Effect of laser powers on the mechanical properties 27SiMn steel with Inconel 718 cladding coatings

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Abstract
In order to know the influence of laser power on the steel (27SiMn) used for repairing the column with Inconel 718 powder materials, and to obtain the optimal laser power parameters with the best mechanical properties of cladding layer, the microstructure, tensile properties and fracture morphology of the Inconel 718 alloy under three laser powers (1800 W, 2100 W and 2400 W) were investigated by using the single-factor variable method, keeping the scanning speed, powder feeding amount and spot diameter unchanged. The results show that with increase of laser power the mechanical properties of the Inconel 718 alloy coating prepared on the surface for the column steel gradually decreased, and the mechanical properties were the best when the laser power is 1800 W. The yield strength of Inconel 718 alloy coating prepared at 1800 W was 61.7% higher than that of the substrate, and its value is 970 MPa. The elongation is reduced by 50% compared with the substrate, and its value is 7%. The microstructure of 27SiMn steel with cladding coating is (Ni, Fe, Cr) phase and Ni₃Fe phase, and the microstructure of the coating is mainly composed of uniform cellular crystals. This study provides a valuable reference for the additive manufacturing of industrial materials of 27SiMn steel with laser-cladding coating.

1. Introduction

The hydraulic support is the core support equipment of modern fully mechanized coal mining, and the column is the key component of this equipment. It plays a role in supporting the roof when working underground and maintaining the safe working space for the mining face. Therefore, the stability and reliability of the hydraulic support is an important factor to ensure the safe and efficient production of the working face [1–3]. The column has been service for a long time in the environment of high stress, high humidity and containing corrosive media such as sulfur and phosphorus [4]. The surface of 27SiMn steel used as the material surface of the column often has a series of engineering failure such as pitting, wear, bubbling and spalling, which seriously threaten the mining efficiency and the safety of mine workers. Improving the strength and plasticity of steel used for pollars is the guarantee of the safety of fully mechanized coal mining [5, 6]. In recent years, laser cladding [7–10] is a repair technology that has developed rapidly in the field of additive remanufacturing. It has many advantages, such as high energy density, small heat-affected zone, low dilution rate, and metallurgical bonding with the matrix. It can form a high strength, high plasticity and corrosion-resistance functional coating based on metallurgical bonding on the surface of 27SiMn steel for column. The coating technology has outstanding advantages and has become the core technology of remanufacturing hydraulic support column parts.

The forming mechanism of laser cladding is very complex. If the process parameters are not properly controlled, it will affect the manufacturing quality of additive, and even produce defects such as micro cracks and porosity [11, 12]. In recent years, many scholars have conducted a lot of investigations on laser cladding technology. Zhong et al [13, 14] have used the method of mixed process parameters to conduct laser cladding of Inconel 718 alloy coatings with high deposition rate, and concluded that different process parameters will make
significant differences in the microstructure and tensile properties of nickel-based alloy coating. Rashid et al. reported the effect of different laser deposition directions on the mechanical properties of 300 M repair parts [15, 16]. The anisotropy of mechanical properties is attributed to the existence of tempered martensitic and martensitic phases in the structure, and the mechanical properties of the specimens clad by the transverse path are better than those clad by the longitudinal and oblique 45 degree paths. Schopphoven et al. [17] reported the use of ultra-high speed laser cladding technology to cladding Inconel 625 alloy coating, and explored the effect of process parameters (laser power and carrier gas flow rate) on the cladding layer of Inconel 625. Teixeira et al. [18] studied the laser melting of alloy 1030A on the surface of high manganese steel, and concluded that the microstructure and the mechanical properties of the coatings were quite different under the different powers. Laser power is an important factor influencing the tissue characteristics and tensile properties of the clad coating [19, 20]. 27SiMn steel is a high-strength steel with excellent mechanical properties. The mechanical properties of the material after laser cladding directly affect its safety in service. At present, there is less research on the on the mechanical behavior of laser cladding of 27SiMn steel by laser power, and there are generally problems of low plasticity and strength of the clad layer [21, 22], which are not conducive to the remanufacture of column parts by laser cladding. In order to improve the plasticity and strength of 27SiMn steel after laser cladding, Inconel 718 powder containing more Ni and Nb strengthening elements was selected as the cladding material, and three laser powers were designed to prepare the cladding coating specimens, which were combined with the substrate and the substrate samples with notch for comparative research. The diffraction pattern of the molten clad specimens was analyzed by x-ray diffractometer to determine the phase structure. The cross-sectional morphology and microstructure characteristics of the samples with different power were analyzed by using ultra-deep field microscopy. The stress-strain curves of the samples under different powers were measured by tensile tests, and mechanical properties such as yield strength, tensile strength, elongation, and sectional shrinkage were obtained. The fracture morphology of the specimen was observed by SEM. This study is expected to provide basic data reference and process guidance for laser cladding repair of hydraulic support column parts.

