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This report focuses on research on the mechanical properties of different substrate/deposited material laser-cladding combinations, specifically those that do not require a heat treatment, as well as the potential of laser cladding as an alternative to chromium plating. A wide variety of substrate and deposited materials is summarized, although there was a substantial lack of research into the desired Inconel 625 laser cladded onto martensitic stainless steel. However, there are multiple research publications of Inconel variations cladded onto austenitic stainless steels reviewed. There is also a summary of recent research on replacing the problematic chromium plating technique with high-speed laser cladding, which is promising.

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ABSTRACT

This report focuses on research on the mechanical properties of different substrate/deposited material laser-cladding combinations, specifically those that do not require a heat treatment, as well as the potential of laser cladding as an alternative to chromium plating. A wide variety of substrate and deposited materials is summarized, although there was a substantial lack of research into the desired Inconel 625 laser cladded onto martensitic stainless steel. However, there are multiple research publications of Inconel variations cladded onto austenitic stainless steels reviewed. There is also a summary of recent research on replacing the problematic chromium plating technique with high-speed laser cladding, which is promising.

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1.0 TI Request

1.1 INQUIRY

1.1.1 First Inquiry

Is there a body of knowledge/research on laser cladding materials that do not require heat treatment?

1.1.2 Second Inquiry

Has anyone developed a hybrid repair of components and are there better material combinations for the repair?

1.2 DESCRIPTION

The inquirer is specifically interested in mechanical testing of laser cladding on various substrates. An example (and current thought/application) is to deposit Inconel 625 onto 410 martensitic stainless steel and possibly avoid furnace stress relief that distorts the component and leads to further repair actions.

The inquirer is involved in developing high-speed laser cladding (very thin deposition) on rotating components where chrome plating would normally be used. It is a high-speed, directed energy deposition (DED) with a very minimal (~0.0001 inch) heat-affected zone. This will involve much testing (high-cycle fatigue, low-cycle fatigue, corrosion, wear, and bond).

Via DED, the team is currently doing component repair using powder with chemistry that matches the base material. Material combinations that do not match, primarily mechanical properties/testing, are also of interest.

The inquirer is running a project to develop a hybrid repair (inspect, pre-machine, DED, finish machine, and inspect—all in one setup). What is being found is that the component still requires heat treatment somewhere in the process due to untempered martensite (base material is 410ss). This is still an improved process from what is done today, but the benefits of a hybrid repair do not materialize (still a route out for heat treatment and will require distortion/more machining).

2.0 TI Response

2.1 INTRODUCTION TO LASER CLADDING

Laser cladding, also known as laser metal deposition, is a technique for adding one material to the surface of another. This is accomplished by feeding a stream of metallic powder or wire (cold or hot) into a melt pool that is generated by a laser beam as it scans across the target surface, depositing a coating of the chosen material with a short exposure time. This allows the material(s) to be deposited accurately, selectively, and with minimal heat input into the substrate. The inherently rapid heating and cooling rates associated with the laser-cladding process enable extended solid solubility in the metastable or nonequilibrium phases of production, offering the possibility of creating new materials with advanced properties. The result is a metallurgically bonded layer which is tougher than can be achieved with thermal spray and less dangerous to health than the process of hard chromium plating.

Laser cladding by a powder injection technique has been widely used in industrial applications such as rapid manufacturing, parts repair, surface coating, and innovative alloy development. The capability to mix two or more types of powders and control the feed rate of each powder flow makes laser cladding a flexible process for fabricating heterogeneous components or functionally graded materials [1]. Researchers have found that the wire-feed method has several advantages regarding its deposition speed and efficiency, with the ability to produce smooth surface with limited porosity, fewer defects, and better material quality at a higher deposition rate [2]. Regardless of the feedstock, this technology allows the material gradient to be designed at a microstructure level because of small, localized fusion and strong mixing motion in the melt pool of laser cladding. Thus, materials can be tailored for a flexible, functional performance in particular applications [1].

2.2 LASER CLADDING WITH HEAT TREATING

Laser cladding with nickel titanium (NiTi) alloy powders, applied as a new coating technology, has become one of the research hotspots for improving substrate surface performance [3]. Residual stress at the interface between the cladded layer and the substrate may cause problems of thermal stability at elevated temperatures [4]. Because of this, the subsequent heat treatment has been considered for improving its chemical homogeneity and phase transformation behavior of the coating [3]. Heat treatment is the process of heating metal without allowing it to reach its molten stage and then cooling it in a controlled fashion to achieve the desired material and mechanical properties. There are three stages of heat treatment: (1) heat the metal slowly to ensure it maintains a uniform temperature, (2) soak/hold the metal at a specific temperature for an allotted period, and (3) cool the metal to room temperature. If done properly, heat treatments can make the metal stronger, more resistant to abrasion, or more ductile [5].

