

Article

Corrosion Behavior of Inconel 625 Coating Produced by Laser Cladding

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Abstract: Anti-corrosion properties of Inconel 625 (In) laser cladding coatings onto the (S235JR) steel (S) were investigated. The coatings were produced with the use of wire (WIn/S) or powder (PIn/S). The mechanical properties of the Inconel 625 coatings were characterized by microhardness measurements. The PIn/S shows the highest hardness. The surface and microstructure of the specimens were observed by a scanning electron microscope (SEM). The surface analysis of the laser cladding coatings by energy-dispersive spectroscope (EDS) indicated that the structure of the WIn, and PIn coatings depend on its production technique. The microstructure of the WIn and PIn coatings have a dendritic columnar character. Corrosion test materials were carried out by using electrochemical methods. The corrosive environment was acidic chloride solution. It turned out that the PIn/S coating, which was produced by laser cladding method with the use of Inconel 625 powder, has the best anti-corrosion properties in an aggressive chloride environment.

Keywords: superalloy; laser cladding; coating; acidic chloride solution; corrosion parameters



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1. Introduction

Nickel-based superalloys, including Inconel 625, are currently used in a variety of industries, i.e., aviation, petrochemical, machinery and other industries [1,2].

On the other hand, due to the high cost of nickel-based superalloys, their use may be highly unprofitable. Therefore, one way to reduce component costs is to use nickel-based alloys as coatings to protect cheaper materials. The nickel, as the basic component of superalloys, perfectly protects the substrate of materials against corrosion, especially in aggressive electrolytes, which include acid chloride solutions. Moreover, chromium (as the second important component of superalloys) significantly increases the resistance of materials to oxidation, especially in the environment of hot gases containing oxygen sulfur compounds. On the other hand, chromium (due to its high affinity to oxygen) forms a durable oxide layer that adheres well to the surface, which perfectly protects the substrate against its further oxidation. It is worth adding that the superalloys contain cobalt and molybdenum in small amounts. Both elements play an important role in protecting materials against pitting and crevice corrosion.

Most often, Inconel superalloy coatings have been produced by thermal methods, among them high velocity oxygen fuel [3–5], and atmospheric plasma spray [6]. There are many disadvantages to coatings produced using both methods. The most important of these are the large heat affected zone (HAZ) and the porosity of the coating. Therefore, other methods of producing protective coatings should be searched for, which allow to obtain coatings with much better mechanical and protective properties.

The laser rapid manufacturing for superalloy components has the most extensive applications in virtue of fine structure, better mechanical characteristics and lower part distortion [7]. Therefore, the authors of the works [8,9] investigated the influence of processing

parameters on the mechanical properties of laser rapid manufacturing of nickel-based superalloys. However, laser rapid manufacturing technology has several drawbacks at the present development stage. These problems, related to the utilization of a laser beam as heat source for the rapid forming of components, such as high expense, low energy consumption efficiency and safety, significantly limit its practical application [10,11]. The laser cladding (LC) technique seems to be an alternative technique, the use of which allows for the production of good protective coatings. The LC technique is the use of a laser beam to melt the filler material, and partially, the substrate to form a metallurgical coating permanently attached to the substrate. The filling material can be applied directly to the surface of the substrate in the form of a wire or a powder with an appropriately selected composition. For this purpose, appropriately constructed laser heads are used. Typically, during the production of LC coatings, the wire is fed into the laser beam from the side, and the powder coaxially into the laser beam. However, the problem of using lasers to produce coatings and components from different types of materials is still being intensively researched. Moreover, the laser beam is used for the surface polishing, surface geometry formation, surface sealing or for homogenizing the chemical composition of the coatings deposited [12,13]. The corrosion resistance of Inconel alloys over a wide temperature and pressure range has resulted in the widespread use of superalloys in a variety of industries.

Laser additive deposition is modern technology using cladding of metals. The deposition process with the use of laser radiation is characterized by high processing precision, low energy consumption, and thus, low deformation of the base material. Moreover, the narrow heat-affected zone (HAZ) influences the use of this technology in advanced applications. The authors [14,15] showed that laser deposition has several advantages over other coating processes, such as thermal spraying. The adhesion between substrate and coating is very strong with minimal dilution where very low HAZ is generated in the substrate. In addition, the porosity of the layer is lower than that observed in thermally sprayed coatings. The repeatability of the process is higher than in the case of other methods of producing thickness coatings. Finally, the LC process is more controlled than thermal spray techniques.

Laser cladding and interface evolutions of Inconel 625 alloy on low alloy steel substrate upon heat and chemical treatments was investigated by [16]. The authors cited stated that the laser clad Inconel 625 layers, typically those areas away from the near-interface regions, regardless of the heat treatment in the molten salts, are strongly resistant to the chemical etching. However, the chemical etching rate of the steel substrate is remarkably affected by the heat treatment; the etching rate at the HAZ is relatively reduced as compared with that at the base materials, which could be related to the increase of compressive residual stress (CRS) in the steel substrate during the heat treatment.

The authors in the article [17] described their research results, which concerned the evaluation of the hot corrosion behavior of Inconel 625 coatings on the Inconel 738 substrate by laser and TIG cladding techniques. The resulting coated specimens and the uncoated substrate were subjected to a hot corrosion test carried out at 900 °C. As the results indicate, the laser clad specimen was found to have a noticeably better hot corrosion resistance than the TIG clad and the uncoated specimens.

Interesting research results on the corrosion resistance of 431 stainless coatings produced by a novel surface modification technology, i.e., extreme high speed laser cladding (EHLA) can be found in [18]. Corrosion tests showed that better corrosion resistance was achieved with a higher cladding speed. The uniform distribution of dendrite sizes and composition helped to improve the coating corrosion resistance. High cladding speeds lead to refined dendrites and uniform distribution of composition which were helpful for the improvement of the coating corrosion resistance.

