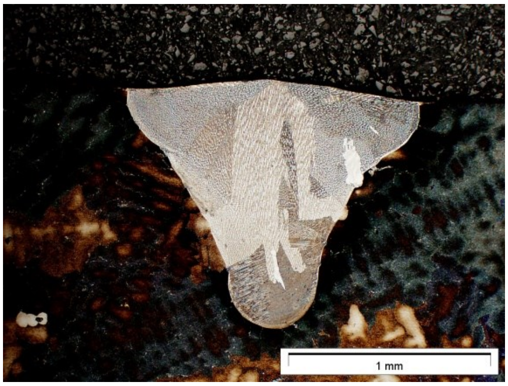
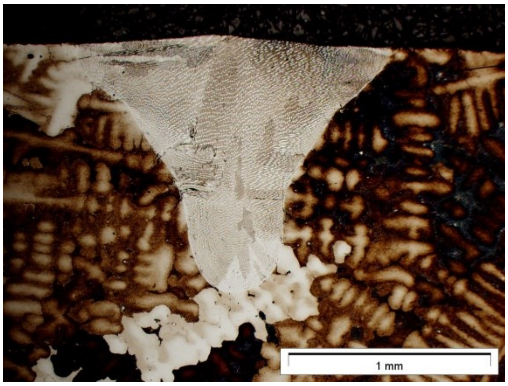


Fig. 4. Macrostructure of the melted areas and pad welds made by plasma arc: a) melted area on the 1 mm thick plate, b) melted area on the 3 mm thick plate, c) melted area on the 5 mm thick plate



a)



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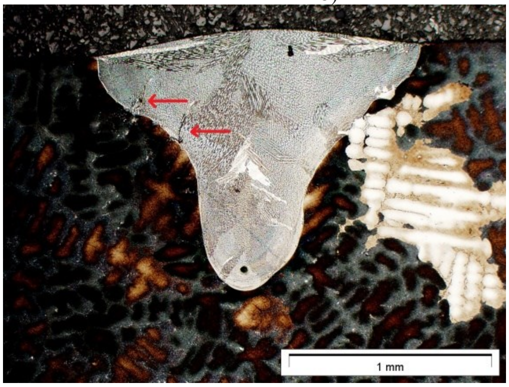
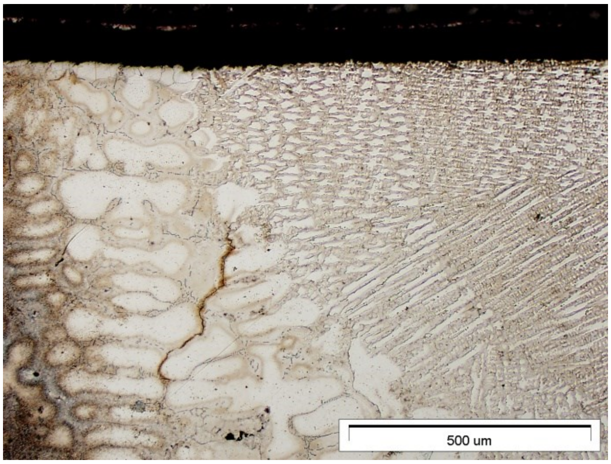
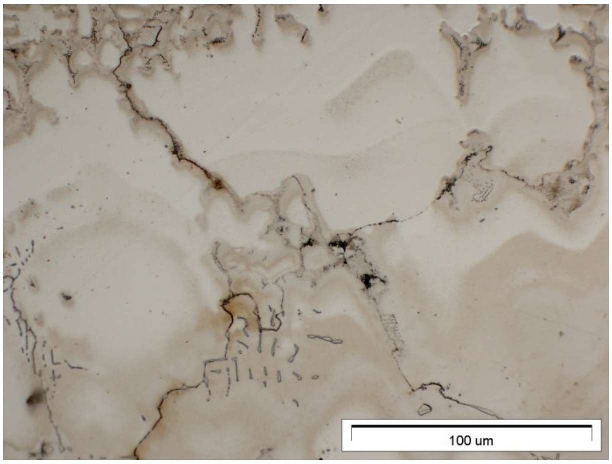


c)

Fig. 5. Macrostructure of the melted areas made by disk laser : a) melted area on the 1 mm thick plate, b) melted area on the 3 mm thick plate, c) melted area on the 5 mm thick plate (the cracks identified are indicated with arrows)