Though nearly none of the research summarized in this report mentions any pre- or postprocess heat treatments in the publications, there are companies [6] and reports [7–10] that support the benefits of and/or need for preheating, annealing, or postweld heat treatments. Multiple reports [8–10] involve laser cladding Ni60 self-lubricated, antiwear composite coatings onto different substrates and exploring the effects of various heat treatments, with all of them claiming positive hardness, wear resistance, and friction results.

In 2015, Lu et al. [8] investigated a Ni60/h-BN self-lubricating, antiwear composite coating on 304 stainless steel and the effects of stress relief annealing heat treatments for one and two hours. After the 1-hour heat treatment, the laser clad coating presented the best antiwear and friction reduction properties. Wang et al. [9] investigated the heat treatment (25 °C, 500 °C, 600 °C, and 700 °C for 1 hour) effects the antiwear composite coatings had on a 35CrMoV substrate in 2022. They concluded that the mechanical properties of the coating were significantly improved by the 600 °C heat treatment, with the microhardness becoming more stable and the average friction coefficient and wear volume reduced.

Liu et al. [10] explored laser cladding Ni60/2.0 wt.%CeO_2 self-lubricating, antiwear composite coatings, also on 35CrMoV steel, that were thermally treated at 25 °C, 500 °C, 600 °C, and 700 °C for 1 hour, respectively, at a heating rate of 10 °C/min. They concluded from the friction coefficient and mass loss experiments that the wear resistance of the coating after 700 °C thermal treatment fully improved. The laser cladding parameters used for these tests are shown in Table 1.

Table 1: Laser Cladding Process Parameters [10]

Parameters	Values
Power	3000 W
Spot sizes	15 mm x 3 mm
Scanning speed	120 mm/min
Overlap ratio	0.4
Gas flow rate of argon	15 L/min
Wavelength	1080 nm

Zhang et al. [11] claimed that heat treatments of laser-cladded coatings could effectively eliminate residual stresses and avoid cracks. Additionally, preheating the substrate could reduce the temperature gradient of the substrate and coating, which is advantageous for a defect-free coating. However, the effect of heat treatment processes on the evolution of the microstructure of the coating is still uncertain and should be a continued avenue of research, as should be surface treatments. Finally, they stated that defects such as element segregation, inclusion, and structural ripples in the coating can be effectively improved with the help of external field-assisted technology. With this technology, the ultrasonic, cavitation, and vibration effects of ultrasonic-assisted deposition technology can promote full mixing, diffusion, and mixing of various elements in a high entropy alloy coating to effectively avoid stress concentration, homogenize the stress field, and optimize the surface properties of the coating.

2.3 LASER CLADDING WITHOUT HEAT TREATING

The broad review of laser cladding technology written by Zhang et al. [11] includes 81 references, most of which were published within the last two years. However, there were not any reports that directly matched the first inquiry, although quite a few involved Inconel alloy coatings and/or martensitic stainless-steel substrates. Inconel 625 is a nickel-based superalloy comprised of nickel (58% min), chromium (20–23%), molybdenum (8–10%), iron (5% max), niobium plus tantalum (3.15–4.15%), and traces of other elements. It is used for marine, nuclear, and rocket engine applications due to its superior resistance to a wide range of corrosive environments of unusual severity as well as high-temperature effects such as oxidation and carburization [12]. Martensitic stainless steels are known for strength, corrosion resistance, and durability, although they can be further divided by their carbon content. Stainless steel 410 is regarded as a general-purpose, martensitic stainless steel and usually supplied in an annealed condition [13].

2.3.1 Martensitic Stainless-Steel Substrates

Saeedi et al. [14] at the Malek Ashtar University of Technology (Iran) investigated the nichrome (NiCr) and NiCr-titanium carbide (TiC) laser cladding on AISI 420 stainless steel substrates. The researchers experimented to determine the optimal process parameters. The elemental, phasic, and microstructural assessments and characterizations of the obtained coatings were done by optical and scanning electron microscopes alongside energy-dispersive spectroscopy (EDS), X-ray diffraction. It was also seen that the hardness of the composite clad containing reinforcement particles was far greater than cladding without such particles because of the increased effect of nucleation and the presence of TiC particles.