2. Experimental procedure

The cladding test was performed with a YLS-3000 fiber laser, and the focal spot size diameter is 2 mm. In the laser cladding process with a spot diameter of 2 mm, the metal powder will absorb most of the energy, and the laser scanning speed is relatively fast, the energy distribution density is reduced, and the metal is not easy to evaporate into holes [24]. Inconel 718 alloy powder was used as the cladding material, and the particle size range is 40–70 μm. The substrate is 27SiMn steel, the base material of the hydraulic support column, with dimensions of 150 mm × 100 mm × 10 mm. The main chemical composition of the powder and substrate are shown in table 1. Before the test, the clad metal powder was dried at 100 °C constant temperature. The surface of 27SiMn Steel plate is polished with sandpaper and wiped with absolute ethanol to remove harmful impurities such as oil and water on the surface. In order to study the influence of laser power on the mechanical properties of cladding coating, the optimal scanning speed, powder feeding amount and protective gas flow speed are 22 mm s⁻¹, 17 g·min⁻¹ and 10 l·min⁻¹ through process optimization, respectively. The adopted cladding process parameters are shown in table 2. A single-layer multi-channel cladding test was carried on 27SiMn steel substrate, in which both the powder feeding gas and the protective gas were high purity nitrogen (concentration 99.9%).

Figure 1 shows the sampling process of tensile specimens (substrate, 8 GR (8% grind region), S1 (1800 W), S2 (2100 W) and S3 (2400 W)). The significance of setting 8 GR sample has two points. The first point is the comparison of mechanical properties between 8 GR sample and engineering applied substrate. When the yield strength of 8 GR sample is lower than the yield strength of the substrates, it indicates that when the substrates appears wear notch in engineering application, the safety is rapidly reduced, and additive manufacturing is required. The second point shows that 8 GR sample does not have notch strengthening effect due to its large gap, which avoids that the high strength of the cladding layer is partly due to notch strengthening effect, and further indicates the application value of the cladding layer for repairing the substrate. As shown in figure 1(a), firstly, a through groove with a width of 36 mm and depth of 0.4 mm is processed with a CNC milling machine in the center of the 27SiMn steel substrate, and the fillet radius at the bottom of the groove is R6. Then, laser cladding is carried out on the grooves with 50% overlap rate according to the longitudinal ‘bow’ path with three different laser powers, while the substrate and 8 GR (8% gr7ind region) specimens were not laser melted, as shown in figure 1(b). Finally, after the cladding surface is finely ground and leveled with the left and right ends of the substrate, the specimen is sampled by wire cutting method. The specification, size and sampling of the tensile specimen are shown in figures 1(c) and (d).