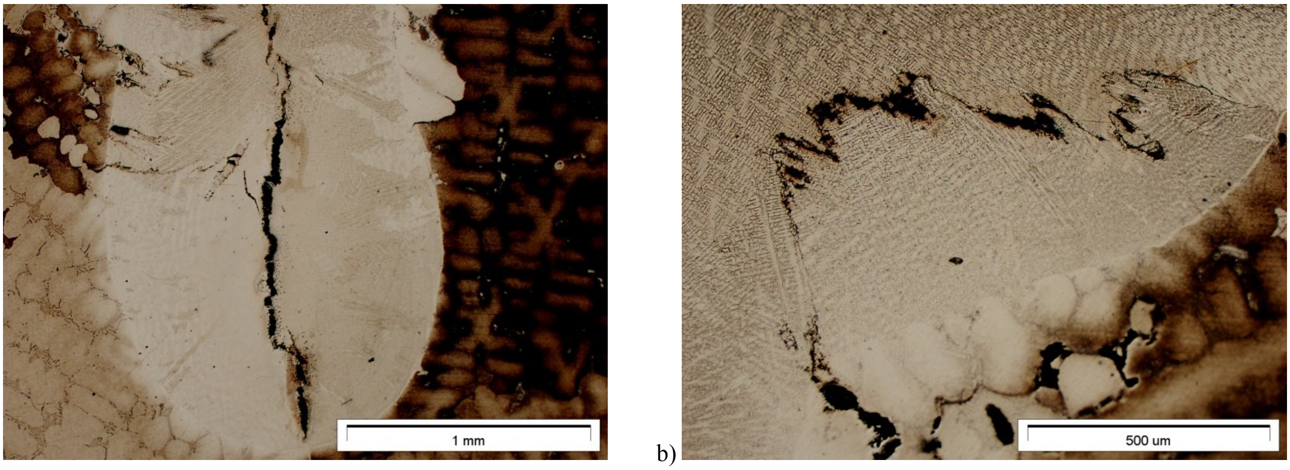
a)



b)

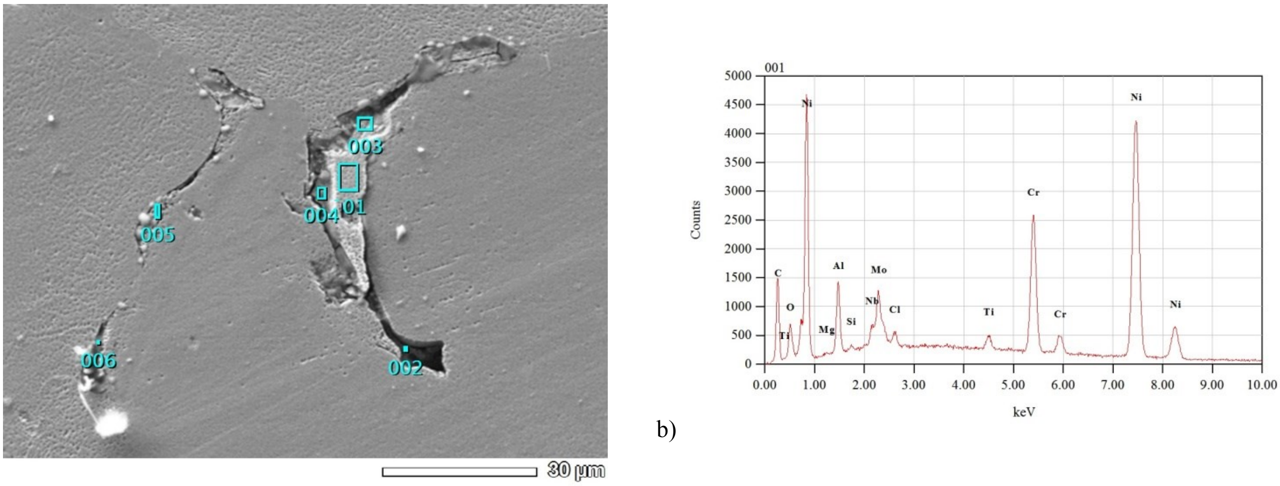
Fig. 6. Cracks identified in the structure of the melted zone on an Inconel 713C casting (TIG): a) cracks along crystal boundaries in the HAZ, b) a crack in the HAZ related to the partial melting of the eutectic mixture and carbides