2.3.2 Austenitic Stainless-Steel Substrates

Abioye et al. [15] performed corrosion and Vickers microhardness (0.3-kg load) testing of laser-cladded Inconel 625; however, it was on austenitic stainless steel 304 rather than martensitic stainless steel 410. While the parameters of the depositions changed on each pass, postprocessing was not done before testing. They found that the average microhardness of the typical single clad bead was 232 ±4.5 $HV_{0.3}$ and that the substrate hardness was not significantly altered, with an average value of 205 ±1.5 $HV_{0.3}$ at the interface. Sivamani et al. [16] aimed to develop a model relating the independent variables of laser power (2200–2800 W), powder-feed rate (30–50 g/min), laser-scanning speed (800–1200 mm/min), and the focal position of the laser beam (15–35 mm) with the Vickers hardness number to achieve the maximum hardness of CO_2 laser cladding of Inconel 625 powder on a stainless steel 304 substrate. The model developed by the curve-fitting method was employed to optimize the hardness using first derivative test, generalized reduced gradient, and grey-relational analysis. The maximum hardness of 374 was achieved first by the derivative test at optimal laser power, powder-feed rate, laser-scanning speed, and the focal position of the laser beam of 2554 W, 999 mm/min, 30 mm, and 40.5 g/min, respectively. Pascu et al. [17] attempted to optimize the operational parameters of the Inconel 718 laser cladded onto stainless steel 304 substrates using a pulsed laser. They related the power, pulse width, and frequency of the cladding to the clad microhardness, which ranged from 182 to 228 $HV_{0.2}$, using a Taguchi design of experiments (DOE). They concluded that for predicable cladding results using a pulsed laser, vary the laser power and frequency while keeping the pulse width constant. They also noted that the cladding microstructure was composed from coarse dendrite near the interface with the substrate and a finer dendrite structure in the upper area of the coating. Mariani et al. [18] found that surface finishing left by laser cladding was not always as smooth as required for most applications, and the Inconel 625 layers on AISI 304L required postprocessing via laser polishing.

Xu et al. [2] used wire laser cladding to obtain TiC-reinforced Inconel 625 coatings on stainless steel 316L and found significant grain refinement. They also reported that the coatings had superior mechanical and corrosion performance. The results indicated that the defect-free Inconel 625 coating presented an obvious microstructure transformation, while the bonding interface can be divided into three different areas. An unmixed area was observed near the bonding interface with precipitated ferrite of different formations. A decrease of the hardness (H) and reduced elastic modulus (Er) profile was detected in this area. Compared to the substrate, the cladded and bonding areas exhibited superior tensile properties at both room temperature and high temperature. The corrosion performance of the coating area was also close to the bonding area and superior to the substrate in different solutions, indicating an excellent protecting effect of Inconel 625 coating. Bloemer et al. [19] also published research on assessing a combination of the use of an empirical-statistical model and DOEs to minimally validate the geometrical characteristics (dilution, coating height, waviness, and porosity) of a laser-induced Inconel 625 coating on an AISI 316L substrate. The microstructure, microhardness, and bending resistance was assessed by depositing a verification coating, which had some pores present. The verification coating showed a columnar dendritic microstructure and a microhardness and bending resistance about 110% and 30% higher, respectively, than that observed for the AISI 316L substrate.

Segura et al. [20] explored the improved mechanical properties and reduced sensitivity to corrosion on an SS 316L substrate through grain boundary and microstructure engineering concepts of utilizing electron-beam, powder bed fusion cladding of Inconel 690. The resultant microstructures produced a tensile yield strength of 0.527 GPa, elongation of 21%, and Vickers microindentation hardness of 2.33 GPa for the Inconel 690 cladding in contrast to a tensile yield strength of 0.327 GPa, elongation of 53%, and Vickers microindentation hardness of 1.78 GPa, respectively, for the wrought 316 L stainless steel substrate. Additionally, the Inconel 690 subgrain boundaries essentially served as surrogates for coherent twin boundaries to avoid carbide precipitation and corrosion sensitization.

Silwal et al. [21] used gas tungsten arc welding (GTAW) cladding of Inconel 625 onto stainless steel 347. The microstructure of the clad bead and the substrate was analyzed. A heat-affected zone (HAZ) cracking was observed in the higher range of primary current. Verdi et al. [22] deposited an Inconel 625-Cr3C2 composite coating onto ferritic and stainless-steel substrates and studied the effect of exposition at high temperatures on the microstructure and mechanical properties. The microstructure was analyzed by scanning and transmission electron microscopy. Depth-sensing indentation tests were performed on the surface of the clads to obtain the evolution of the elastic modulus and the hardness with the exposition time.

