# THE REPAIR OF INCONEL 713LC TURBINE BLADE WITH ARTIFICIAL DEFECTS BY COLD SPRAY TECHNOLOGY

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**Abstract**

Cold spray (CS) is a promising technology for the restoration of worn parts manufactured from numerous materials. The most important benefits are the preclusion of phase transformation caused by bonding by plastic deformation at low temperatures, providing oxide-free coatings with internal compressive residual stresses. The deposition of Ni-superalloys, namely Inconel, is a challenging task due to the insufficient acceleration of powder particles while using nitrogen as a processing gas. This leads to a low deposition efficiency (DE) and the formation of rather low-quality coatings. This study presents the first results of the restoration of artificial defects fabricated on a real turbine blade manufactured from Inconel 713LC (substrate) and the influence of the substrate preheating. This work aims to validate the Inconel 713LC as a material suitable for cold spraying. The powder particles, substrate, and coatings were characterized by the scanning electron microscopy (SEM). The powder particle size varied from 22 to 53 μm. The X-ray diffraction was performed to assess the phase composition and the hardness measurement for comparison of the powder particles and the coating hardness. Metallographic analysis was conducted to study the interface between coating and artificial defects and to evaluate the restoration capability of cold sprayed Inconel 713LC. The Inconel 713LC coating was successfully deposited onto the real turbine blade with artificial defects. The geometry of defects has a significant influence on the quality of the coating. Phase transformations studied by means of X-ray diffraction were not detected.

**Keywords:** Cold Spray, Inconel, repair, artificial defects

## 1. INTRODUCTION

The cold spray (CS) technology is considered the youngest thermal spray technology which is also included into the family of additive manufacturing technologies due to its precision and low temperature influence on processed materials. The technology is based on the acceleration of particles (mostly metal) by the supersonic gas jet with temperatures reaching up to 1200 °C. Feedstock with a powder particle size from 1 to 100 μm is injected by overpressure into the divergent part of the de Laval nozzle where the particles are accelerated up to 1200 $m \cdot s^{-1}$. Nitrogen or helium serves as a processing gas because of their specific molecular weights and sonic velocities. Nitrogen has approximately seven times higher molecular weight, but its sonic velocity is 2.89 times lower than that of helium at the same Mach number and gas temperature [1,2]. Due to these facts, helium is capable to accelerate powder particles to higher velocities using the same processing parameters [2,3]. Nevertheless, the price and technological simplicity to obtain nitrogen result in its increased popularity. This is also caused by an expensive and complex spraying booth with a gas recycling system while using helium as a processing gas [3].

Each powder material has its own critical velocity, which describes the threshold velocity for successful deposition. In general, the critical velocity depends mainly on the density of the material, the ultimate tensile strength, the melting temperature, and the actual temperature of the powder particles upon impact. The powder

particles spend only a short period of time in the hot gas stream (up to 1200 °C); therefore, the deposition process takes place in the solid state, and that is one of the most important benefits of this technology [4].

The choice of powder and substrate material and substrate surface treatment is important regarding the bonding mechanism. In the case of the CS deposition of hard powder particles on a hard substrate, the main bonding mechanism is believed to be microwelding. To improve the quality of the interface between the substrate and the coating, the substrate should be polished prior to deposition [5-7].

Wu et al. [8] successfully deposited IN713C on the IN718 substrate with a gas pressure of 45 bar and a temperature of 1000 °C. The resulting coating consisted of 10 layers and had only 0.3 mm in thickness with a low internal porosity of 1.23 % and a hardness reaching up to 500 HV0.5. The low thickness of the coating suggests a low deposition efficiency of the process. Ma et al. [6] compared IN718 coatings sprayed using helium and nitrogen as processing gas in the as-sprayed and heat-treated state. The study shows a decrease in porosity with increasing gas pressure, while using nitrogen as a processing gas from 30 to 70 bar. An even greater decrease in porosity was provided by using helium at the same gas temperature (1000 °C) but with lower pressure (30 bar). The porosity of all samples decreased even more after the implementation of heat treatment (990 °C/4 h) into the process. The mentioned studies show that Inconel superalloy coatings are feasible when using nitrogen as a processing gas with processing parameters reachable by industrial CS system.

