Tribology and corrosion behavior of gray cast iron brake discs coated with Inconel 718 by direct energy deposition

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Abstract
Gray cast iron (GCI) is a conventional material used in industrial applications and it is well known for its usage in brake disc fabrication. In the case of vehicles that serve passenger transport, one of the solutions to prolong the lifetimes of brake discs can be to laser clad their surface with harder and corrosion-resistant materials. This research aims to improve the mechanical properties of the brake discs using Inconel 718 (IN718) metallic powder to laser cladding the parts' surfaces by a direct energy deposition (DED) method. By using the proper process parameters, the interface between the substrate and the deposited material was uniform and adherent and forming a compact bonding of the two materials, without pores or cracks. It was found that the average hardness of the IN718 deposited material was twice higher than the one of the GCI substrates. By comparing the friction coefficient (CoF) of the IN718 coatings with that of the brake discs, a difference of 0.12 in favor of IN718 was assessed. The depth of the wear track was analyzed for both materials and showed that the pin trace on the GCI (−150 µm) surface was 3 times deeper than the trace produced on the surface coated with IN718 (−50 µm). The corrosion resistance of the IN718 coating was superior by four orders of magnitude to that of GCI substrate in 3.5 wt.% NaCl aqueous solution.

Keywords Direct energy deposition · Brake discs · Inconel 718 · Wear resistance · Corrosion behavior

Abbreviation
GCI Gray cast iron
IN718 Inconel 718
DED Direct energy deposition
CoF Friction coefficient
EHLA Extreme high-speed laser material deposition
APS Air plasma spraying
HVOF High-velocity oxygen fuel
GTAW Gas tungsten arc welding
LW Laser welding
TBC Thermal barrier coatings
LC Laser cladding

Introduction
Gray cast iron (GCI) is widely used in industry fields involving metallurgical processes due to its excellent physicochemical properties (good casting behavior, superior conductivity, excellent thermal stability, high hardness, and good abrasion resistance), which prevent overheating and surface wear, and its low cost [1–3]. However, under severe usage circumstances, the wear performance, hardness, and corrosion resistance of GCI can be drastically reduced. The
coarse grains and inferior surface quality of GCI are the main disadvantages that impede on the widening of the possible applications and relatively reduced service life. An important application of GCI is the brake disc, which is an essential component of the braking system for automobile, aviation, and rail vehicles. In the last decade, the environmental pollution caused by the emission of particles released during the braking process has attracted an increased attention and concern from environmental agencies, following proves from numerous studies and research efforts from all over the world [4–7]. Due to the fact that GCI has mechanical properties compatible with this type of application, and the components made from it can be cast and machined at a low cost, it will be difficult to identify a similar material to replace it. Aiming to overcome the above disadvantages, surface modification technology could be introduced to improve the performance of GCI. This can be the most suitable solution, as the brake discs made of GCI could be coated with materials for reducing wear and corrosion, while also succeeding to maintain or improve their functional performance [8].

The Fraunhofer Institute for Laser Technology ILT and RWTH Aachen University have developed an improved coating method using laser cladding as the basic technique, called “Extreme High-speed Laser Material Deposition (EHLA).” This technique seems to be extremely efficient in the process of coating brake discs with metallic layers with superior properties both from an economic and technical point of view, due to the use of high processing speeds (up to 8 m/s, compared to 0.008–0.03 m/s) [9, 10].

DED is one of the numerous methods of coating metal surfaces with other metallic materials (air plasma spraying (APS), high-velocity oxygen fuel (HVOF), thermal spray, gas tungsten arc welding (GTAW), laser welding (LW), thermal barrier coatings (TBC)) that can obtain excellent performance against wear and corrosion. DED is an additive manufacturing technology which allows coating in a single step of a layer with thickness dimensions between 0.3 and 2 mm. Such a layer made of metallic or composite materials possesses remarkable characteristics, such as reduced heat-affected zone, minimal dilution, and improved wear [11–14] and corrosion resistance [15–19]. DED can be found in literature as laser cladding (LC) or laser melting deposition (LMD) and has huge potential for refurbishing and transforming the surface of crucial components and expanding their service life [20–22]. However, the literature studies have shown that the DED technology applied to GCI materials has certain restrictions [23, 24]; deposition of Co [25] and NiCrBSi [26] on GCI substrates has been studied using high-power continuous emission laser sources, but cracks were observed in the structure of the deposited substrate. These defects were caused by the residual stresses that occur during the build of the deposited structure.

IN718 is a high-strength precipitation-hardening nickel-base alloy that has exceptional characteristics, including excellent mechanical properties in severe conditions, low creep at high temperatures, high oxidation resistance, and hot corrosion resistance up to 650 °C, as well as good welding behavior [16, 27, 28]. Therefore, it is extensively used in various industries, such as petrochemical industries aerospace and marine.

Stanciu et al. [29] deposited double layers of NiCrBSi and IN718 by laser cladding on a steel substrate. Thus, they obtained an increase in corrosion resistance, a reduction in dilution with the substrate, and a hardness gradient with increased values on the deposited NiCrBSi layer. Another study showed a successfully deposited NiCo coating on IN718 substrate by pulsed laser cladding. In this case, the hardness of the deposited layer was higher with 21% than the one of the IN718 substrate and the coating’s surface residual stress was compressive stress, which prevents crack generation and improves fatigue strength [12]. Using a pulsed laser source, the heat-affected area was smaller [30], cracks were reduced due to low heat input [31], and the hardness of the deposited layer increased with the use of a high pulse rate [32]. To eliminate the voids that occur during the laser cladding process on GCI, a study about remelting of the deposited material was carried out. The results revealed that laser remelting was an effective way to eliminate the voids generated in the interface zone and the microhardness of the hardened region was ~ 600HV [33]. Another research investigated the effects of process parameters on the geometric characteristics, microstructure, and corrosion resistance of the Co-based coating on 42CrMo pipeline steel. The authors obtained excellent corrosion resistance through the adjustment of the process parameters [15]. The microstructure and tribological properties of the deposited layer were studied based on process parameters during laser cladding Ni-based on QT500-7 ductile cast iron. The hardness, corrosion resistance, and tribological properties were significantly improved by optimizing the process. When the WC content is in 5–35%, the microhardness increased 3 times. When the WC content is 20%, the corrosion current is three times lower than the one of the substrates which means that the corrosion resistance of the coating is higher. The wear rate of the substrate is almost seven times higher than the cladding layer with different WC mass fractions [34].

The effects of laser remelting (LR) speed of IN718 alloy layers obtained by LMD have been studied by Xin et al. [35]. Using a high speed of LR process (3 times higher than the speed used in the case of the LMD processing), the mean primary dendrite spacing values of the remelting area decreased from 6.35 to 3.28 μm gradually and the hardness increased with 12 HV. Mazzucatto et al. [36] conducted a research study on the influence of LMD process parameters on the mechanical properties of IN718
depositions at room temperature and several deformation rates (i.e., 0.001, 200, and 800/s) using a split Hopkinson drawbar. The results established an important influence of the LMD process parameters on the mechanical properties of the as-built metal compared to as-cast material and a good repeatability of the process. The influence of process parameters in the case of the laser processing of cast iron in terms of dilution, layer width, and heat-affected zone was studied by Fan et al. [37]. They developed a control scheme for the laser plating process to achieve a low level of dilution and to reduce the width of the heat-affected zone. Liu et al. [38] studied the effect of combined heat treatment (solid solution 1050 °C + double aging) on IN718 laser-coated layers. They showed that the hardness increased from 350 to 500HV and the residual stress turned into compression stress after the heat treatment.