DX-2000 x-ray diffractometer was used to analyze the diffraction pattern to obtain the material composition and phase composition of the specimens. The cross-section and microstructure (upper, middle and lower) of the cladding layer were observed by VHX-7000 optical microscope. The stress-strain curves of the tensile specimens
Table 1. Chemical composition of Inconel 718 and substrates.

| Material                  | Ni   | Cr   | Nb   | Mo   | Ti   | C     | Cu   | Co   | Mn   | Si   | Fe   |
|---------------------------|------|------|------|------|------|-------|------|------|------|------|------|
| Inconel 718 27SiMn steel | 0.51 | 0.30 | 0.03 | 0.15 | 0.01 | 0.0034| 0.32 | 0.0005| 0.14 | 0.0034| 1.20 |
| Ni Cr Nb Mo Ti C Cu Co Mn Si Fe |  |  |  |  |  |  |  |  |  |  |  |

Mater. Res. Express 9 (2022) 096511
were measured by using WDW–100 composite material testing machine. The microscopic fracture morphology of the tensile specimens was analyzed by Feiner PhenomTM scanning electron microscope. The strain rate was set to 0.001 s$^{-1}$ during the tensile test, and the measured mechanical properties were 0.2% yield Stress, UTS (ultimate tensile strength), elongation, and cross-sectional shrinkage rate.

3. Results and discussion

3.1. Physical phase characterization and analysis

Figure 2 shows the XRD patterns of the substrate and the melt-coated coatings prepared at different powers. In figure 2, the matrix, S1, S2 and S3 have three strong diffraction peaks ($2\theta$) at the diffraction angles of 44.6°, 64.8° and 82.2°, corresponding to the three crystal planes (111), (200) and (220) of $\gamma$-(Ni, Fe, Cr) crystal plane, respectively. The results show that the matrix phase is $\gamma$-(Ni, Fe, Cr). Compared with the matrix sample, the diffraction peaks of the clad specimens S1, S2 and S3 are different, and there are of $\gamma''$-Ni$_3$Fe phase at the crystal planes (111), (102) and (220). According to the Ni-Fe binary phase diagram [25], Nickel and Iron can form an infinite solid solution, and Iron and some Nickel can form $\gamma''$-(Ni, Fe) phase at 1440°C. In the solidification process, with the decrease of temperature, the $\gamma''$-(Ni, Fe) phase undergoes solid-state phase transformation and form Ni$_3$Fe phase in the temperature range of 347°C–517°C.

Because the test specimens have the same cross-sectional area and under the same measurement conditions, the continuous phase volume fraction can be estimated using the total integrated area of the phases in the XRD spectra. The peak fitting procedure of the Pearson VII function was used to determine integration areas of the (Ni, Fe, Cr) and Ni$_3$Fe phase diffraction peaks [26, 27], and the Ni$_3$Fe phase volume fraction ($V_f$) [28] was estimated using equation (1),

$$V_f = \frac{A_{(Ni,Fe,Cr)}}{A_{(Ni,Fe,Cr)} + A_{Ni_3Fe}}$$

where $A_{(Ni,Fe,Cr)}$ and $A_{Ni_3Fe}$ are the integrated areas of the diffraction peaks of (Ni,Fe,Cr) phase and Ni$_3$Fe phase, respectively. The estimated Ni$_3$Fe phase $V_f$ values are listed in table 3. For the specimens with laser power of 1800
W, 2100 W and 2400 W, the relative volume fractions of Ni3Fe phase were 0.08%, 0.09% and 0.1%, respectively, which were greater than the volume fraction of Ni3Fe phase in the 27SiMn steel.

