Characterization and analyses on micro–hardness, residual stress and microstructure in laser cladding coating of 316L stainless steel subjected to massive LSP treatment

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Abstract: The effects of massive laser shock peening (LSP) treatment on micro–hardness, residual stress and microstructure in four different zones of laser cladding coating was investigated. Furthermore, micro–hardness curves and residual stress distributions with and without massive LSP treatment were presented and compared, and typical microstructure in different zones of both coatings were characterized by transmission electron microscope (TEM) and cross–sectional optical microscope (OM) observations. Results and analyses showed that massive LSP treatment had an important influence on micro–hardness and residual stress of the cladding coating. Special attempt was made to the effects of massive LSP treatment on microstructure in three zones of the cladding coating. In addition, the underlying mechanism of massive LSP treatment on microstructure and mechanical properties of the cladding coating was revealed clearly.

Keywords: laser shock peening; laser cladding coating; micro–hardness; residual stress; microstructure

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1. Introduction

Laser cladding is an additive manufacturing process that utilizes a laser to metallurgical bond performance coatings to a product's base material, which is used to produce metallurgical well-bonded and much higher quality coating by the advantages of reduced production time, enhanced thermal control, small heat-affected-zone (HAZ), high satisfactory repair of parts, and production of a functionally graded part [1–3]. A major application of laser cladding is in the repair and refurbishment of high-value components such as tools, turbine blades, gas turbine and internal combustion engine parts, as well as various components of a military nature. One distinct disadvantage of laser cladding, however, is that the high heat input results in tensile residual stress, decreased micro-hardness and loose structure in the bonding zone of the cladding coating, which will have a detrimental effect on mechanical properties and fatigue life of the repaired high-value components by laser cladding [4–7].

If tensile residual stress can be eliminated and surface coarse grain can be refined, mechanical properties of the cladding coating will be significantly improved. Among many surface treatment techniques, laser shock peening (LSP) is a novel surface treatment process for improving the fatigue durability, wear performance, and corrosion resistance of metallic materials and alloys by generating deeper compressive residual stress with a depth of more than 1 mm and refined grain in the surface layer [8–10]. Hence, LSP is a better choice as a post processing method to improve mechanical properties, corrosion behavior of metallic materials and alloys [8,11,12]. In actual engineering applications, multiple locations of the metallic component were usually treated in a massive parallel mode to accomplish uniform surface properties across the entire sample surface, which is massive LSP treatment.

The effects of LSP on the welded joints and the component with tensile residual stress have been investigated. For instance, Hatamleh *et al.* [4,5] have investigated the effects of LSP on fatigue crack growth in friction stir welded 7075 and 2195 aluminum alloy joints. Results showed that LSP

turned tensile residual stress with a value of 143 MPa for the welded specimen into compressive residual stress with a value of 179–179 MPa for the laser shocked (LSPed)specimen, and a significant reduction in fatigue crack growth rate using LSP occurs compared to the native welded specimens. Iordachescu *et al.* [13] have studied the LSP influence on local properties and overall tensile behavior of AA2024–T351 friction stir welded joints, showing the ability of LSP to improve the mechanical strength and cracking resistance of AA2024–T351 friction stir welded (FSW) joints. Zhang *et al.* [14] have found that compared with single–sided LSP impacts, the mechanical properties of the laser welded ANSI 304 stainless steel was clearly improved by two–sided LSP impacts due to more and deeper elongated dimples in the fracture. Dorman *et al.* [15] have investigated the effect of LSP on residual stress and fatigue life of clad 2024 aluminum sheet containing scribe defects to reveal the benefits of LSP on the cladding layer in thin sheet material. The above researches have highly focused on the effects of LSP on micro–hardness, residual stress, tensile properties friction behavior and wear resistance of metallic materials and alloys. In fact, the uniformity of residual stress distribution during massive LSP treatment is also an important factor to influence the mechanical properties and fatigue life of metallic materials and alloys [16], and there is no publication to present cross–sectional profiles of residual stress and micro–hardness along depth direction. Furthermore, there is little literature involved in the effects of LSP on the mechanical properties and microstructure in the side bonding zone of the cladding coating. Therefore, a detailed understanding between mechanical properties and local microstructure in different zones of the cladding coating is worth investigating.

With the above background in mind, the aim of this work was to investigate the effects of massive LSP treatment on micro–harness, residual stress and microstructure in different zones of laser cladding coating of 316L stainless steel. Furthermore, cross–sectional profiles of micro–hardness and residual stress were presented by three–dimensional surface fitting algorithm. Special attentions were paid to the effects of massive LSP treatment on microstructure in the

inter-diffusion zone and the side bonding zone of the cladding coating. In addition, the underlying influence mechanism of massive LSP treatment on microstructure and mechanical properties of the cladding coating was clearly revealed.