When it comes to laser coating GCI, there are many problems to be solved: obtaining a good adhesion between the two materials due to the different chemical compositions and mechanical properties, reducing the dilution at the interface of the deposited layers, limiting the formation of Laves phases in order to reduce cracking and stress [39].

Conventional coating techniques such as electroplating or thermal spraying can produce poorer metallurgical bond between GCI and the protective layer, caused by porosity. Besides, there are some thickness uniformity problems that can be solved only when using expensive plasma equipment. Using DED, it is possible to create a strong metallurgical bond and the remaining powder can be recycled [40]. Additionally, the coating produced by a single track is usually between 0.5 and 1 mm thick, which is more than enough to cover a surface with protective material by one single pass. These advantages make this method relevant for the industrial application and it can become industrially viable in the near future. Therefore, the 3R principals, i.e., “reduce, reuse, recycle” [41], and the circular economy conception are fully aligned with DED technology by combining economic growth and environmental protection, promoting the extension of the useful life of products which have exhausted their physical and/or functional service life and would otherwise be discarded, thus maximizing their utilization capacity and maintaining their value for as long as possible [42].

This study aims to improve the wear and corrosion properties of GCI by adding a layer of IN718 in order to enable the fabrication of long-term brake discs for the automotive industry. In terms of sustainability, this is a method that can be applied for refurbishment of the utilized brake discs instead of replacing them.

One main novelty of the paper is the coating by laser cladding of the brake discs with IN718, a very hard and anticorrosive nickel-based alloy. The behavior of this material when deposited on GCI substrate has not been explored before. Moreover, this is the first report in the literature of functional testing of coated brake discs: two of them were mounted on an automobile and tested in an authorized center for periodic technical inspection of the cars. The improved product performances were considered in accordance with the public road’s regulations imposed by the European Union.

## 2 Materials and methods

The metallic powder used for this study was nickel-based superalloy IN718 purchased from Hoganas GmbH (Germany, Goslar) with spherical shape particles and 45–90-µm diameter. Before experiments, the material was submitted to a thermal treatment at 60 °C for 4 h in furnace in order to eliminate the absorbed humidity from the atmosphere. The chemical composition of the powder material is listed in Table 1.

For this study, GCI samples obtained by cutting an automobile brake disc into 60 mm × 20 mm × 5 mm coupons were used as substrates. The typical microstructure of GCI is characterized by a dispersed carbon lamella formation surrounded by α-ferrite and pearlite phases. The chemical composition of the GCI substrate is listed in Table 2. The substrate was machined by turning to remove surface debris and impurities and then cleaned with acetone and ethanol in order to completely remove the debris.

Physical and thermal properties of the GCI and IN718 such as specific heat capacity, coefficient of thermal expansion, and thermal conductivity are presented in Table 3.

From the values of physical properties, results show that IN718 powder is compatible with the GCI in terms

| C          | Si          | Mn    | P    | S    | Cu | Fe |
|------------|-------------|-------|------|------|----|----|
| 3.2–3.5    | 1.8–2.2     | 0.6–0.9 | ≤ 0.2 | ≤ 0.12 | ≤ 0.58 | Balance |

Table 1 Chemical composition of IN718 [wt%]

Table 2 Chemical composition of GCI [wt%]
of crystalline structure, melting temperature, and thermal expansion coefficient, while differences appear in the case of the thermal conductivity. The powder type for laser cladding was chosen based on the criteria of compatibility with the main physical properties of hypoeutectic cast iron (carbon content between 2 and 4.11 wt%, microstructure with uniform vermicular graphite spread in a mass of pearlite), in order to obtain the increase of the corrosion resistance and of the coefficient of friction, without generating stress at the interface between the deposited material and the substrate. Other types of metallic powder, such as WC–Co (wt.% 86 WC, wt.% 10 Co, wt.% 4 Cr), Co-Cr (wt.% 63 Co, wt.% 30 Cr, wt.% 7 Mo), and NiCo (wt.% 21.9 Co, wt.% 16.9 Cr, wt.% 12.6 Al, wt.% 0.6 Y, wt.% 0.4 Si, wt.% 0.3 Hf, Ni balance), were used with the scope to identify the best material combinations. In the case of WC–Co, the results were full of trapped pores inside the deposition layer, and for the other two, the coatings started to crack during and after the processing. Moreover, NiCo alloy showed an ununiform and discontinuous deposition.

The experimental set-up used for obtaining IN718 deposition layers by the DED technique consists in a 3-kW Yb:YAG laser source (TruDisk 3001, Trumpf, Ditzingen, Germany) emitting in continuous mode, with wavelength $\lambda = 1030$ nm connected by optical fiber to a deposition optics. The optics was mounted on a robotic arm (TruLaser Robot 5020, Trumpf, Ditzingen, Germany) with 8 degrees of freedom using an electro-magnetic plate.

The deposition line is equipped with a three-beam nozzle which ensures a uniform powder distribution, independent of the process motion (Fig. 1). The laser beam is guided and focused on the workpiece through the focusing optics, while the powder stream is blown into the laser spot through 3 nozzles. The deposited layers were obtained by using 600-W laser power, 0.01-m/s scanning speed, 4-g/min powder debit, and 14-slpm gas mix (He-Ar). These process parameters were established based on trial and error of a single line traced. Under the 600 W of laser power, the traced lines were unparallel and discontinuous with adherent unmelted particles, and beyond this value, the temperature exceeded 1500 °C which is undesirable due to the possibility of C release from GCI substrates that can be trapped in the deposited material and lead to pores apparition. A lower scanning

| Table 3 Physical and thermal properties of materials |
|-----------------------------------------------------|
| Material | Density [kg/m$^3$] | Melting temperature [°C] | Thermal conductivity [W/m K] | Caloric capacity [J/kg K] | Thermal expansion coefficient [$10^{-5}$/K] |
|----------|---------------------|--------------------------|-----------------------------|--------------------------|--------------------------------------|
| GCI      | 7000               | 1208                     | 39                          | 513                      | 1.2                                  |
| IN718    | 8190               | 1260–1335                | 11.2                        | 435                      | 1.3                                  |

Fig. 1 Schematic representation of laser cladding and C atoms dynamics in the deposited layer
speed increased the process temperature and a higher velocity created discontinuity of the deposited material. A smaller quantity of the powder debit was not enough to obtain continuum and parallel borders of the traced layer, while a higher amount of powder created an unnecessary quantity of unmelted powder.