3.2. Cross-sectional morphology and organization of the clad layer

Figure 3 shows the cross-sections of the single-layer 6-channel metallographic specimens obtained at different powers. In figure 3, the Inconel 718 coating is well formed, with a smooth surface and no obvious porosity or microstructures inside the coating. The cross-sectional characteristics of the clad layer at different power levels are similar and consist of a clad layer (Clad), a heat affected zone (HAZ) and a substrate (Substrate). At 1800 W, 2100 W and 2400 W laser power, the distances from the top of the cladding layer to the bottom of the heat affected zone were 1282 μm, 1551 μm and 1279 μm, respectively. It shows that with increasing laser power, its values increases first and then decrease. At 1800 W power, the cladding layer has a maximum width of 9725 μm, which is greater than the cladding width of 2100 W (8627 μm) and 2400 W (9435 μm) power, respectively. Similarly, the heat-affected zones with 1800 W power has the maximum depth (663 μm), which is also greater than the depth of the heat affected zone with 2100 W (554 μm) and 2400 W (502 μm) power. Therefore, with the increase of laser power, the width of cladding layer and the depth of heat affected zone increase first and then decrease.

In the microstructure of figure 4, the cladding layer prepared with a power of 2100 W has the deepest heat-affected zone and a large damage area to the matrix, which is not conductive to repair. Figure 4 shows the microstructures of S1(1800 W), S2(2100 W) and S3(2400 W) cladding specimens. Laser cladding is a rapid heating and solidification process, and the growth direction of the microstructure is from the bottom of the molten pool to the top of the molten pool. In the relationship between temperature gradient (G) and solidification rate (R), when the G/R ratio is larger, the microstructure of the cladding layer is easy to form columnar crystals or dendrites with larger morphology; when the G/R ratio is smaller, the microstructure of the cladding layer is easy to form smaller cellular crystals or planar crystals [29]. The laser cladding coating cannot directly achieve the
geometric accuracy of the device. After the column parts are repaired, the upper surface of the cladding layer will be ground and polished, so that the upper part of the cladding layer will be removed. Therefore, the upper structure of the cladding layer has a low impact on the mechanical properties of the cladding layer, that is, the middle structure of the cladding layer and the lower structure of the cladding layer have a great impact on the mechanical properties.

Figures 4\textsuperscript{a1}, \textsuperscript{b1} and \textsuperscript{c1} shows the upper structure of the cladding layer at different laser powers.

Figure 3. Cross-section of cladding layer of S1(1800 W), S2(2100 W), S3(2400 W).

Figure 4. Microstructure of the upper (\textsuperscript{a1}, \textsuperscript{b1} and \textsuperscript{c1}), middle (\textsuperscript{a2}, \textsuperscript{b2} and \textsuperscript{c2}) and lower (\textsuperscript{a3}, \textsuperscript{b3} and \textsuperscript{c3}) of the cladding layer at different laser powers.
The microstructure is larger than that of the upper part of the cladding layer at 1800 W power. At 2400 W power, the microstructure of the upper part of the cladding layer is mainly dendrite, and the size of its microstructure is larger than that of the corresponding region at 2100 W power. Therefore, with the increase of laser power, the size of the upper microstructure of the cladding layer gradually increases.

Figures 4(a2), (b2) and (c2) show the middle structure of the cladding layer at different powers. At 1800 W power, the microstructure in the middle of the cladding layer is mainly cellular crystals, and the size of its microstructure is small. At 2100 W power, the microstructure in the middle of the cladding layer is mainly dendrite, which has uniform distribution and large size. At 2400 W power, the central structure of the cladding layer is mainly columnar crystals, which are orderly distributed and slender in size. When the laser power is 1800 W, the middle of the molten layer is connected with the upper/lower part, and the heat dissipation is slow. At this time, the cooling rate is smaller compared to the upper and lower part of the cladding layer, and the G/R value is the lowest. The growth of grains in the melt pool is slow and the nucleation rate is greater than the growth rate, which makes the grains finer, so the microstructures are fine cellular crystals. When the laser power increases, the energy absorbed in the melt pool is positively correlated with the laser power. The increase of energy in the molten pool makes the temperature gradient G in the molten pool increase and the value of G/R increases. The cellular crystal structure in the middle region fully grows and extends outward along the opposite direction of the maximum heat flow. Therefore, uniform dendritic crystals were formed at 2100 W and elongated columnar crystals were formed at 2400 W.