So far, there is no information in the literature on the production of protective coatings by laser cladding using Inconel 625 as wire (W) or powder (P) on a steel substrate.

In the present study, anti-corrosion properties of Inconel 625 laser cladding coatings onto the S235JR substrate were investigated. The coatings were produced with the use of

Inconel 625 as wire or powder. The corrosion test of the materials in the acidic chloride solution (1.2 M Cl^-) were carried out by using the electrochemical methods.

2. Materials and Methods

The coatings were performed using a high power CO_2 laser with a Trumpf Lasercell 1005 machine (Trumpf GmbH, Ditzingen, Germany) with a laser cladding head that had a focal length of 270 mm and was integrated with a coaxial powder feeder (GTV PF 2/2) [19]. The metallic powder was transported through three nozzles of cladding head. On the other hand, the wire was fed to the laser beam zone by means of a roller conveyor. Moreover, the coating production area was protected with a helium stream. Multilayer cuboid specimen using laser deposition technology was manufactured. Layers were cladded alternately alongside X and Y axis until assumed geometry was attained. Process head was oriented perpendicular to surface of substrate material, with no inclination at upper layers. The following parameters were used to develop a cuboid specimen ($320 \text{ mm} \times 120 \text{ mm} \times 5 \text{ mm}$); laser power of 2–6 kW, laser spot diameter of 2.0 mm, scanning speed of 800 mm/min, powder feed ratio of 15 g/min, and wire diameter of 1.2 mm, wire feed rate of 900 mm/min.

Inconel 625 superalloy in the form of wire or powder was used to produce a protective coating onto the S235JR steel. The chemical composition of the steel is as follows: wt.% 0.200 C, 0.045 P, 0.045 S, 0.09 N, and 99.62 Fe. S235JR steel is used in construction and many industries. This steel has good mechanical properties, but is not corrosion resistant especially in an environment of strong electrolytes. In order to increase the corrosion resistance of S235JR steel, an attempt was made to coat its surface with a layer of Inconel 625. Before, the steel surface was cleaned by sandblasting method.

The Inconel 625 powder was delivered by LPW Technology (Runcorn, UK), with particle sizes in the range of 45–106 μm , Figure 1.

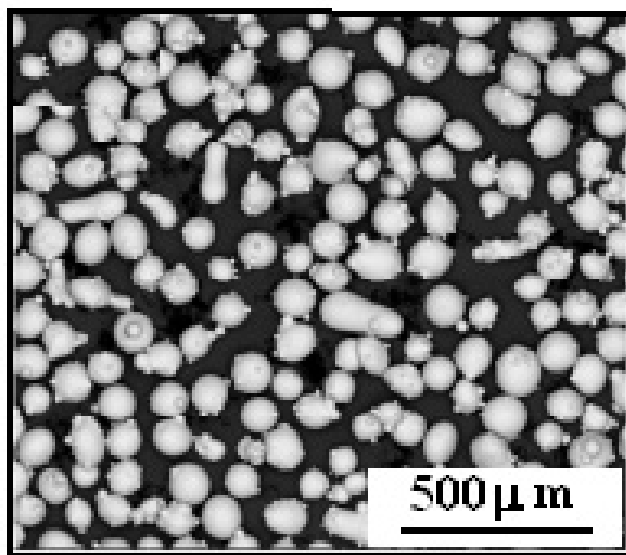


Figure 1. Morphology of Inconel 625 powder.

The shape of Inconel 625 powder particles was mostly spherical with microspherical features attached to them. However, several elongated and with irregularly shaped particles were also observed.

The chemical composition of Inconel 625 wire (BIMO Tech, Wroclaw, Poland) was very similar to that of Inconel 625 powder. However, chemical composition of Inconel 625 feedstock is presented in Table 1.

Table 1. Chemical composition of Inconel 625 feedstock.

Element	Ni	Cr	Nb	Mo	Si	Mn	Fe	Co	Al	Ti	C
wt. %	58.0	21.6	3.6	8.8	0.5	0.5	4.9	1.0	0.4	0.4	0.1

The surface of the S235JR steel was laser cladding with Inconel 625 using wire (WIn) or powder (PIn). The Inconel 625 coatings onto the S235JR substrate (S) were designated as: WIn/S and PIn/S, respectively.

The measurement of microhardness of the tested materials was made by the Vickers method (HV), using the Falcon 500 hardness tester of the INNOVATEST (Maastricht, The Netherlands). An indenter was used in the form of a diamond pyramid, whose load varied from 0.02 to 20 N. The depth of indentation was about 3 μm .

The surface and microstructure was observed by using a scanning electron microscope (SEM) Joel (Tokyo, Japan), JSM-5400. The accelerating voltage of SEM was 20 kV. The chemical composition of the materials surface were measured by energy dispersive spectrometer (EDS). Additionally, to observe the surface topography an inverted metallographic microscope (MO) (Delta Optical, Warszawa, Poland), IM-100, was used.

The electrochemical measurements (corrosion tests) were carried out by using PG-STAT 128N (Auto Lab, Amsterdam, The Netherlands) potentiostat/galvanostat, piloted by NOVA 1.7 software from the same company. The experiments were carried out in a three electrode cell.

The working electrode was made of the S235JR steel without and with Inconel 625 coatings, which were produced using wire (WIn) or powder (PIn). The geometric surface area of the working electrode was 1.0 cm^2 . The remaining electrode surface was protected against contact with the electrolyte by epoxy glue. Before each measurement, the surface of the electrode was washed with bidistilled water, ultrasonically, and dried at room temperature; afterwards, it was immersed in the test solution, and the measurement was started.

The saturated calomel electrode (SCE(KCl)) was used as the reference, and the counter electrode (10 cm^2) was made from platinum mesh (99.8% Pt).