The laser beam (Ø = 800 µm) was concentrated on the surface of the substrate via a 200-mm focal distance lens. The trajectory of the deposition layers was designed and programmed into the robot movement code generator, TruTops Cell® (Trumpf, Ditzingen, Germany). The chosen scanning strategy used for laser cladding of the brake disc was a spiral-like trajectory, to keep a low temperature during the process and to diminish the risk of C evaporation from the substrate as much as possible. In order to obtain a bulk structure, the optimum interspace distance of the spiral was found to be at 1 mm, while the distance between layers was 0.2 mm, which translates in a 40% ratio overlap. Each layer deposited using these process parameters had a height of 600 µm. In order to achieve a 2.4-mm thickness of the deposited material on the final product, 4 layers were successively deposited on top of each other. The optimal number of 4 superposed layers was determined from height measurements performed on cross sections of layers deposited with different numbers of tracks. The number of 4 layers was selected because the coating reached the desired thickness with minimum time, energy, and material consumption. This thickness was established to allow the post-processing of the surfaces in view of leveling. Following this operation, at least a 1-mm-thick deposited layer should remain over the GCI brake disc. To ensure repeatability of the process, 4 brake discs were fully coated and the height was measured in 4 points for each disc to identify the growth difference error that can be seen in Fig. 2. The deposited layer’s height was 2.52 ± 0.06 mm. However, these experimental data differ from the theoretical height obtained in the manufacturing software of 2.4 mm. The cause is that the layers are not simply deposited one on top of the other with a precise theoretical height. The layer underneath the next one is remelted by the laser beam and the new layer sinks partly in the previous one.

The temperature of the molten pool was recorded by a non-contact pyrometer, IGA 5 (Fort Collins, Colorado), and the substrate temperature via a chromel–alumel thermocouple wire. The deposited samples produced by the DED technique on the GCI substrate were cut into small coupons of 10 mm × 10 mm × 10 mm by disc cutting method, which were used to analyze the microstructure, the hardness, the wear, and the corrosion resistance. The surfaces were mirror-like prepared to reveal the microstructure using silicon carbide sandpaper grinding (400 to 2500 grit paper), diamond abrasive paste polishing (3–0.1 µm particle size), washed with running water, dried via cold air, and then chemically etched using Kalling 2 reagent (ATM, Mammelzen, Germany). The geometrical characteristics of the cross section of the clad areas were analyzed and measured using an Olympus GX51 (Tokyo, Japan) optical microscope equipped with AnalySis software for image processing. The microstructure of cross sections through the laser clad samples was analyzed also by scanning electron microscopy (SEM) using an Inspect S microscope (FEI, Holland) equipped with energy-dispersive X-ray spectroscopy (EDS) sensor type AMETEC Z2E.

The hardness was measured by scratch testing performed using a multi-function Tribometer MFT-2000 (Rtec-instruments, Yverdon-les-Bains, Switzerland) under a constant load of 25 N with 0.15 mm/s speed and a diamond Rockwell 200 µm radius on a 3-mm length at 23 °C temperature environment and 40% relative humidity. The scratch hardness number was calculated using Eq. (1) [43], by dividing the applied normal force on the stylus by the projected area of scratching contact, considering the hemispherical-tipped stylus groove of a radius of curvature r. The projected area of the contact surface is therefore a semi-circle whose diameter is the final scratch width.

\[
H_{SP} = \frac{8P}{\pi w^2}
\]

where:
- \(H_{SP}\) – scratch hardness number [GPa];
- \(P\) – normal force [N]; and
- \(w\) – scratch width [µm].

The same system was used for pin on disc tribological testing behavior under the following conditions: 60 N applied load for 5 min, 150 rpm speed, and a 6-mm diameter pin with a spherical head made of Steel 440C. The testing machine is equipped with dedicated software for data analyses and interpretation. Prior to measurements of
the hardness and wear resistance on the IN718 deposited material and the GCI substrate, the surfaces were preliminarily prepared by grinding and polishing.

The electrochemical measurements (corrosion tests) were carried out by using the linear polarization resistance (LPR) technique, which is a corrosion rate monitoring method that can give an indication of the corrosion resistance of materials in an aqueous environment. The corrosion tests were carried out in a three-electrode cell using a PARSTAT 4000 (Princeton Applied Research—AMETEK, USA) potentiostat/galvanostat connected to the VersaStudio software produced by the same company. The measurements were conducted according to ASTM G5—94(2011)e1 standard. The working electrode was made of the GCI without and with IN718 coating. The saturated calomel electrode (SCE) was used as the reference, and the recording electrode was made from a platinum mesh (99.8% Pt). Prior to each measurement, the surface of the working electrode was cleaned ultrasonically in pure water and dried at room temperature. The used corrosive environment (electrolyte) was NaCl 3.5%. The potentiodynamic polarization (PDP) curves were recorded by applying a potential in a range of $\pm 2000$ mV, with the scanning rate of 1 mV/s. The PDP curves were used to designate the corrosion potential, corrosion current density, and the slope of the anodic and cathode curve of the tested materials. All measurements were carried out at a temperature of $24 \pm 0.2 ^\circ C$, and to ensure repeatability, the tests were performed three times for each specimen.

3 Results and discussion

3.1 Microstructure

Both longitudinal and transversal cross sections through deposited layers were performed and the resulting surfaces were prepared for analyses. Figure 3a displays the optical microscopy image of a transversal cross-sectioned mirror-polished deposited layer of Inconel 718 on GCI substrate. Four cuts were performed in arbitrary places of the sample in order to check for the presence of defects. Tests were performed for determination of the optimal distance between two lines of deposited material, in order to obtain an esthetically pleasing, but also a defect-free continuous deposition. A 40% overlap ratio between the meander lines when depositing the material was found to be the optimal value for achieving a homogenous, crack, and pores-free surface in the alloyed region. This was consistent for all depositions on four studied samples. A typical cross section is presented in Fig. 3b, showing a defect-free bounding interface between the coatings and substrates. The deposited material thickness varies from 700 µm up to 900 µm for one-layer deposition. Some detailed images from the interface between the IN718 deposition layers and the GCI support material are presented in Fig. 3c, d.

It can be noticed that the graphite lamellae were deformed and coalesced at the interface between substrate and deposited material. In addition, small islands of Ledeburite (Le) were formed in the confluence zone between

![Fig. 3 Optical microscopy images of a cross section of GCI substrate coated by DED with IN718 after the metallographic etching. Magnification bar: 1000 µm (a), 500 µm (b), 100 µm (c), and 50 µm (d)](image-url)
the deposited IN718 alloy and the GCI substrate. In the transversal cross section of laser deposition (Fig. 4a), the interface line is wavy, indicating the formation of mixing zones with widths corresponding to each passing of the laser beam. In contrast, the interface with the GCI substrate in the longitudinal cross section is quite linear and has a narrow mixing zone (MZ). The structure in the laser deposition area shows a cellular dendritic growth (Fig. 4b), oriented in the direction of heat flow, which is specific to a deposit of molten material on a solid substrate. Laves phases formed in the mixing zone between the laser-deposited layers and the GCI substrate, in the form of small light-colored islands precipitated interdendritically (Fig. 4c). The recorded temperature of the melt pool during the DED process was $1450 \pm 50 ^\circ C$, which leads to the formation of Laves phases that form in case of IN718 at temperatures exceeding $1150 ^\circ C$, as shown by Liu et al. [44]. The distribution of the chemical elements along a line that crosses the interface between the laser-deposited layer of IN718 and the substrate of GCI is shown in Fig. 4d. A mixing zone of ~200 microns wide is formed at the interface, where an obvious decrease of Ni and Cr concentrations can be observed.