This work describes the future use of Inconel 713LC as a material suitable for repairing parts using CS technology from the point of view of phase transformations during deposition, effectivity of the process, evolution of hardness and feasibility of the repair process. This study is the first attempt to use this specific Inconel superalloy as feedstock powder and suggests improvements to increase sprayability via CS technology.

## 2. MATERIALS AND METHODS

In this work, Inconel 713LC (Sandvik Osprey Ltd., UK) with a powder size in the range from 22 to 53 μm was deposited on the Inconel 713LC substrate prepared from the real turbine wheel blade. The powder feedstock was prepared by gas atomization in inert gas and obtained a spherical morphology with satellites and/or agglomerated particles. The morphology of the feedstock powder was observed by scanning electron microscopy (Ultra Plus, Zeiss, Germany).

For the assessment of the repair capability of CS technology, artificial defects were ground and drilled into the two turbine blades used as substrates. The ground scratches had a maximum of 3 mm in width, and the holes were drilled by a borer with 6 mm in diameter. After manufacturing the defects, the substrates were sandblasted (F30 alumina), ground, and polished with diamond pastes (7, 3 and 1 μm). The duration of each grinding and polishing step was 5 minutes and it was carried out with a handheld multitool (Dremel 3000, Bosch, Netherlands). Before deposition, the blades were cleaned in an ultrasonic bath with acetone and dried with hot air. For calculating the process efficiency, the weights of the powder and substrates were measured before and after deposition.

The coatings were deposited using Impact Innovations 5/11 cold spray gun (Impact Innovations GmbH, Germany) connected to a six-axis robotic arm (IRB 4600, ABB Ltd., Germany). The “OUT 1” de Laval nozzle manufactured from SiC was chosen for the deposition. The nozzle had a length of 130 mm and was used in combination with a short prechamber supplied with the system. The deposition parameters were selected based on the technological limits of the cold spray setup, experience, and the Kinetic Spray Solution software. The pressure and temperature were 50 bar and 1020 °C, respectively. The standoff distance was chosen to be 30 mm in combination with 400 $mm \cdot s^{-1}$ as the scanning speed. The trajectory used was the Zig-Zag with a 1 mm step (**Figure 1b**). The deposition angle between the gun and the substrate holder was set to be 90°. Before deposition, the first blade (substrate) was preheated with hot nitrogen (10 passes without

powder) and will be further designated as “G” while the second blade was preheated by IR (infrared) ceramic heaters and will be further designated as “IR”. The coatings on the individual substrates after sampling are illustrated in (**Figure 1**)**.** The arrows show the examined cross sections.

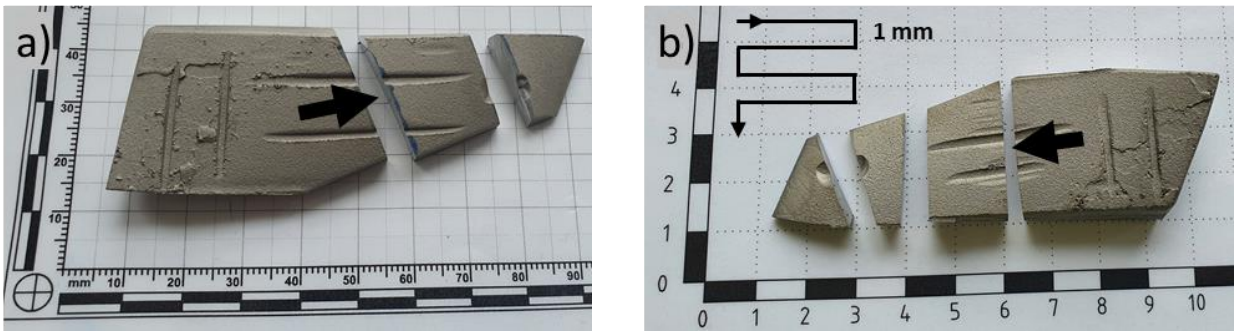


**Figure 1** Coated turbine blades after sampling, a) substrate “G”, b) substrate “IR”

The microstructure, morphology, and chemical composition of the powder and coatings were analyzed by a scanning electron microscope (SEM) equipped with an EDS spectrometer. SEM analysis was also used to study the quality of the interface between the substrate and the coating and the individual layers of coating. The coating thickness was measured on a polished cross-section of a standard metallographic sample using Olympus StreamMotion software.