Figures 4(a1), (b1) and (c1) show the lower structure of the cladding layer under different power. Under the power of 1800 W, 2100 W and 2400 W, the microstructure of the lower part of the cladding layer is slender columnar crystals arranged in order, and the crystal sizes are different under the three powers. The lower structure of the cladding layer is close to the matrix, and the energy at the bottom of the melt pool first diffuses to the matrix, so that the temperature gradient G in the lower part of the clad layer is higher than that in the middle of the cladding layer, resulting in the increase of the G/R value. After crystal nucleation, it preferentially grows in the opposite direction to the direction of maximum heat flow, so as to form columnar crystals vertical to the bonding interface and arranged orderly. When the laser power increases, the energy absorbed in the melt pool is positively correlated with the laser power. The increase of energy in the molten pool makes the temperature gradient G in the molten pool increase, and the G/R value increases. The crystal fully grows in the direction perpendicular to the bonding interface and the growth rate is much greater than the nucleation rate. Therefore, with the increase of the laser power, the columnar crystals formed in the lower part of the cladding layer gradually become thicker.

### 3.3. Analysis of tensile properties of the clad layer

Figure 5 shows the stress-strain curves and mechanical data of the substrate, 8GR and three different powers of the cladding specimens (S1, S2 and S3). The mechanical data are listed in table 3. In figures 5(a) and (b), the strength and plasticity of the substrate is higher than those of the 8GR specimen, because the material properties are the same. The 8GR specimen is obtained by removing some materials from the substrate. Therefore, the strength and plasticity of 8GR specimens are lower than that of the substrate. The strength of the substrate is lower than that of the cladding specimen (S1, S2 and S3), because the Ni and Fe elements in Inconel 718 coating can form Ni3Fe compound, which can promote the thermomechanical stability of the cladding layer and increase the strength of the cladding specimen. The plasticity of the substrate is higher than that of the cladding specimens (S1, S2 and S3), which is due to the precipitation of more c-compounds in Inconel 718 coating than that of the substrate, and the dispersion and precipitation of c-compounds, which reduces the plasticity of the clad specimen.

In figures 5(c) and (d), the yield strengths of the three fused specimens (S1, S2 and S3) and their tensile strengths are much higher than those of the substrate. The S1 specimen had the highest yield strength (970 MPa), which was 61.7% higher compared to the substrate. The difference of tensile strength for S1-S3 specimens was small, with an increase of 50.2% compared to the substrate. The S1 specimen had the largest tensile strength of 1140 MPa. So, the S1 specimen has the best mechanical properties.

From figures 5(e) and (f), the elongation of the three cladding specimens (S1, S2 and S3) is lower than that of the substrate, and the shrinkage at section is higher than that of the substrate. The elongation of S1 specimen is the highest (0.07), which was 50% lower than the substrate. The S1 specimen had the highest sectional shrinkage (0.38), which was 50% higher compared to the substrate. Because the elongation and reduction of area reflect the plastic index of mechanical properties, S1 specimen has good plastic properties in all cladding specimens.

The excellent order of mechanical properties, plasticity and strength of all clad specimens is $S1 > S2 > S3$. In the process of preparing the coating, with the increase of laser power, the dendrites and columnar crystals increase in the specimen structure, and grain refinement leads to the increase of its strength. Therefore, the process parameters of S1 sample can be used in Inconel 718 powder to repair the steel for the hydraulic support...
column, and the strength of the repair material exceeds the strength of the substrate, thus providing an effective guarantee for the safe work of the hydraulic support.

3.4. Tensile fracture analysis

Figure 6 shows the fracture morphology of the substrate, 8GR and the cladding specimens (S1–S3) at three different powers. The fractures of the five specimens shown ductile fracture characteristics. The plasticity of the specimen is determined by the number and size of dimples in the fracture morphology. The high number and volume of dimples can form tear ridges (TR), which is an important sign of high plasticity.