### 3.2 Compositional analysis

In Fig. 5 corresponding to Fe, Cr, and Ni, there is a clear mixing zone between the IN718 layer and GCI substrate. This mixing zone is differently colored as compared to the color associated to each element. This different coloring is caused by the reduced proportions of Fe, Cr, and Ni as compared to the bulk IN718 layer caused by mixing with GCI. This mixing zone is 40–50 µm thick and includes preponderantly Fe, Cr, and Ni and traces of Mn, Ti, Mo, Nb, Si, and Al. Apparently, for Fe, Ni, and Cr, the submersion in the GCI substrate stops after 50-µm penetration in depth, while for other elements like Mn, Ti, and Al, it can go for depths of more than 300 µm. At the interface between IN718 and GCI, there is a narrow area of liquid metal, in which the transfer of atoms between the two materials is performed, but the high concentration of Ni determines the buffer layer effect, which greatly limits their inter-diffusion. The high carbon concentration in the GCI matrix also limits the diffusion pathways of the chemical elements from the laser deposition. The temperature on the molten metal areas measured in real time with the thermal camera had values of approximately $1450 ^\circ C$. This value is close to the melting temperature of

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**Fig. 4** SEM images of cross section zones through laser deposition layers. Transition zone between two layers of IN718 laser deposition and GCI substrate (a); cellular dendritic grains of In718 laser deposition (b); detail of mixing zone highlighting the Laves phase’s location (c); line scan through the interface of laser clads on transverse direction (d)
Fig. 5 Chemical element distribution on the transverse cross section of laser-deposited layers. SEM image of the analyzed area (a); EDS global image (b); EDS element distribution maps. Magnification bar 200 μm (c)
pure Fe (1538 °C) and that of IN718 (1450 °C). The very low volume of the molten metal and the effective action time of the heat source do not allow the formation of deep mixing areas between cast iron and alloy IN 718, the effect being rather a wetting and a mixture in semi-viscous state.

For the quantitative highlighting of the dilution effects at the interface between the two materials, EDS spot analyses were performed in different areas: on layers 1 and 2 of IN718 deposition, at the interface with the GCI substrate, in the cast iron at approx. 25 μm below the interface, on the mixing zone at the intersection between layers 1 and 2, on the carbon-rich areas situated on the interface with the GCI substrate (Fig. 6).

EDS measuring points (spots 9 and 10) are placed in the mixing zone between GCI and IN718 deposited layer, while spots 4, 6, 7, and 8 are situated on the interface between clad and the GCI substrate. The chemical composition for each EDS measurement point is shown in Table 4. Small amounts of Cu (of 0.47 wt% to 0.58 wt%) from GCI are present in the EDS analysis, but were not taken into account in Table 4.

According to EDS chemical analysis data, the Ni concentration decreased from the standard values of 52.8 wt% (according to the spectral chemical analysis on powder material IN718, Table 1) to less than 31 wt% at the interface with the GCI substrate, and the iron content increases as mixing effect of the two materials. The variation of Ni concentration in different points of the cross sections is due to the dilution effect. The maximum dilution effect occurs in the mixing zone of IN718 deposited on the gray cast iron substrate (about 31.33 wt% Ni). For the first layer, the dilution is lower, and the Ni content reaches 45.86 wt% (spot 1), while in the next layer the Ni concentration reaches the nominal value specified in the powder quality certificate. Below the GCI substrate separation line, the Ni concentration reaches about 0.1 wt%, indicating the lack of diffusion effect of this element in the substrate.

A similar evolution can be observed in the case of Cr, whose concentration decreased from 19.2 wt% in standard composition (Table 1) to 18.09 wt% in the second laser-coated layer and then to 15.68 wt% in the first laser-clad layer. Small quantities of Cr have been detected below the interface with the substrate (0.29 to 0.83 wt%).

Other chemical elements from IN718 alloy, such as Nb, Mo, Ti, and Al, have a decrease in chemical concentration as they approach the substrate interface. However, on the interface area (spot 4, Table 4), an increase in the concentration of Nb (7.23 wt%) has been obtained, due to the formation of Laves phases or carbides [45]. No fragile compounds and no cracking effects have been detected at the clad interface with the GCI substrate.

In the mixing zone of the overlap molten layers (spot 10, Fig. 6a), a decrease of Ni and Cr concentration was observed, together with an increase of Fe concentration (75.26 wt%). This evolution is due to mixing effects between the layers during DED. When the first laser layer is deposited, the IN718 powder and a surface layer of GCI are melted together. Some of the alloying elements from IN718, like Cr, Nb, and Ti, form carbides and Laves phase. The convection currents from the molten metal allow carbon from GCI to rapidly react with the high carbon affinity elements (Cr, Nb, Ti) from IN718, in the interface area. The carbon atoms cannot diffuse too much into the deposited metal, this phenomenon being limited by the low diffusion coefficient of C in the Ni-rich alloy and by the short interaction time with the laser beam.

In carbon-rich (2–6.67 wt%) Fe alloys such as GCI, this element is found either free (nodular graphite, lamellar, stellate, vermicular) or in cementite or ledeburite. The Mari-goni convection model can be used to explain the mechanism of carbon migration from the graphite lamella through the melt pool and scattered in the deposited structure, close to the interface. Due to rapid heating–cooling cycles, the C structures can coalesce and migrate from the GCI in the deposited structure and be trapped inside the new layer during solidification. However, we demonstrated that using the optimal process parameters the free carbon accumulation in the deposited layer can be almost completely ruled out.

### 3.3 Hardness

Sets of ten measurements were performed in 6 different of each sample in order to achieve an accurate value of the deposited material’s hardness. The average hardness of GCI in a commercial brake disc was 290 ± 9 HV, while the hardness of the IN718 deposited material, conducted on the polished surface of the deposited layer, showed a 430 ± 16 HV value, which is higher by ~50%, as compared to the substrate. It must be mentioned that tests were performed in various locations of the coated samples and on multiple samples, indicating a homogeneous hardness of the coating. The values for cast IN718 commercially available alloys are ≤ 380 HV [46]. In the case of selective laser melting (SLM), lower microhardness values of around 281 ± 18 HV [47] or 330–390 HV [48, 49] were reported. For DED, the hardness increases by 10% as compared to the highest reported values in case of SLM or casted samples could be due to the high Nb content close to the surface. It is known that the increase of the Nb content favors the formation of hard phases in Inconel alloys [50, 51]. Nb is soluble in the Ni-based austenite and it strengthens it by producing both an elastic stress caused by the atomic size difference and an internal stress by the difference of elasticity modulus between austenite and Nb atoms [52, 53]. From Table 4, one can see that closer to the surface the Nb content is ~ 3 wt.%, while in the vicinity of the interface with the GCI substrate, it was not detected by EDS.
3.4 Tribological properties

The wear resistance of GCI substrate and IN718 deposited layers was tested at room temperature under dry sliding conditions and the friction coefficient evolution is shown in Fig. 7. The IN718 surface presents a superior wear resistance compared to the substrate specimen at the same wear parameter conditions. The CoF between the round head of the Steel 440C stylus and the GCI substrate was 0.536 with the tendency to decrease after 200 s of continuous testing, while the coated substrate in steady. This is a sign that the surface was leveled by the stylus and became smoother after repeated passages over the same area. Oppositely, the IN718 coatings displayed a 0.12 higher CoF vs the 440C pin, as compared with the substrate specimens. In this case, the CoF was not affected by the repeated interaction between the pin and the coating over the 300-s testing interval, which was indicative of a higher hardness. The pin had not succeeded to induce a smoothening of the surface after repeated passage over the same surface in the testing interval.