The examinations of the macrostructure of the melted areas made by plasma arc revealed no cracks in the 1 mm and 3 mm thick plates (Fig. 4 a,b); as for the 5 mm thick plate, cracks were identified in the HAZ (Fig. 4c). Detailed metallographic examinations indicate that the cracks formed as a result of the partial melting in the interdendritic spaces in the base material and the rupture of a thin interdendritic liquid film that occurred due to deformations taking place during the weld pool crystallisation. This was confirmed by the results of the examinations under the scanning electron microscope and the results of the EDS microanalysis of the chemical composition in the crack area (Fig. 8). It was determined that the chemical composition of the phases identified on the crack surface is similar to that of the base material, which indicates that the crystals were partially melted and subsequently a thin liquid film crystallised on their surface. This cracking mechanism is related to the partial melting of the material in the partially-melted zone, which is described in the literature [9].



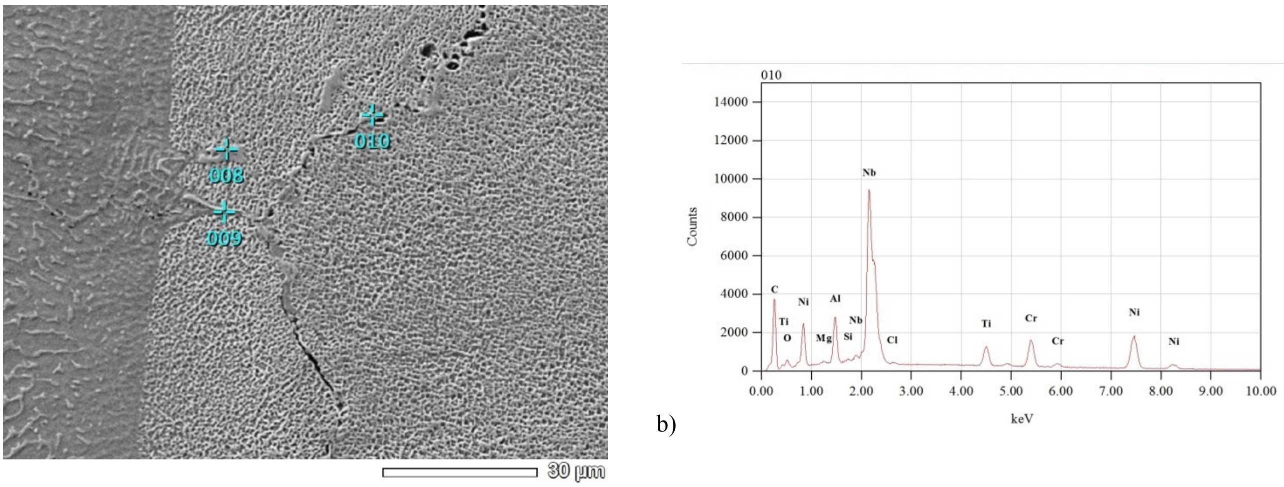
a) b)

Fig. 7. Cracks in the structure of the laser melted area on an Inconel 713C casting: a) hot cracks in the melted zone, b) crack along crystal boundaries at the fusion line



a) b)

Fig. 8. Results of the chemical composition microanalysis of the crack area in the HAZ — specimen melted by plasma arc



a) b)

Fig. 9. Results of the chemical composition microanalysis at the fusion line — specimen melted by laser

Markedly better results were achieved for the cladding process with the use of the filler material. The metallographic examinations revealed no microcracks; only the shape of the clad welds was unfavourable, as the angle between the clad weld surface and the base material was very wide (approx. 90°). However, due to the fact that subtractive machining is allowed for in precision casting repair technologies, this non-conformity is acceptable.
The analysis of the areas melted by laser beam revealed that the shape of the melted area was correct and depended on the beam power and the positioning of the beam (Fig. 4). In all specimens melted by laser, hot cracks were identified in the melted zone (Fig. 7), which is related to the rapid crystallisation process and the resultant strains, deformations, and shrinkage.
The analysis of the crack areas indicated that one of the cracking mechanisms was the mechanism described in [9]. The heat of the laser beam causes partial melting of carbides (e.g. NbC) along grain boundaries; subsequently, an eutectic mixture forms during crystallisation (Fig. 9). The shrinkage involved in this process leads to the formation of a crack.
Based on the tests performed, it was concluded that the technology with the highest potential for application to repairs of Inconel 713C precision castings is plasma arc cladding with the use of a filler material. However, in the process of developing a cladding technology, it is necessary to bear in mind that Inconel 713C is a low-weldability alloy having limited metallurgical and constructional weldability.

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