The supporting electrolyte (corrosive environment) was obtained by mixing the sodium chloride (POCH, Gliwice, Poland), and hydrochloric acid (POCH, Poland), so the concentration of Cl^- ion was 1.2 M, and the pH was 1.5. The electrolyte was not deoxygenated.

The potentiodynamic polarization (LSV) curves were recorded. All measurements were carried out under a potential range from -1000 to 1200 mV vs. SCE(KCl), whereas the potential change rate was $1 \text{ mV} \cdot \text{s}^{-1}$ with holding time of 60 s at -1000 mV in order to clean the electrode surface. The LSV curves were used to designate the corrosion parameters, polarization resistance, and corrosion rate of the tested materials. For this purpose, the method of extrapolation of rectilinear sections of the Tafel potentiodynamic polarization curves were used.

The chronoamperometric curves (ChA) were obtained for the potential values which were selected on the basis of the LSV curves for the characteristic points on the LSV curves. For this purpose, one potential value concerned the cathodic process, and two for the anodic process.

All measurements were carried out at a temperature of 25 ± 0.2 $^\circ\text{C}$, which was maintained by an air thermostat. However, the electrochemical measurements were repeated three times for each specimen.

3. Results and Discussion

3.1. Vickers Hardness of Materials

The hardness (HV) values of the Inconel 625 coatings, which were produced by laser cladding using wire (WIn/S) or powder (PIn/S) are listed in Table 2.

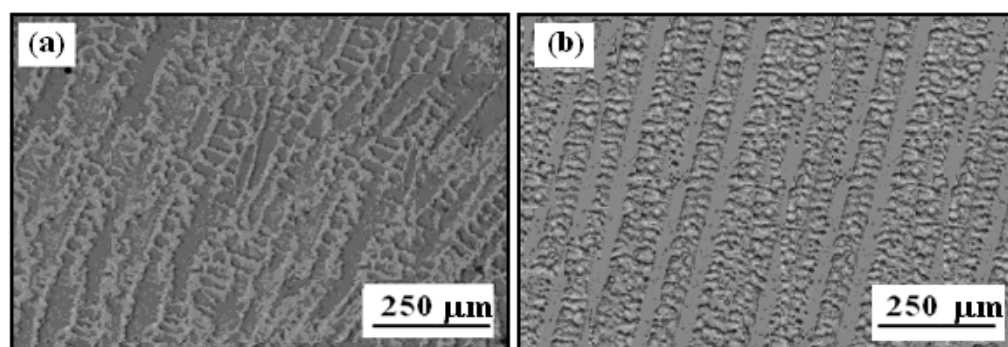
Table 2. Vickers hardness of Inconel 625 coatings onto the S235JR substrate.

Name Coating	HV10
WIn/S	259 ± 4
PIn/S	311 ± 3

The Vickers hardness of the PIn coating is about 311 HV10, and is about fifty units larger compared to the WIn coating (Table 2). It seems that the structure of the PIn coating is fine crystalline and more compact. Therefore, the Inconel 625 coating onto the S235JR steel, which was produced using a powder, should have good mechanical properties, including high abrasion resistance.

3.2. Scanning Electron Microscope Images

Figure 2 shows the scanning electron microscope (SEM) images of the Inconel 625 laser cladding coatings with the use of wire or powder as feedstock. The microstructure of deposited material, i.e., Inconel 625 onto the S235JR steel is assumed as dendritic structure (Figure 2a,b). Deposited materials as WIn/S and PIn/S have fine columnar structure, with characteristic oriented parallel to deposition direction of dendrites.

**Figure 2.** SEM images of the dendritic structure of Inconel 625 laser cladding coatings onto the S235JR substrate with the use of: (a) Wire or (b) Powder.

In both cases, a dendritic microstructure was observed, which is a typical result of laser-processed materials with high cooling rates. Deposited materials have fine columnar structure, with characteristic oriented parallel to deposition direction of dendrites. However, a more regular dendritic structure was obtained for the PIn coating (Figure 2b). It can be assumed that the mechanical properties of the PIn/S will be more favorable than of the WIn/S. Moreover, in the case of the PIn coating, a more homogeneous surface of the protective layer was obtained compared to the WIn/S, as during laser cladding, the coating material as Inconel 625 powder was more evenly transferred to the surface of the substrate.

On the other hand, Figure 3 shows the cross-section of the Inconel 625 coatings deposited onto the S235JR by laser cladding method with the use of wire or powder. It is worth noting that both coatings are of good quality, and no pores or cracks are visible.

During the cladding process, the laser beam very intensively affects the structure of the substrate and the subsequent applied layers. The high temperature of the laser beam creates a large temperature gradient between the center and the edges of the melt. This produces surface stress gradients that are similar to those observed during laser welding. On the other hand, surface stress gradients were created by the transport of heat by convection to the bottom/inside of the coating, which was induced by electromagnetic forces in the molten material [20]. Therefore, a different cross-section image was observed for the WIn and PIn coatings (Figure 3). However, thickness of the fusion zone (substrate—HAZ) and Inconel 625 coatings onto the S235JR steel are listed in Table 3.