The wear tests performed on the GCI substrate and IN718 superalloy deposited layers were finalized with an inspection of the worn areas via three-dimensional mapping with a confocal microscope (Fig. 8a, b — left). Figure 8a, b (right) represent a cross section of the worn surface in a specific point of the map. The circular wear reciprocating test showed significant tribological differences between the uncoated and IN718-coated samples, tested at room temperature. Figure 8a reveals a low value of the wear track depth for the IN718 deposited layers (−50 µm), while the wear track depth of the GCI-uncoated substrate (Fig. 8b) was 3 times deeper (−150 µm) compared to the samples coated with IN718, which demonstrate the improved wear resistance of the coated material.

Based on the wear depth and the mass loss (Fig. 9a), the wear rate can be calculated by Eq. (2) [34]:

\[ w_r = \frac{V}{SF} \]  

Table 4 Chemical composition of EDS spot analyses for Fig. 9 [wt%]

| EDS spot | Ni | Cr | Nb | Mo | Ti | Al | Si | Mn | C | Fe |
|----------|----|----|----|----|----|----|----|----|---|----|
| 1        | 45.86 | 18.09 | 2.68 | 2.00 | 0.79 | 0.88 | 0.63 | 0.52 | 0.63 | Balance |
| 2        | 37.22 | 14.24 | 0.85 | 1.38 | 0.33 | 0.79 | 0.91 | 0.37 | 0.50 |
| 3        | 36.28 | 15.68 | 1.08 | 1.79 | 0.46 | 0.81 | 1.16 | 0.47 | 0.46 |
| 4        | 31.33 | 11.83 | 7.23 | 2.29 | 1.50 | 0.55 | 1.00 | 0.35 | 0.73 |
| 5(GCI)   | 0.10 | 0.29 | 0.20 | 0.22 | 0.17 | 0.57 | 2.48 | 0.47 | 0.73 |
| 6        | - | 0.83 | - | - | - | - | - | - | 0.54 | 2.25 |
| 7        | 1.27 | 1.56 | - | - | - | - | - | - | 2.42 | 0.46 |
| 8        | 0.34 | 1.34 | - | - | - | - | - | - | 2.46 | 0.81 |
| 9        | 45.31 | 18.34 | 3.56 | 2.24 | 1.07 | 0.99 | 0.61 | 0.35 | 0.62 |
| 10       | 14.64 | 5.87 | 0.28 | 0.56 | 0.25 | 0.58 | 1.56 | 0.35 | 0.65 |

where \( w_r \) is the wear rate, \( V \) is the wear volume, \( S \) is the total friction distance, and \( F \) is the load. The wear rate graphs of the IN718 deposited layer and the GCI substrate are presented in Fig. 9b and show how the wear rate of the coated GCI surface is smaller by an order of magnitude compared to the uncoated GCI. This result confirms once again the excellent wear resistance of the IN718 deposited layers.

3.5 Corrosion properties

It is expected that the IN718 layer has superior corrosion properties to GCI substrates, as the IN718 is mainly a Ni–Cr alloy, both elements being known for their ability to form a natural oxide protective layer against corrosion. The following tests aim to show the magnitude of the IN718 corrosion protection superiority as compared to GCI. The corrosion tests were conducted in 3.5% NaCl aqueous solution. Figure 10a shows the variation of the open circuit potential, while Fig. 9b presents the PDP Tafel curves for the investigated samples. From the Tafel curve, the corrosion potential (Ecorr), corrosion current density (icorr), the slope of the anodic (βa), and cathode (βc) curve of the tested materials were determined. The values of the corrosion parameters of the tested materials are listed in Table 4.

From Fig. 10b and Table 5, it can be observed a significantly high value difference of the Ecorr, which indicates the improved corrosion resistance of the IN718-coated material compared with the bare GCI. The higher the corrosion potential of the material, the lower the corrosion current, resulting in a superior corrosion resistance. Also, a smaller value of the corrosion current density (icorr) indicates a better corrosion resistance and it validates once again that the IN718-deposited layers protect the brake disc from corrosion. The lower Ecorr for the deposited
layers is not related to the morphology of the parts, but to the native oxide layer that forms on the surface of IN718. Both Cr (over 12%) and Ni form natural adherent oxide layers on the surface in ambiental conditions that are insulators. This oxide layer protects the underneath metal from corrosion and oxidation. As the electrical measurements

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**Fig. 7** Coefficient of friction in case of GCI and IN718 registered in the circular motion

![Graphical representation of wear track depth (a) and a selected section (b) of the IN718 vs GCI surfaces](image)

**Fig. 8** Graphical representation of wear track depth (a) and a selected section (b) of the IN718 vs GCI surfaces
are performed on the surface of the coatings, it is normal that $E_{\text{corr}}$ of the oxide is much lower than $E_{\text{corr}}$ of the metals.

Based on the parameters presented in Table 5, we can calculate the polarization resistance according to ASTM G59-97 (2014) standard, given by Eq. (3) [54]:

$$R_p = \frac{\beta_a \beta_c}{2.3i_{\text{corr}}(\beta_a + \beta_c)}$$

(3)

where.

$R_p$ is the polarization resistance; $\beta_a$ is the slope of the anodic curve of the tested materials; $\beta_c$ is the slope of the cathode curve of the tested materials; $i_{\text{corr}}$ is the corrosion current density.

The polarization resistance is defined as the resistance of a sample to corrosion during the application of an external current.

Based on the corrosion current density $i_{\text{corr}}$, the CR can be calculated using Faraday law as Eq. (4) [55]:

$$CR\left(\frac{\text{mm}}{\text{year}}\right) = \frac{i_{\text{corr}} \times k_1 \times EW_{\text{metal}}}{\rho}$$

(4)

where.

- $CR$ is the corrosion rate in millimeters per year.
- $i_{\text{corr}}$ is the corrosion current density in amperes per square meter.
- $k_1$ is a constant.
- $EW_{\text{metal}}$ is the equivalent weight of the metal in grams per gram equivalent.
- $\rho$ is the density of the metal in grams per cubic centimeter.
1.3

$k_1$ is a constant that defines the units for the corrosion rate and its value is 3272 mm/(A cm year); $EW_{Metal}$ is the equivalent weight in grams, which for metallic compounds is 27.92; $\rho$ is density, which for GCI is $\sim$ 7 g/cm³ and for IN718 is 8.12 g/cm³.