The phase composition of the powder and coating was examined by X-ray diffraction (X’Pert pro, Phillips, Netherlands) using a Cu Kα radiation operated at a current of 30 mA and a voltage of 40 kV. The diffraction patterns were scanned between 20° and 105° with the step 0.016°. The post-processing of the diffraction data was executed using X’Pert Highscore software (Malvern Panalytical Ltd., Netherlands).

Hardness measurements of the powder, substrate and coatings were performed using the Qness Q10A hardness tester (QATM GmbH, Germany) with a force of 50 g on the powder, and 500 g on the substrate and coating. The hardness of the substrate and the coating was measured in a cross-section perpendicular to the spraying direction.

## 3. RESULTS AND DISCUSSION

As mentioned above, the Inconel 713LC powder was used for the restoration of artificial defects by CS technology. The measured chemical composition of the powder is in agreement with the chemical analysis executed by the manufacturer. The microstructure of the powder particles was of a dendritic character and the interdendritic spaces exhibited a different chemical composition if compared to the dendrites. Different segregation behavior of elements, e.g., Mo, Nb, and Zr, during rapid cooling (gas atomization process) causes an increase in their concentration in interdendritic spaces. Due to this phenomenon, interdendritic spaces possess lower concentrations of Ni and Al [9,10].

All X-ray diffraction spectra obtained from the feedstock powder and the deposited coating show the same phase composition as expected. The CS process precludes any excessive heating, melting, and presence of any phase transformations. The only difference is the thickness of individual peaks, which is caused by plastic deformation (increase in dislocation density) during cold spraying in the case of coating [9].

The change in hardness was examined by measuring the powder particles (435 ± 24 HV0.05), the substrate (375 ± 18 HV0.5) and the coating (HV0.5). In this case, an important phenomenon occurs during spraying: the harder the substrate and powder particles are, the lower the probability of successful deposition. To overcome this setback, higher deposition parameters or helium as a processing gas should be used [10].

The anticipated trend in the substantial increase in hardness of the coating (if compared to the hardness of powder particles) caused by the deformation strengthening was increased by bombardment of the coating by impacting powder particles that did not deposit onto previously deposited layers but were deflected. This phenomenon is in the literature called “the hammering” or “shot peening” effect [11,2]. The deformation strengthening was also present in the subsurface layer of the substrate, which is consistent with the current literature [8]. The hardness of the substrate material close to the substrate/coating interface increased to 418 ± 17 HV0.5 in case of the “G” substrate and to 415 ± 28 HV0.5 for the “IR” substrate, while the hardness of the substrate farther from the interface was 375 ± 18 HV0.5. The hardness of the coating increased, compared to powder, on the substrate indicated as “G” and on the substrate indicated as “IR” up to 696 ± 29 HV0.5 and 655 ± 37 HV0.5, respectively. The slight decrease in the measured hardness can be attributed to the more pronounced heating of the “IR” substrate. Wu et al. measured the hardness of the IN713C coating (10 layers) and obtained values reaching ~500 HV0.5 near the substrate/coating interface. The subsurface layer of the substrate also had an increase in hardness after deposition, namely from ~250 to ~300 HV0.5 [8].

The overall process efficiency was calculated as the difference in substrate weight before and after deposition (weight of the coating), divided by the initial weight of the powder put into the powder container minus the weight of the powder after deposition and the cleaning process. Powder losses during deposition were caused by overspraying and deflecting of particles from the substrate or already deposited coating. Overspraying outside of the substrate was needed during deposition using a Zig-Zag trajectory to achieve the set constant scanning speed of the gun while spraying onto the substrate. The robotic arm equipped with the gun needed time and space to safely decelerate from the set scanning speed (400 $mm \cdot s^{-1}$) and then accelerate again. The other minor powder losses were caused by the powder remaining in the powder feeder, the powder line, and the powder sprayed prior to the deposition itself to flush out any remaining powder from previous deposition.