The tensile fracture of the substrate is a typical cup and cone fracture with a grayish appearance, and its shear lip area is 45° from the plane of the fiber area, and there is a vertical downward crack in the center of the tensile fracture area of the substrate. This crack is wide in the middle and narrow at both ends. It can be obtained that the crack originates in the central region of the tensile specimen, and the extension direction points from the central fiber region to the shear lip region on the edge. As the applied stress gradually exceeds the yield strength of the material during the stretching process, the crack gets extended, as shown in figure 6(a1). In figure 6(a2), there are a large number of dense dimples in fracture morphology and form large tear ridges, thus accelerating the crack growth.

The fracture characteristics of the 8GR specimen are basically similar to those of the substrate. The difference is that the density and number of dimples are significantly smaller than that of the substrate, resulting in less plastic properties absorbed by 8GR specimen during tension, as shown in figures 6(b1) and (b2). The results show that the sample has small plastic deformation, which is consistent with the results in figure 5(a).

![Figure 5](image-url)

**Figure 5.** The stress–strain curves and mechanical data of the substrate, 8GR and three different powers of the cladding specimens (S1–S3). (a) Stress–strain curves; (b) stress–strain local magnification; (c) yield strength; (d) tensile strength; (e) elongation and (f) cross-sectional shrinkage rate.
The fracture morphology of the cladding specimens (S1-S3) consists of three parts, the cladding layer (Clad), the heat affected zone (HAZ) and the substrate. Since the heat-affected zone (HAZ) has less influence on the fracture of the specimen [16], only the fracture characteristics of the fusion layer region are analyzed. The fracture morphology in the area of the cladding layer of the specimens (S1, S2 and S3) is composed of dimples. The number and size of dimples in S1 fracture morphology were higher than those in S2 and S3, and the number and size of tears formed through the dimples were also higher than those in S2 and S3. In general, the plasticity in the area of S1 cladding layer of the specimen is higher than that of S2 and S3. This result coincides with the analysis of the microstructure in figure 4.

4. Conclusion

This paper investigates the effect of laser power on the surface laser coating of Inconel 718 alloy on 27SiMn steel. By analyzing the phase analysis, cross-sectional morphology, microstructure, tensile properties and fracture organization of the cladding layer, the following conclusions were obtained.

(1) The matrix phases of the XRD patterns of the cladding coatings are $\gamma$-(Ni,Fe,Cr) phase and Ni$_3$Fe phase. The volume fractions of Ni$_3$Fe phase increase with increasing laser powers. The width of the cladding layer, the depth of the heat-affected zone and the top of the cladding layer to the bottom of the heat-affected zone show a trend of increasing and then decreasing with increasing laser powers. When the laser power is 2100 W, the values of cladding width, of cladding thickness and of heat affected zone reach the maximum. Its values are 9725 $\mu$m, 1551 $\mu$m and 663 $\mu$m, respectively. In the middle and lower parts of the cladding layer, the
microstructure of the specimen clad by 1800 W is mainly cytosine, and the microstructure tends to be uniform. The rest of the power is dominated by coarse columnar or dendritic crystals.

(2) The strength and plasticity of the substrate were higher than those of the uncoated notched specimens, and the strength of the coated specimens was higher than that of the substrate, indicating that the elevated mechanical properties of the coated specimens were caused by the Inconel 718 alloy coating. The plasticity and strength of the cladding specimens gradually decreased as the laser powers increased. At 1800 W, each mechanical property index reached its maximum values, and its yield strength, tensile strength, elongation, and section shrinkage were 970 MPa, 1141 MPa, 7%, and 38%, respectively, which showed better mechanical properties. 1800 W is the best laser power parameter for repairing steel for hydraulic support columns.

(3) With the increase of laser powers, the number of tearing ridges in the fracture tissue of the cladding specimen gradually decreases, and the plasticity of the specimen gradually decreases, and the plasticity is better at the power of 1800 W.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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