The resulted values of polarization resistance ($R_p$) and corrosion rate (CR) are presented in Table 6 for both investigated materials, IN718 deposited by DED and the GCI substrate.

It was found that the surface coated with IN718 by DED increased by four times the polarization resistance of the electrode. This information is validated by the corrosion rate of the GCI, which is three times lower than the CR of the IN718 deposited layers, in 3.5 wt.% NaCl aqueous solution.

### 3.6 Functional tests

Once the IN718 deposited layers demonstrated to have improved mechanical properties, the optimal parameters were used to fully coat two brake discs by DED (Fig. 11a). After deposition, a post-processing step by turning machining (Fig. 11b) was inherent in order to achieve the dimensions specified in the technical drawing.

Brake discs coated by DED with IN718 layers and post-machined by turning were tested for measuring the braking force on a roller brake tester at an authorized car service. The discs were mounted on a Renault Megane and tested in conformity with the European Union legislation for vehicle circulation (Fig. 11c). The European Parliamentary Research Service has developed a transport policy oriented towards safety and security through common standards and rules [56].

The friction force and the braking coefficient are the interest parameters for these tests. In the case of brake discs, the friction force can be calculated using Eq. 5 [57]:

$$F_f = c_f \times P_f$$

where.

$F_f$ is the friction force; $c_f$ is the friction coefficient; $P_f$ is the pressing force of the brake pad. The test results showed a value of $\sim$2700 N.

The braking coefficient represents the ratio between the sum of the braking forces on the wheels on which the brake is applied, the effectiveness of which is verified and the

### Table 5 Corrosion parameters of GCI substrate and IN718 deposited layers by DED

| Sample  | $E_{oc}$ (mV) | $E_{corr}$ (mV) | $i_{corr}$ (µA/cm²) | $\beta_c$ (mV) | $\beta_a$ (mV) |
|---------|----------------|-----------------|---------------------|----------------|----------------|
| GCI     | -729           | -760            | 3.925               | 237.21         | 59.82          |
| IN718   | -604           | -597            | 1.501               | 98.91          | 103.08         |

### Table 6 Polarization resistance and corrosion rate of GCI substrate and Inconel 718 deposited layers

| Sample  | $R_p$ (kΩxcm²) | CR (mm/year) |
|---------|----------------|--------------|
| GCI     | 5.29           | 0.05         |
| IN718   | 22.20          | 0.01         |

Fig. 11 Brake discs coated by DED with IN718 (a), final product post-machining (b), and functionally tested on a vehicle in an authorized car service unit (c)
weight of the vehicle and can be calculated using Eq. (6) based on a national regulation [58]:

\[
c_b = \frac{\sum_{i=1}^{n} F_{is} + F_{id}}{G} \times 100% \tag{6}
\]

where.

\(F_{is}\) (daN) – braking force on the left wheel on the left side of the front axle \(i\); \(F_{id}\) (daN) – the braking force on the right wheel on the right side of the front axle \(i\); \(n\) – number of front axles; \(G\) (daN) – the weight of the vehicle.

The braking coefficient value for the DED IN718-coated brake discs was 71. We mention that the critical value over which a braking system of a vehicle is considered reliable is 58, according to the legal regulations for circulation of vehicles on the public road [58].

Overall, the braking system consisting of the brake disc and brake pad fulfilled the testing standards for vehicles imposed by European regulations and a conformity certificate was obtained.

### 4 Conclusions

In this paper, the properties of a IN718 metallic deposited layer obtained by a direct energy deposition laser method on GCI substrates were analyzed. The coating material IN718 alloy was initially in form of spherical powder, which was guided by a three-beam nozzle and melted by the laser beam, obtaining an adherent, compact, and uniform layer after solidification, on the surface of the GCI substrate.

The results reveal improved mechanical properties of GCI coated with IN718 by DED and the following conclusions can be drawn:

- The interface between substrate and the deposited material was uniform, forming a compact bonding of the two materials. The 40% overlap ratio was selected as the optimal value in order to achieve a homogenous, crack, and pores-free surface in the alloyed region. The diffusion of main chemical elements (Ni, Cr, Nb, Ti) from IN718 laser-deposited layers on the GCI substrate was negligible and no fragile compound that can produce cracks has been detected at the interface.
- The average hardness of GCI is 290 ± 9 HV, while the hardness of the IN718 deposited material was 430 ± 16 HV value, which is ~50% higher.
- The GCI substrate had a friction coefficient (CoF) of 0.5 and dropped to 0.4 during testing because of the surface leveling following multiple passes of the pin over the same area, while the IN718 coatings presented CoF higher by 0.12 as compared to the substrate material and were not affected significantly by erosion during testing. The depth of the wear track for the layers deposited with IN718 was −50 µm, while the depth of the wear track of the exposed substrate GCI was 3 times higher (−150 µm). IN718 succeeded to protect the substrate against wear, which translates into an extension of the brake disc lifetime.
- The corrosion resistance of the coating was superior to that of the GCI substrate in 3.5 wt.% NaCl aqueous solution. It was found that the surface coated with IN718 by the DED method increased by four times the polarization resistance of the electrode and displayed a 40% smaller value of the corrosion current density (\(i_{corr}\)), which indicates a better corrosion resistance. Therefore, this coating method has the potential to improve the corrosion behavior of the brake discs, hence prolonging their lifetime.
- The couple between the coated brake discs and the brake pads was tested by measuring the braking force and the friction coefficient in a real environment in an authorized car testing facility. They fulfilled the testing standards for vehicles imposed by European regulations and received a conformity certificate.

The brake disc coating with a hard and highly resistant to corrosion alloy could be an interesting solution for the automobile’s wheels engineering industry. The cost is kept low, as the main part of the disc is made of reasonable GCI, while the deposited layer adds a prolonged lifetime of the part and reduces pollution caused by metal particles expelled in the atmosphere during braking.

In terms of future work, there are still some unanswered questions for future scientific testing and functional tests in view of product development: (i) The high content of C in GCI can be affected close to the surface during laser irradiation, causing a changing microstructure and/or composition of the GCI. On the long term, how this affects the performances of the substrate is not yet known. (ii) The brake discs are very difficult to process post-cladding of IN718, so a reliable method for surface finishing without extensive costs has to be found. (iii) Moreover, the discs have not yet been tested on a track circuit for a long period of time in various driving conditions: weather, driving style, on different brake pad materials.

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Data availability The data and all related information presented in this study are available on request from the corresponding authors.

Declarations

Institutional review board statement Not applicable.