CS deposition onto the substrates “G” and “IR” were two individual experiments. The substrate “G” was preheated by 10 passes of the gun (duration of 2.15 min) heated up to the deposition parameters (1020 °C, 50 bar) and the overall weight of the powder used for this experiment was 111.85 g. The deposition process consisted of 20 layers and the weight of the powder deposited on the substrate was 2.34 g, resulting in 2.07 % process efficiency. The heating of the “IR” substrate took 15 minutes, and the measured surface temperature was approximately 300 °C. The deposition process consisted of 30 layers and the weights of the powder used and deposited were 253.26 g and 4.69 g, respectively. The resulting process efficiency was similar, namely 1.85 %.

The low process efficiency could have been caused by the presence of satellites on feedstock powder particles and agglomerates and/or low gas temperature during spraying, resulting in insufficient powder particle velocity, as Ma et al. mentioned in their work [6]. In this case, the process efficiency is probably also negatively influenced by the presence and geometry of the artificial defect on the substrate, where the deposition angle differs from 90°. A substantial increase in efficiency would be achieved by using helium as a processing gas [2,3].

The uneven thickness of the coating in the artificial groove and its closest vicinity was caused by the specific geometry of the groove, while the rest of the substrate was uniformly coated with a coating thickness ~170 µm for the substrate “G” and ~250 µm for the substrate “IR” (**Figure 2**).

The coatings with the highest thicknesses were deposited into the drilled holes in both substrates, approximately 540 µm on the “G” substrate and ~840 µm on the “IR” substrate, where the difference in impact angle was the lowest. The angle of impact differed from 90° mainly for particles that impacted at the edges of holes or grooves. This phenomenon resulted in substantially lower coating thicknesses at those edges (~32 µm) in comparison with the middle of the grooves, as shown in (**Figures 3a** and **3b)**, where the maximum

thicknesses were ~330 µm and ~600 µm, respectively. The combination of material buildup with Zig-Zag trajectory and sudden change in the deposition angle could have caused coating delamination between individual layers (**Figure 3**). The lack or absence of bonding of the particles caused their deflection, and the deflected particles negatively influenced the deposition of other impacting particles by colliding with them, resulting in an overall low process and deposition efficiency.