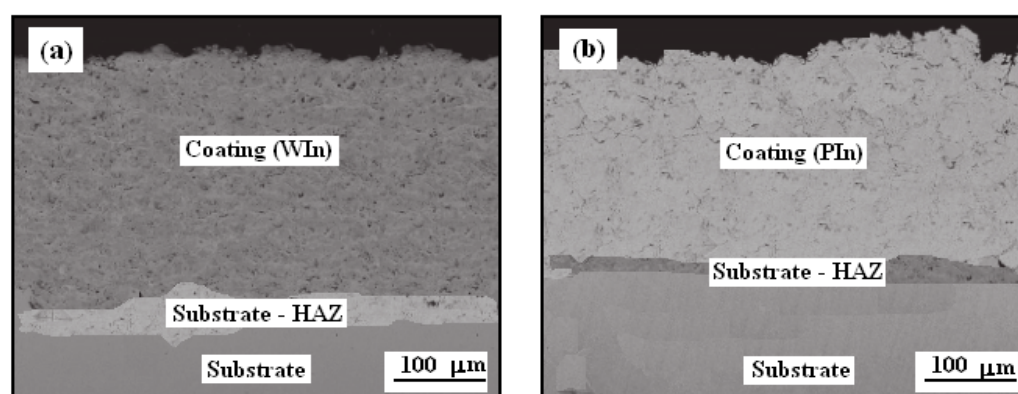


Figure 3. SEM cross-section of Inconel 625 coatings onto the S235JR substrate produced by laser cladding method with the use of: (a) Wire and (b) Powder.

Table 3. Thickness of the substrate—HAZ and Inconel 625 coatings onto the S235JR steel.

Name Coating	Thickness	
	Substrate—HAZ µm	Coating µm
WIn/S	20–33	220–233
PIn/S	11–16	180–198

The fusion zone (substrate—HAZ) layer for the WIn coating is much thicker compared to the PIn coating. Similarly, the WIn coating is thicker compared to the PIn/S (Table 3). Therefore, it can be assumed that the mechanical properties of the PIn coating will be greater than that of the WIn/S.

3.3. Microstructure of Materials

Figure 4 shows an example of the metallographic microstructure of cross-section of the Inconel 625 coating onto the S235JR steel processed by laser cladding with the use of powder. However, similar X-ray microanalysis of cross-section of WIn coating were recorded for the Inconel 625 coating, which was produced with the use of wire, but they are not presented in this work.

The Inconel 625 coating was found to adhere well to the substrate. In addition, iron and nickel permeated through the heat-affected zone as a result of the melting of Inconel 625 and the substrate material. Thus, the laser cladding process produces a homogeneous structure of the Inconel 625 coating on the S235JR substrate.

Figure 5 depicts the SEM/EDS image of cross-section of the PIn coating, and the results of point X-ray microanalysis of the chemical composition of tested material. The average nickel and chromium content in the tested coatings were around wt.%: 55.1 and 19.3 for the WIn/S, and 55.9 and 20.3 for the PIn/S. It is worth noting that more components (i.e., Ni and Cr, and other elements) are transferred to the substrate of S235JR steel during laser cladding with Inconel 625 powder. Moreover, the nickel and chromium content is lower in the depth of both WIn/S and PIn/S (Figure 5, spectrum 4–6). Probably in the cladding process, both elements diffuse deep into the substrate—HAZ. Therefore, the Inconel 625 coatings adhere well onto the substrate. In addition, nickel, chromium and iron permeated through the heat-affected zone as a result of the melting of Inconel 625 and the substrate material.

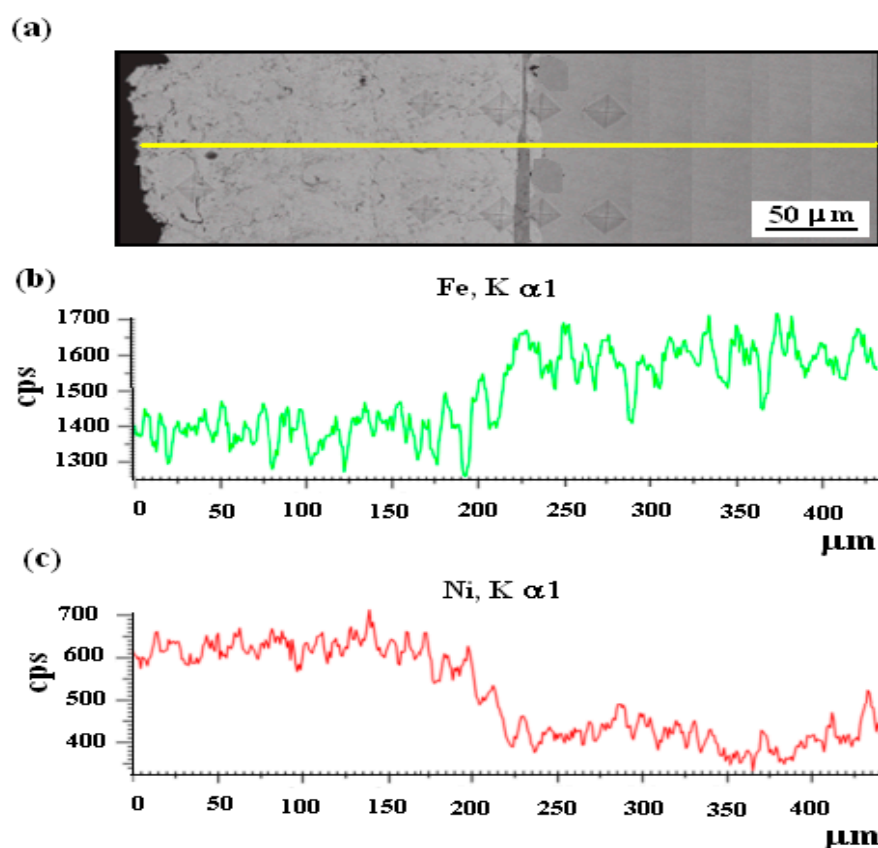


Figure 4. X-ray microanalysis of cross-section of PIn coating and substrate: (a) Metallographic microstructure (with the line scanning), and content distribution; (b) Iron, and (c) Nickel.