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References

1. Rashid A (2014) Overview of disc brakes and related phenomena-a review. Int J Veh Noise Vib 10:301. https://doi.org/10.1504/IJVNV.2014.065634

2. Thornton R, Slatter T, Jones AH, Lewis R (2011) The effects of cryogenic processing on the wear resistance of grey cast iron brake discs. Wear 271:2386–2395. https://doi.org/10.1016/J.WEAR.2010.12.014

3. Lu S, Zhou J, Wang L, Liang J (2021) Influence of MoSi2 on the microstructure and elevated-temperature wear properties of Inconel 718 coating fabricated by laser cladding. Surf Coatings Technol 424:127665. https://doi.org/10.1016/J.SURFCOAT.2021.127665

4. Roubicek V, Raclavska H, Juchelkova D, Filip P (2008) Wear and environmental aspects of composite materials for automotive braking industry. Wear 265:167–175. https://doi.org/10.1016/J.WEAR.2007.09.006

5. Grigoratos T, Martini G (2015) Brake wear particle emissions: a review. Environ Sci Pollut Res 22:2491–2504. https://doi.org/10.1007/S11356-014-3696-8/TABLES/5

6. Nogueira APG, Carlevaris D, Menapace C, Straffelini G (2020) Tribological and emission behavior of novel friction materials. Atmos 2020, Vol 11, Page 1050 11:1050. https://doi.org/10.3390/ATMOS11101050

7. Dizdar S, Lyu Y, Lampa C, Olofsson U (2020) Grey cast iron brake discs laser cladded with nickel-tungsten carbide—friction, wear and airborne wear particle emission. Atmos 2020, Vol 11, Page 621 11:621. https://doi.org/10.3390/ATMOS11060621

8. Tonolini P, Montesano L, Pola A et al (2021) The effect of laser-cladding on the wear behavior of gray cast iron brake disc. Procedia Struct Integr 33:1152–1161. https://doi.org/10.1016/J.PROSTR.2021.10.129

9. The Welding Institute (2019) What is extreme high speed laser application (EHLA)? In: Tech. Knowl. https://www.twi-global.com/technical-knowledge/faqs/what-is-ehla. Accessed 21 Jan 2022

10. Li T, Zhang L, Bulbeti GGP et al (2019) Extreme high-speed laser material deposition (EHLA) of AISI 4340 Steel. Coatings 2019, Vol 9, Page 778 9:778. https://doi.org/10.3390/COATINGS9120778

11. Zhu L, Liu Y, Li Z et al (2020) Microstructure and properties of Cu-Ti-Ni composite coatings on gray cast iron fabricated by laser cladding. Opt Laser Technol 122:105879. https://doi.org/10.1016/j.optlastec.2019.105879

12. Wang T, Wang C, Li J et al (2021) Microstructure and wear properties of laser-clad NiCo alloy coating on Inconel 718 alloy. J Alloys Compd 879:160412. https://doi.org/10.1016/J.JALLCOM.2021.160412

13. Zhu L, Yang Z, Xin B et al (2021) Microstructure and mechanical properties of parts formed by ultrasonic vibration-assisted laser cladding of Inconel 718. Surf Coatings Technol 410:126964. https://doi.org/10.1016/J.SURFCOAT.2021.126964

14. Thawari N, Gullipalli C, Katiyar JK, Gupta TVK (2021) Effect of multi-layer laser cladding of Stellite 6 and Inconel 718 materials on clad geometry, microstructure evolution and mechanical properties. Mater Today Commun 28:102604. https://doi.org/10.1016/J.MTDCOMM.2021.102604

15. Cui C, Wu M, Xiao X et al (2021) The effect of laser energy density on the geometric characteristics, microstructure and corrosion resistance of Co-based coatings by laser cladding. J Mater Res Technol 15:2405–2418. https://doi.org/10.1016/J.JMRT.2021.09.073

16. Zhong C, Gasser A, Kittel J et al (2016) Improvement of material performance of Inconel 718 formed by high deposition-rate laser metal deposition. Mater Des 98:128–134. https://doi.org/10.1016/J.MATDES.2016.03.006

17. Li Y, Dong S, Liu X et al (2021) Interface phase evolution during laser cladding of Ni-Cu alloy on nodular cast iron by powder preplated method. Opt Laser Technol 135:106684. https://doi.org/10.1016/J.OPTLASTE.2020.106684

18. Yi P, Zhan X, He Q et al (2019) Influence of laser parameters on graphite morphology in the bonding zone and process optimization in gray cast iron laser cladding. Opt Laser Technol 109:1016–1047. https://doi.org/10.1016/J.OPTLASTE.2018.08.028

19. Xie J, Huang Z, Lu H et al (2021) Additive manufacturing of tantalum-zirconium alloy coating for corrosion and wear application by laser directed energy deposition on Ti6Al4V. Surf Coatings Technol 411:127006. https://doi.org/10.1016/J.SURFCOAT.2021.127006

20. Olofsson U, Lyu Y, Åström AH et al (2021) Laser cladding treatment for refurbishing disc brake rotors: environmental and tribological analysis. Tribol Lett 69:1–11. https://doi.org/10.1007/S11249-021-01421-1/TABLES/5

21. Mahmood MA, Popescu AC, Oane M et al (2021) Grain refinement and mechanical properties for AISI304 stainless steel single-tracks by laser melting deposition: mathematical modelling versus experimental results. Results Phys 22:103880. https://doi.org/10.1016/J.RINP.2021.103880

22. Benedetti M, Lisiecki A, Mahmood MA et al (2022) Post-processing techniques to enhance the quality of metallic parts produced by additive manufacturing. Met 2022, Vol 12, Page 77 12:77. https://doi.org/10.3390/MET12010077

23. Liu Y, Zhan X, Yi P et al (2018) Research on the transformation mechanism of graphite phase and microstructure in the heated region of gray cast iron by laser cladding. Opt Laser Technol 100:79–86. https://doi.org/10.1016/J.OPTLASTE.2017.09.051

24. Zhang T, Li P, Zhou J et al (2021) Microstructure evolution of laser cladding Inconel 718 assisted hybrid ultrasonic-electromagnetic field. Mater Lett 289:129401. https://doi.org/10.1016/J.MATERIALS.2021.129401

25. Ocelík V, De OU, De BM, De HJTM (2007) Thick Co-based coating on cast iron by side laser cladding: analysis of processing conditions and coating properties 201:5875–5883. https://doi.org/10.1016/J.SURFCOAT.2006.10.044

26. Fernández E, Cadenas M, González R et al (2005) Wear behaviour of laser clad NiCrBSi coating. Wear 259:870–875. https://doi.org/10.1016/J.WEAR.2005.02.063