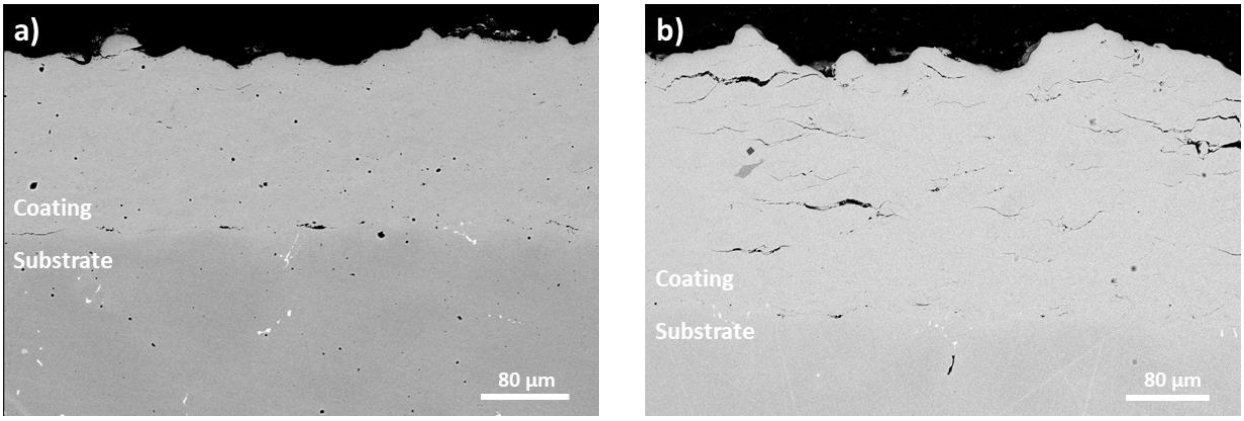


**Figure 2** Micrographs of the coating and the substrate/coating interface (SEM, BSE): a) “G”; b) “IR“

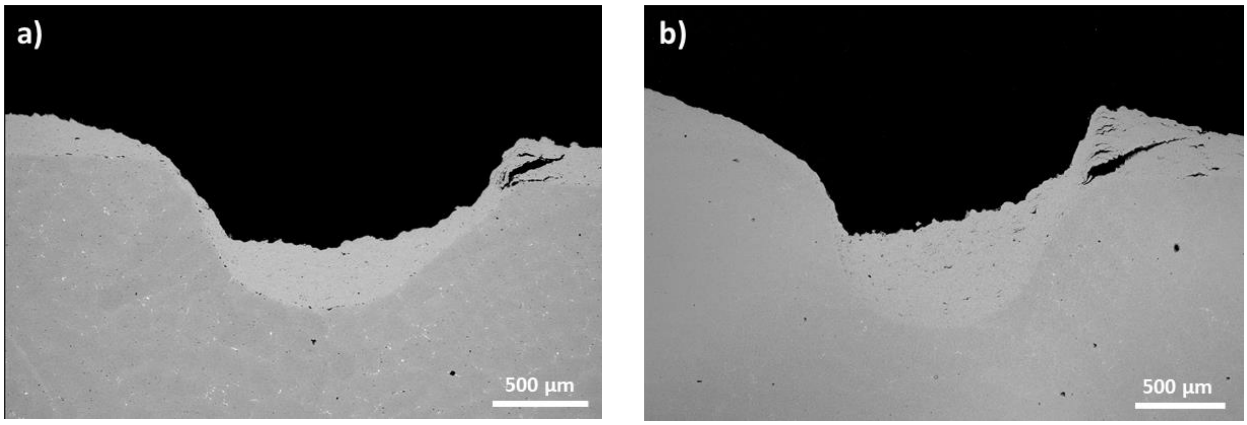


**Figure 3** Micrographs of grooves after deposition (SEM, BSE): a) “G”; b) “IR”

The black spherical “holes” present in (**Figures 2** and **3**) are carbon particles – the artefacts created during sample preparation for SEM analysis. The porosity of the coating is negligible in areas where the individual layers bond well together. This fact was associated with a low process efficiency and the hammering effect of the deflected particles [12]. Visible increase in porosity caused by imperfect bonding between layers is shown in (**Figures 2b** and **3b**), in the coating deposited in the groove. The delamination between layers was attributed to the preparation of a metallographic sample during which high forces and long grinding and polishing times were applied for individual steps.

## 4. CONCLUSION

Based on X-ray diffraction analysis, the absence of phase transformations during deposition was confirmed. The methodology to calculate the process efficiency used in this work is simple and includes overspraying and losses caused by cleaning the powder container. The low process efficiency implies the low restoration capability of Inconel 713LC using this particular setup including processing parameters. The quality

of the interface and the coating was, from the visual point of view, satisfactory in both investigated cases. The low porosity, the interface without a high amount of defects and the high coating hardness can be attributed to the significant hammering effect caused by hard impacting and deflecting Inconel particles.

An increase in the restoration capability could be provided by using a higher processing gas temperature (or helium) in combination with a longer nozzle and a larger prechamber (ensuring higher powder temperature). This would result in an increase in process and deposition efficiency and a better bonding between Inconel powder particles. The other possibilities for increasing the restoration capability are a change of the defect geometry, the implementation of a more suitable trajectory, and/or annealing of the feedstock powder.

In this case, the substrate preheating by infrared ceramic heaters proved to be a significantly less effective solution than substrate preheating by hot processing gas flowing from the gun before the start of the deposition.

## ACKNOWLEDGEMENTS

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