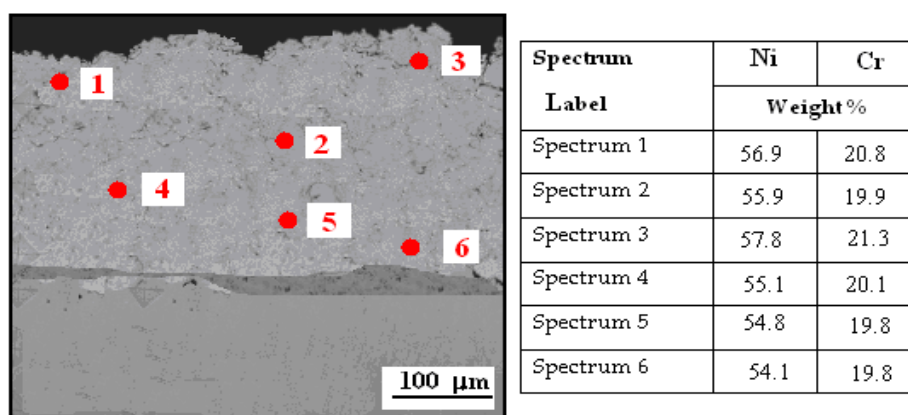


Figure 5. SEM micrograph, and EDS of PIn coating onto the S235JR substrate, and the results of point X-ray microanalysis of the chemical composition of tested material.

Thus, the laser cladding process produces a homogeneous structure of the Inconel 625 coatings onto the S235JR substrate.

The study of the homogeneity of the structure of Inconel 625 coatings were carried out with a high-quality method of X-ray spectroscopy with electron dispersion. Figure 6 presents quality EDS analysis of nickel, chromium, niobium and molybdenum map distribution onto the WIn coating. A similar map of the distribution of elements was obtained for PIn/S.

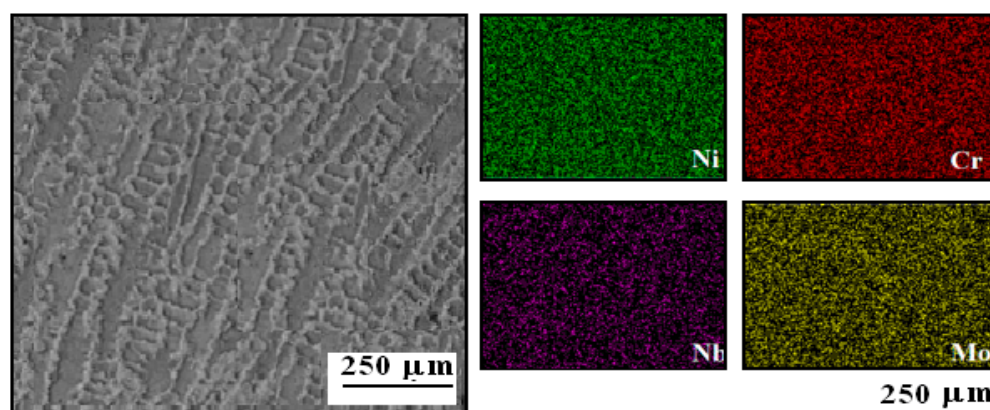


Figure 6. Quality EDS analysis of nickel, chromium, niobium, and molybdenum map distribution of WIn coating.

EDS analysis of the basic chemical elements of the WIn and PIn coatings onto the S235JR substrate showed a homogeneous structure, without disturbing the decomposition. Moreover, there is no difference in the fusion line of the individual layers which indicates good mechanical and anti-corrosion properties of the tested coatings.

3.4. Corrosion Test

Potentiodynamic polarization (LSV) measurement was carried out in order to gain knowledge about anti-corrosion properties of Inconel 625 laser cladding coatings onto the S235JR substrate. The coatings were produced by a laser method using Inconel 625 wire or powder. Figure 7 shows potentiodynamic polarization curves of S235JR steel without and with Inconel 625 coatings in an acidic chloride solution.

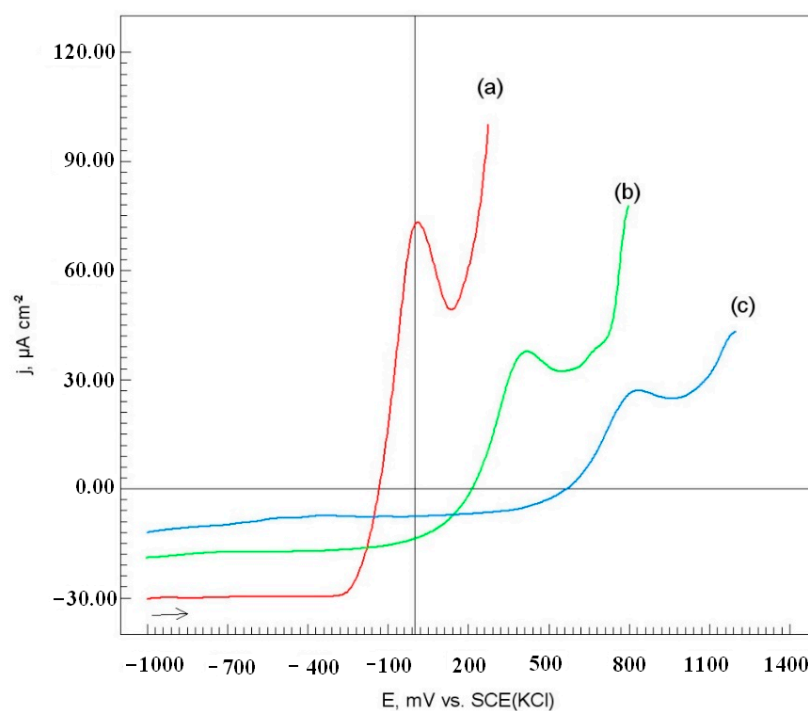
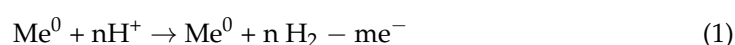


Figure 7. Potentiodynamic polarization curves of Inconel 625 coatings onto the S235JR substrate produced by laser cladding method: (a) Without coating, and with the use of (b) Wire, and (c) Powder. Solutions contained 1.2 M Cl^- , pH 1.5, dE/dt 1 mV/s.