27. McLouth TD, Bean GE, Witkin DB et al (2018) The effect of laser focus shift on microstructural variation of Inconel 718
produced by selective laser melting. Mater Des 149:205–213. https://doi.org/10.1016/J.MATDES.2018.04.019
28. Huang K, Li W, Pan K et al (2021) Microstructure and corrosion properties of La2Zr2O7/NiCoAlY thermal barrier coatings deposited on Inconel 718 superalloy by laser cladding. Coatings 2021, Vol 11, Page 101 11:101. https://doi.org/10.3390/COATINGS1110101
29. Stanciu EM, Pascu A, Tiorean MH et al (2016) Dual coating laser cladding of NiCrBSi and Inconel 718. Mater Manuf Process 31:1556–1564. https://doi.org/10.1080/10426191.2015.103866
30. Zhang H, Zhou Y, Zou Z, Zhao W (2015) Comparative study on continuous and pulsed wave fiber laser cladding in-situ titanium-vanadium carbides reinforced Fe-based composite layer. Mater Lett 139:255–257. https://doi.org/10.1016/J.MATLET.2014.10.102
31. Lee HK (2008) Effects of the cladding parameters on the deposition efficiency in pulsed Nd:YAG laser cladding. J Mater Process Technol 202:321–327. https://doi.org/10.1016/J.JMATERIALSPRO.2007.09.024
32. Pinkerton AJ, Li L (2003) An investigation of the effect of pulse frequency in laser multiple-layer cladding of stainless steel. Appl Surf Sci 208–209:405–410. https://doi.org/10.1016/S0106-3535(02)01420-4
33. Li Y, Dong S, Yan S et al (2019) Elimination of voids by laser remelting during laser cladding Ni based alloy on gray cast iron. Opt Laser Technol 112:30–38. https://doi.org/10.1016/j.optlastec. 2018.10.055
34. Li W, Yang X, Xiao J, Hou Q (2021) Effect of WC mass fraction on the microstructure and friction properties of WC/Ni60 laser cladding layer of brake discs. Ceram Int 47:28754–28763. https://doi.org/10.1016/J.CERAMINT.2021.07.035
35. Xin B, Ren J, Wang X et al (2020) Effect of laser remelting on cladding layer of Inconel 718 superalloy formed by laser metal deposition. Mater 2020, Vol 13, Page 4927 13:4927. https://doi.org/10.3390/MA13214927
36. Mazzucato F, Forni D, Valente A, Cadoni E (2021) Laser metal deposition of Inconel 718 alloy and As-built mechanical properties compared to casting. Mater 2021, Vol 14, Page 437 14:437. https://doi.org/10.3390/MA14020437
37. Fan H-Y, Tu-Nan -R, Gusev DS, Lyukhter AB (2017) Influence of technological parameters on the geometry of single-track laser clad nickel based alloy on grey cast iron substrate. J Phys Conf Ser 941:012037. https://doi.org/10.1088/1742-6596/941/1/012037
38. Liu P, Sun S-Y, Xu S-B et al (2018) Effect of solid solution + double ageing on microstructure and properties in the layer by layer of the Z-Y interface of Inconel 718 alloys fabricated by SLM. Mater Res 21:20180395. https://doi.org/10.1590/ 1980-5373-MR-2018-0395
39. Stapelberg MG, Stapelberg MG (2021) Multi-scale investigations of the resistance to helium embrittlement with direct energy deposited Inconel 718 by. Bachelor Eng Nucl Sci Eng Massachusetts Inst Techn
40. Gorji NE, O’Connor R, Brabazon D (2021) XPS, SEM, AFM, and nano-indentation characterization for powder recycling within additive manufacturing process. IOP Conf Ser Mater Sci Eng 1182:012025. https://doi.org/10.1088/1757-899X/1182/1/ 012025
41. Di Pace L, Beone T, Di Donato A et al (2021) DEMO radioactive wastes: decarburization, recycling and reuse by additive manufacturing. Fusion Eng Des 168:112439. https://doi.org/10.1016/J.FUSENGDES.2021.112439
42. Monteiro H, Carmona-Aparicio G, Lei I, Despeisse M (2022) Energy and material efficiency strategies enabled by metal additive manufacturing – a review for the aeronautical and aerospace sectors. Energy Rep 8:298–305. https://doi.org/10.1016/J.ERGYR. 2022.01.035
43. Li D (2014) Scratch hardness measurement using mechanical tester
44. Liu F, Lyu F, Liu F et al (2020) Laves phase control of Inconel 718 superalloy fabricated by laser direct energy deposition via δ aging and solution treatment. J Mater Res Technol 9:9753– 9765. https://doi.org/10.1016/J.JMART.2020.06.061
45. Zhang YN, Cao X, Wanjarra P (2013) Microstructure and hardness of fiber laser deposited Inconel 718 using filler wire. Int J Adv Manuf Technol 69:2569–2581. https://doi.org/10.1007/ S00170-013-5171-Y
46. Inconel 718 from China manufacturer - Taixin Steel Co., Limited. http://www.allloysos.com/inconel-718.html. Accessed 23 Feb 2022
47. Jiang R, Mostafaei A, Pauza J et al (2019) Varied heat treatments and properties of laser powder bed printed Inconel 718. Mater Sci Eng A 755:170–180. https://doi.org/10.1016/J.MSEA.2019.03.103
48. Zhang Y, Li Z, Nie P, Wu Y (2013) Effect of cooling rate on the microstructure of laser-remelted INCONEL 718 coating. Metall Mater Trans A Phys Metall Mater Sci 44:5513–5521. https://doi.org/10.1007/S11661-013-1903-8/TABLES/4
49. Yang H, Yang J, Huang W et al (2018) The printability, microstructure, crystallographic features and microhardness of selective laser melted Inconel 718 thin wall. Mater Des 156:407–418. https://doi.org/10.1016/J.MATERIALSPRO.2018.07.007
50. Liu H, Guo K, Sun J, Shi H (2022) Effect of Nb addition on the microstructure and mechanical properties of Inconel 718 fabricated by laser directed energy deposition. Mater Charact 183:111601. https://doi.org/10.1016/J.MATCHAR.2021.111601
51. Wang J, Wang Y, Su Y, Shi J (2022) Evaluation of in-situ alloyed Inconel 625 from elemental powders by laser directed energy deposition. Mater Sci Eng A 830:142296. https://doi. org/10.1016/J.MSEA.2021.142296
52. Regulation No 90 of the Economic Commission for Europe of the United Nations (UN/ECE). http://www.unece.org/trans/main/wp29/wp29wgs/wp29gen/wp29docsts.html. Accessed 25 Feb 2021
53. E/ECE/32/4/Rev.1/A dd.7/Rev.6 Art.1 e/ E–E/TRANS/505/Rev.1/Ann.89/Rev.7/Law Insider. https://www. lawinsider.com/contracts/c/He1b10g1j1m. Accessed 23 Feb 2022
54. Seibi AC, Rostron P, Elramady A et al (2012) Effect of radial expansion of Cr-Mo steel tubes on their corrosion behavior in sea water. Mater Sci Appl 2012:587–595. https://doi.org/10. 1243/MSEA.2012.3908
55. Yang J, Yang H, Yu H et al (2017) Corrosion behavior of additive manufactured Ti–6Al–4V alloy in NaCl solution. Metall Mater Trans A Phys Metall Mater Sci 48:3583–3593. https://doi.org/ 10.1007/S11661-017-4087-9/FIGURES/8
56. Service El EPR (2020) Implementation of the roadworthiness package. https://www.europarl.europa.eu/RegData/etudes/ STUD/2020/654175/EPRES_STU(2020)654175_EN.pdf. Accessed 4 May 2022
57. Marques F, Woliński Ł, Wojtysz M et al (2021) An investigation of a novel LaGre-based friction force model. Mech Mach Theory 166:104493. https://doi.org/10.1016/J.MECHMACHTHEORY. 2021.104493
58. MT MT- (2018) REGLEMENTĂRI privind inspecția tehnică periodică a vehiculelor înmatriculate sau înregistrate în România - RNR 1. https://www.rarom.ro/cs-uploads/RNTR 1.pdf. Accessed 4 May 2022

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