2.3.3 Other Notable Efforts

Lamikiz et al. [23] evaluated the mechanical properties of different laser-cladding tests on Inconel 718. They produced hybrid (half-cladded material and half substrate) and rapidly manufactured (only cladded material) specimens that were tested as deposited and then after a precipitation-hardening treatment. The results, presented as traditional stress/strain curves, showed that the laser-cladding strategy could have a significant influence on the mechanical properties of the part and that there was a high risk to obtain lower mechanical properties of wrought Inconel 718. Guévenoux et al. [24] studied the mechanical response of Inconel 718 repaired thin walls by laser cladding the powder onto 1.6-mm-thick Inconel 718 wrought plates. They performed in-situ scanning electron microscopy tensile tests that showed plastic strain localization appeared as the loading amplitude increased. They found that the cladded region was much more deformed than the substrate and there was a strain fluctuation at the grain size scale in the repaired area. They explicitly stated that no heat treatments were applied to the samples.

For optimization purposes, Vollmer and Sommitsch [25] evaluated the bonding characteristics between the substrate and coating of laser-cladded coatings. A special testing device, shown in Figure 1, was developed to measure the adhesive tensile strength of specimens consisting of Ferro55 and Ni25 powders cladded onto C45W and 16MnCr5 steel substrates. After hardness tests were performed on the coatings, tensile tests were done to determine the maximum tensile force, as the adhesive strength cannot be done with a tension value because it is impossible to reach a uniaxial stress condition with the small specimen geometry. They did tests preheating the substrates and as received, with varying results. They concluded that the C45W substrate yielded better results.

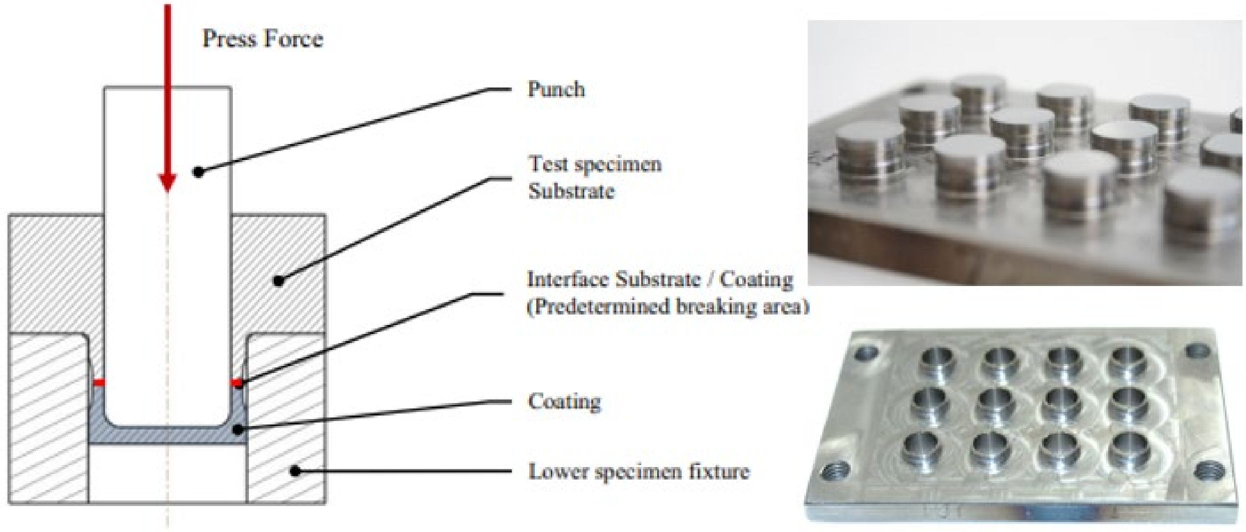

Figure 1: Diagram of Bonding Test (Left), Before Testing (Top Right), and After Testing (Bottom Right) [25].

2.4 CHROMIUM PLATING

Hard chromium plating has been facing prohibitive measures from the European Union, leading the industry to try and seek alternative solutions. Laser cladding had been discounted as a solution in the past because it was not deemed fast enough or capable of delivering thin enough coatings. However, developments in the technology (specifically, extreme high-speed laser application) now allow for higher speed deposition with thinner layers in a more power efficient manner, meaning that laser cladding can provide an effective alternative to hard chromium plating for particular applications [1]. This is needed, as the chrome electroplating process requires replacing because of the carcinogenic chemicals required in manufacturing [26].