The process of hydrogen depolarization occurs in the cathode region of the potentiodynamic polarization curves. On the other hand, oxidation of the surface of S235JR steel

or WIn and PIn was observed in the anodic area (Figure 7). The course of the LSV curves depend on the type and method of producing of Inconel 625 coatings onto the S235JR steel. However, the shift of the LSV curves toward the positive potentials may represent an increase in the corrosion resistance of Inconel 625 coatings, especially the PIn coating, which was produced with powder. This problem will be discussed extensively later in the article.

It has been demonstrated that the Inconel 625 coatings effectively protect S235JR substrate from contacting with the aggressive corrosive environment (Figure 7, curves (a)–(c)). Moreover, the anti-corrosion properties of the Inconel 625 coating depend on the method of producing the coating. The Inconel 625 coating, which was produced using nickel superalloy powder, showed the best anti-corrosion properties (Figure 7, curve (c)). It is worth noting that, in the acid corrosive environment, the cathodic branches of the potentiodynamic polarization curves correspond to the simplified reduction of a hydrogen ion [12,13,21]:

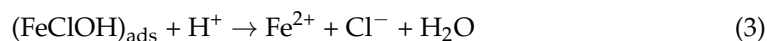


where Me are the Fe, Ni, Cr, and other metals.

It turned out that when the potential of the electrode was changed in the anodic direction, the adsorption layer with the participation of chloride ions [22] was created onto the S235JR surface:

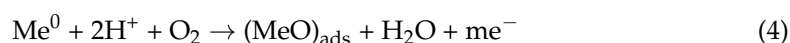


The adsorption layer of $(\text{FeClOH})_{\text{ads}}$ on the electrode surface corresponds to the peaks on the LSV curves which appears for the potential of 10 mV vs. SCE(KCl) (Figure 7, curve (a)). The $(\text{FeClOH})_{\text{ads}}$ layer partially prevent the electrode surface against further oxidation in the corrosive environment. Unfortunately, the $(\text{FeClOH})_{\text{ads}}$ in the acidic chloride solution was dissolved in accordance with a chemical reaction:



thus, a further sharp increase in the current intensity is observed due to the oxidation of the electrode surface (Figure 7, curve (a)). Moreover, a similar reaction mechanism for iron in the acidic chloride environment was proposed by Chin and Nobe [23].

However, when S235JR steel surface was covered with Inconel 625, the anodic reaction was as follows:



where $(\text{MeO})_{\text{ads}}$ means the $(\text{NiO})_{\text{ads}}$, $(\text{Cr}_2\text{O}_3)_{\text{ads}}$, and other oxides. In this case, the electrode surface was covered mainly with a layer of $(\text{NiO})_{\text{ads}}$, and $(\text{Cr}_2\text{O}_3)_{\text{ads}}$. Both oxides adhered well to the electrode surface. On the other hand, peaks appeared on the potentiodynamic polarization curves for 415 mV, and 830 mV vs. SCE(KCl) (Figure 7, curves (b) and (c)). Thus, under the experimental conditions, the electrode surface covered with the Inconel 625 layer underwent a passivation process. Therefore, a clear inhibition of the corrosion process of the protective coating was observed. The values of the potential (E_c), and critical current density (j_c) of the passivation process of the Inconel 625 coatings onto the S235JR substrate were determined. The values of the potential, and critical current density are summarized in Table 4.

Table 4. Potential and critical current density of Inconel 625 coatings onto the S235JR substrate.

Name Coating	E_c mV vs. SCE(KCl)	j_c $\mu\text{A}/\text{cm}^2$
WIn/S	415	38
PIn/S	830	27

It turned out that the potential related to the critical current density is the most positive for the Inconel 625 coating (Figure 7, curve (c)), which was produced with a powder. A clear shift of the E_c value (about 400 mV) means that the surface of the PIn/S is more resistant to electrochemical corrosion compared to the WIn coating. Moreover, a much lower value of the critical current density for the PIn/S was observed (Table 4). However, a much more pronounced effect of protecting the substrate against corrosion was achieved with the Inconel 625 coating, which was produced using a powder. On the other hand, for a more positive electrode potential (about 800 mV, and 1100 mV vs. SCE(KCl), respectively), the alloy surfaces, i.e., WIn/S and PIn/S were depassivated and further oxidation of the tested materials was observed (Figure 7, curves (b) and (c)).

3.4.1. Corrosion Parameters

The potentiodynamic polarization curves (Figure 7) were used to designate the corrosion parameters of the tested materials, i.e., S235JR steel, WIn/S, and PIn/S. For this purpose, the method of the extrapolation of rectilinear sections of the Tafel LSV curves were used [21,22]. The values of the corrosion parameters of the tested materials are listed in Table 5.

Table 5. Corrosion parameters of S235JR steel and Inconel 625 coatings.

Materials	E_{corr} mV vs. SCE(KCl)	$-b_c$	b_a	j_{corr} $\mu\text{A}/\text{cm}^2$
		mV/dec		
S235JR	−130	230	120	13.5
WIn/S	210	250	140	4.1
PIn/S	570	350	160	2.4

The corrosion potential (E_{corr}) of the investigated materials have shifted significantly towards the positive values compared to the S235JR substrate. This means that coating the S235JR steel surface with Inconel 625 makes the material more corrosion resistant under the experimental conditions. Moreover, the PIn coating is the most resistant to electrochemical corrosion in chloride solution. The slope of the cathode ($-b_c$) section of the potentiodynamic polarization curve for PIn/S is about 100 mV higher compared to the WIn/S (Table 5). Thus, the mechanism of the cathode process is different on the surface of both electrodes, i.e., WIn/S and PIn/S. Moreover, the anode segment slope (b_a) of the LSV curves for both coatings are similar (Table 5). This means that the anodic process of WIn/S and PIn/S does not depend on the production method of Inconel 625 coatings onto the S235JR substrate. The lowest value of the corrosion current density (j_{corr}) was observed for the PIn coating (Table 5). So, the most resistant to electrochemical corrosion in a chloride corrosive environment is PIn/S, which was processed by laser cladding method with the use of powder of Inconel 625.