2.4.1 Laser-Cladding Alternatives to Chromium Plating

One technology currently under investigation for replacing conventional coating processes (chromium plating or thermal spraying) is the high-speed laser cladding. Using high-speed laser cladding (high-speed laser metal deposition [HS-LMD])—a DED process—a laser beam heats coaxially fed powder particles to nearly melting temperature before being deposited to the desired surface. Layers generated by this process can be typically adjusted to range between 50 and 300 µm per layer [26]. Vogt et al. [26] examined Rockit401 and Inconel 625 coatings deposited by HS-LMD. They investigated the influence of high surface rates on properties such as defects, hardness, and crack susceptibility, as well as achievable layer thicknesses.

Christoforou et al. [27] examined the potential of replacing the chrome plating layer of a steel rod mill pinion with a nickel-based tungsten-carbide composite layer and intermediate Inconel 625 layer deposited by laser cladding. They performed microhardness and nanoindentation techniques. Three-bend tests were done on test specimens from a pinion sample to observe crack propagation resistance. Some results are included in Table 2. While they noted that laser clad coatings can be produced at the scale of 30 µm (~0.001 inch) using EHLA, they may not be as applicable to the load bearing applications being investigated.

Table 2: Result Comparison of Chrome Plating and Laser Cladding Coating [27]

	Chrome Plating	Ni-WC	Inconel 625	Substrate
Hardness (Hv)	1000	2154	459	431
Elastic modulus (GPa)	103–248	269	161	174
UTS (MPa)	103–482	—	—	—
Crack density (cracks/cm)	200–1500	0.3	0	0

Sommer et al. [28] examined using high-speed laser cladding (HSLC) of AISI stainless steel 316L on thin-sheet, AISI 430Ti, ferritic, stainless-steel substrates. The results demonstrated that clad widths as high as 1413 µm and dilution depths as low as 144 µm can be obtained by high-speed laser cladding of thin-sheet substrates. Other HSLC studies include Lampa and Smirnov [29] investigating an iron-based alloy consisting of 18% Cr and 2.5% Ni and Xu et al. [30] investigating an iron-based alloy powder on a China 45 steel substrate to replace chrome plating.

Wang et al. [31] examined the chromium plating layer failure of a piston rod and the proposed repair using an Ni-based alloy mixed with Nb powder by means of laser cladding. The microhardness and wear resistance of the cladding layer were tested. The Ni-base +15% Nb cladding layer was aged to measure the change in hardness and wear resistance and compared with the chromium plating layer.

2.4.2 Chromium-Based Laser Claddings

Karuppasamy et al. [32] aimed to enhance the corrosion resistance behavior of stainless steel 410 by laser cladding Colmonoy-5 alloy particles. The microstructure, hardness, and corrosion resistance were investigated. Natarajan et al. [33] did a similar study with Colmonoy-5 particles cladded onto stainless steel 420 substrates. X-ray diffraction, SEM, and EDS determined the resulting phases and coating morphologies. Vickers microhardness test was carried out to study the hardness and load-carrying capacity of the cladding specimen. Natarajan et al. [34] also investigated the hardness, microstructure, and corrosion resistance of laser-cladded Colmonoy-6 particles on a stainless steel 316L substrate. The results showed that the cladded samples experienced greater hardness and lower values of surface roughness and provided better corrosion resistance when compared with substrate samples.

2.4.3 ASTM Standard for DED Metal Deposition

ASTM has released a standard for DED (ASTM F3187-16, “Standard Guide for Directed Energy Deposition of Metals” [35]). It states that this document is intended to serve as a guide for defining the technology application space and limits, DED system set-up considerations, machine operation, process documentation, work practices, and available system and process monitoring technologies. The only mechanical test method referenced in this document is ASTM D6128-16, “Standard Test Method for Shear Testing of Bulk Solids Using the Jenike Shear Tester” [36], which is commonly used for powder testing. This is a means of testing the properties of the powder used in laser cladding rather than the mechanical bond.

3.0 CONCLUSIONS

Laser cladding is a metal and ceramic deposition method that has been widely used in industrial applications such as rapid manufacturing, parts repair, surface coating, and innovative alloy development. There has been much recently published research exploring various process parameters and materials and the use of pre/postprocessing methods to optimize the process. While there was a lack of published research into the cladding of Inconel and martensitic stainless steel, there was a wealth of information on Inconel and austenitic stainless steel and a variety of other materials. Additionally, laser cladding, particularly high-speed laser cladding, is being explored as an alternative for chromium plating. The advancements focus on thinner layers, quicker deposition speeds, and increased mechanical properties of laser cladding. This makes it a favorable alternative, with decreased health risks and environmental effects. While the recent research into these areas is positive, many avenues must still be explored for laser cladding to expand its use in critical applications.

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