3.4.2. Polarization Resistance and Corrosion Rate

In order to determine the value of the polarization resistance (R_p) of the substrate, and Inconel 625 coatings in an aggressive chloride environment, fragments of potentiodynamic polarization curves (Figure 7), which relate to the active dissolution area of the tested materials, i.e., S235JR, WIn/S and PIn/S were selected. The polarization resistance of the electrode is described by the equation:

$$R_p = \frac{B}{j_{\text{corr}}} \quad (5)$$

and:

$$B = \frac{b_a \times b_c}{2.303 (b_a + b_c)} \quad (6)$$

The R_p values are summarized in Table 6. It was found that covering the surface of S235JR steel with Inconel 625 coating increases the polarization resistance of the electrode. The highest polarization resistance was exhibited by the protective oxide coating ((MeO)_{ads}), which was produced by laser cladding onto the S235JR steel with the use of Inconel 625. However, the greatest increase in the R_p value was recorded for the PIn coating (Table 6). This means that the PIn/S is additionally sealed, probably with nickel and chromium oxides. Therefore, during the electrode process, the mass and charge exchange between the electrode and the electrolyte solution slows down.

Table 6. Polarization resistance and corrosion rate of S235JR steel or Inconel 625 coatings.

Materials	R_p $m\Omega \cdot cm^2$	CR mm/Year
S235JR	2.5	15.7
WIn/S	9.5	4.7
PIn/S	19.9	2.8

The corrosion rate (CR) of the substrate, and Inconel 625 coatings were calculated based on the equation:

$$CR \text{ (mm/year)} = 1.16 j_{\text{corr}} \quad (7)$$

which the authors of the works in [24–26] proposed.

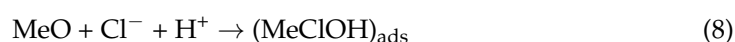
The surface corrosion rate of S235JR steel is high, i.e., 15.7 mm/year. As a result of covering the substrate surface with the Inconel 625 layer, a drastic reduction in the corrosion rate of the tested materials was observed. It turned out that the CR of the PIn coating is over three times lower compared to that of the WIn/S in an aggressive 1.2 M chloride environment (Table 6).

3.5. Chronoamperometric Measurements

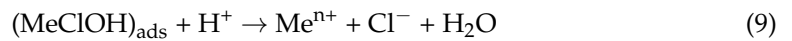
Figure 8 shows the chronoamperometric (ChA) curves of the Inconel 625 coating onto the S235JR substrate. The coating was produced by a laser method using powder (PIn).

The potentials of the working electrode was selected based on the potentiodynamic polarization curve (Figure 7, curve (c)). One potential value for the cathode process (hydrogen reduction) and two potential values for the anode process (oxidation of the electrode material) were selected. The exposure time of specimens in the aggressive chloride environment (1.2 M Cl[−]) was five hours. However, similar ChA curves were recorded for the Inconel 625 coating, which was produced with the use of wire (WIn), but they are not cited in this work.

The change in the cathodic current density value depending on the time of electrolysis, the curve (a) (Figure 8) relate to the reduction of hydrogen ions onto the surface of the Me electrode (reaction (1)). An unstable change in the current density value means that the surface structure of the electrode changes as it begins to oxidize. The curve (b) (Figure 8) which was recorded at a potential of 830 mV vs. SCE(KCl) should be attributed to the formation of the adsorption of the (MeO)_{ads} layer onto the Inconel 625 coating (reaction (4)). The electrode surface becomes passivated by adsorption of mainly nickel and chromium oxides. Therefore, under the experimental conditions, a systematic decrease in the current density during electrolysis is observed. Thus, the adsorbed oxide layer is tight and protects the steel substrate well against contact with an aggressive chloride solution. On the other hand, the curve (c) (Figure 8) was recorded for a potential of 960 mV vs. SCE(KCl), i.e., in the passive region of Inconel 625. It is also worth noting that in this case, the current density systematically decreases during the duration of the electrolysis. It seems that under these conditions, the adsorbed oxide layer can be additionally sealed by adsorption of Cl[−] ions [27]:



The adsorption layer $(\text{MeClOH})_{\text{ads}}$ in the acidic chloride solution was dissolved in accordance with a chemical reaction:



thus, a further sharp increase in the current intensity is observed due to the oxidation of the electrode surface (Figure 7, curves (b) and (c)).

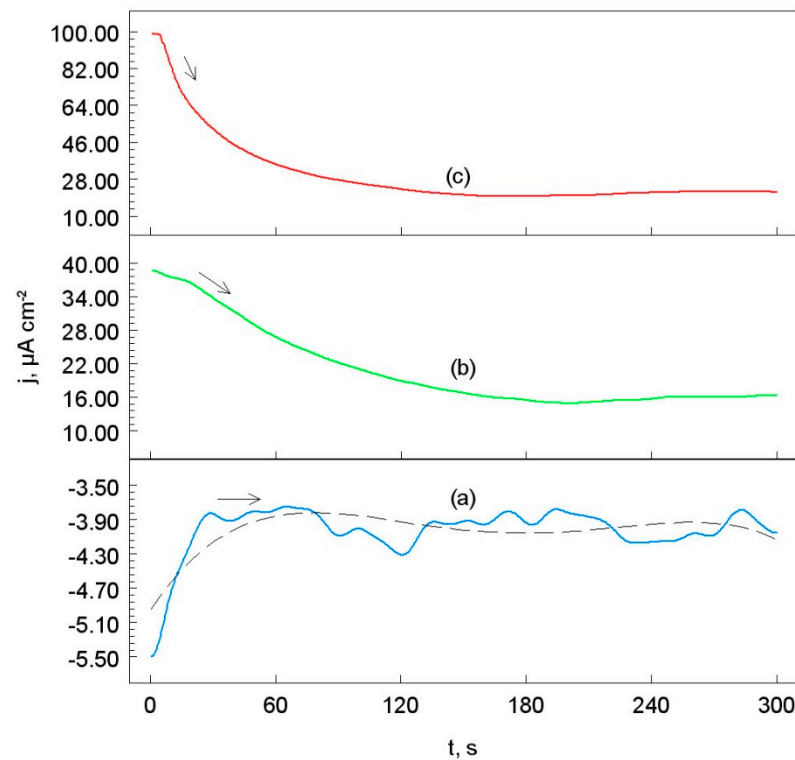


Figure 8. Chronoamperometric curves of Inconel 625 coating onto the S235JR substrate produced by laser cladding method with the use of powder, obtained for: (a) -900 mV; (b) 830 mV, and (c) 960 mV. Solution contained 1.2 M Cl^- , pH 1.5 . (Dashed line refers to the average current density values).

3.6. Inverted Metallographic Microscope Images after Corrosion Test

Figure 9 shows the inverted metallographic microscope (MO) images of the Inconel 625 coating onto the S235JR substrate without, and with coatings produced by laser cladding method with the use of wire, and powder, after corrosion test in 1.2 M Cl^- . The exposure time of the specimens was five hours.

The oxide layer from the surface of tested specimens was removed with diluted nitric acid. In this case, the exposure time was about three minutes. After the removing of the oxide layer from the S235JR substrate, it turned out that the surfaces of the examined steel have undergone electrochemical corrosion in the aggressive chloride environment. It is worth noting large damage of the steel surface, Figure 9a as a result of electrochemical corrosion (reactions (2) and (3)). However, Figure 9b shows the WIn coating onto the S235JR substrate with was produced by laser cladding method with the use of wire. After exposure of the WIn/S to an aggressive chloride environment, slight damage of the Inconel 625 coating was found as a result of electrochemical corrosion. On the other hand, permanent damage of the WIn coating was observed in the form of deep pits which exposed the substrate material. Moreover, much smaller effects of electrochemical corrosion was observed for the Inconel 625 coating, which was produced with the use of powder, Figure 9c. Under the conditions of the experiment, the PIn coating was slightly damaged as a result of the corrosion process in an acid chloride environment.

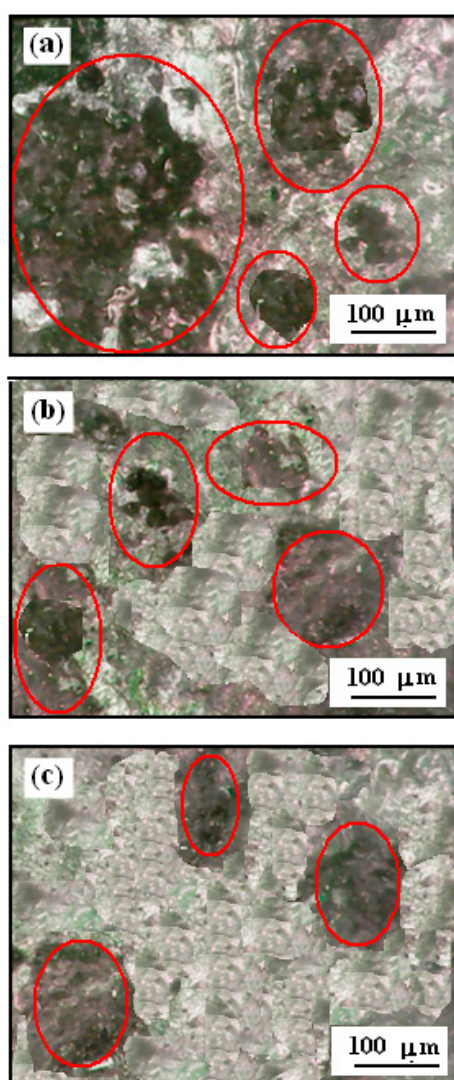


Figure 9. MO images of Inconel 625 coatings onto the S235JR substrate: (a) Without, and with coatings produced by laser cladding method with the use of (b) Wire, and (c) Powder, after corrosion test in 1.2 M Cl^- , pH 1.5. Exposure time was five hours. Corrosion pits are marked in red.

It turned out that the most resistance to electrochemical corrosion of the coating was obtained by laser cladding method using Inconel 625 powder as a material for the production of the coating onto the S235JR substrate.

4. Conclusions

The anti-corrosion properties of Inconel 625 coatings onto the S235JR substrate were investigated. The coatings were produced by laser cladding method with the use of Inconel 625 as wire (W) or powder (P). The microstructure of the WIn and PIn coatings have a dendritic columnar character, with the dendrite orientation related to the direction of crystallization. The Inconel 625 coating produced with the use of powder, i.e., PIn/S, shows the highest hardness compared to the WIn/S. In an acid chloride solution (1.2 M Cl^- , 1.2M), the WIn and PIn coatings onto the S235JR steel were passivated. The oxide layers $(\text{NiO})_{\text{ads}}$, $(\text{Cr}_2\text{O}_3)_{\text{ads}}$, and other metals additionally protects WIn/S and PIn/S against corrosion. However, the corrosion rate of the PIn coating is over three times lower in relation to the WIn/S in the aggressive chloride environment.

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Conflicts of Interest: The authors declare no conflict of interest.

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