2. Experimental procedures

2.1 Specimen preparation and laser processing parameters

The substrate material is a 316L austenite stainless steel, and its chemical composition was 0.03C, 1.00Si, 2.00Mn, 0.045P, 0.03S, 10.0–14.0Ni, 16.0–18.0Cr and balance Fe (wt.%). In the present work, 304 stainless steel powders with a diameter of 150–200 μm was chosen as the cladding powder, and the corresponding chemical composition was 0.08C, 1.00Si, 2.00Mn, 0.035P, 0.03S, 8.0–11.0Ni, 16.0–18.0Cr and balance Fe (wt.%). The physical maps and the dimensions of the cladding region were shown in Fig. 1(a). The front photograph and side photograph of the groove after laser cladding can be shown in Fig. 1(a) and Fig. 1(b), respectively. From Fig. 1(b), four regions, including the inter-diffusion zone, the transition zone, the side bonding zone and the underside bonding zone, can be obviously recognized. The groove with an isosceles trapezoid cross-section was machined in the top layer of 316L stainless steel plane. The length of the upper side is 9 mm, and the length of the lower side is 7 mm, and the depth of the groove was 2 mm. This groove was used to be filled by laser cladding with multiple layers.

Laser cladding experiment was carried out by a YLS-4000-CT-Y11 ytterbium-doped fiber laser, and a new technology of powder feeding inside a hollow laser beam had been adopted [17,18]. The schematic illustration of coaxial laser cladding was shown in publication [17], and the processing parameters of laser cladding are set as following: laser output power was 1800 W, spot diameter was 3 mm, laser overlapping ratio was 22.5%, the scanning speed was 4 mm/s, and the velocity of protective gas was 5 L/min. After the laser cladding treatment, the sample surface was progressively mechanically polished by SiC paper with grit number from 600 to 1200 (including 150#, 240#, 360#, 600#, 800# and 1200#) for attaining smooth surface, followed by cleaning in

water. Ultrasound in absolute ethanol was used to degrease the sample surface, and then massive LSP treatment was conducted shortly after preparation.

Massive LSP treatment was performed using a Q-switched Nd: YAG laser operating at 5 Hz repetition-rate with a wavelength of 1064 nm. For this application, a pulse laser with a duration of 10 ns and an energy of 9 J was used as the energy source of LSP treatment. The spot diameter was 3 mm. A water film with a thickness of about 1 mm was used as a transparent confining layer. To protect the sample surface from thermal damage caused by high-temperature plasma, a professional aluminum tape with a thickness of 100 μm (made in USA) was used as an ablation medium for plasma initiation. At the top surface of laser cladding coating, the rectangle with an area of 30 mm $\times$ 9 mm was treated by massive LSP treatment, which was shown as the region filled with section line in Fig. 1(a). Fig. 1(c) showed the partial enlargement drawing of LSPed region showing the LSP path (the red dash line) at the top surface of laser cladding coating. During massive LSP treatment, the laser beam was kept perpendicular to the sample surface at all times, and the overlapping rate between two adjacent round spots was 50% in the transverse and longitudinal directions to ensure that the LSPed region had no blind area.

2.2 Measurements of residual stress and micro-hardness

Micro-hardness test was carried out using a Vickers indenter under a 300 g load and 15 s hold time on the measurement points. For each point, an average micro-hardness value has been determined on the basis of the measured data from 10 indentations.

Residual stress at the sample surface with and without LSP treatment was determined by XRD technique with the $\sin^2 \varphi$ method. The X-ray source was Cr-K α ray, and the diameter of X-ray beam was about 2 mm. The scanning starting angle and terminating angle were 125° and 132°, respectively, and the feed angle of the cladded scanning was 0.1°/s. To investigate residual stress distribution of the cladding coating with and without LSP treatment, seven blue points at Line 1 were set as the measurement locations of residual stress, as shown in Fig. 1(c). **In order to obtain the**

three-dimensional micro-hardness and residual stress profiles along cross-section of the cladding coating. material removal by electropolishing was used, and the cladding coating was removed by a depth of 0.1 mm to the top surface every time. After each removal with a depth of 0.1 mm, residual stress and micro-hardness values of seven measurement points at Line 1 were measured and recorded. Thus the cladding coating with a thickness of 2 mm will be removed by 20 times. Hence, the measurement values of residual stress and micro-hardness at a certain cross-section were formed a matrix, respectively. Finally, the distribution maps of residual stress and micro-hardness can be presented by three-dimensional surface fitting algorithm of MATLAB 2010a software. Furthermore, the errors of the micro-hardness and residual stress at each measurement point were also recorded.

2.3 Microstructural observations

Before and after massive LSP treatment, the cladding coating used for metallographic investigation were cut as the cross-sections perpendicular to the sample surface, and then subjected to several successive steps of grinding and polishing. Next, these cross-sections were etched using a professional reagent that consists of 4 g picric acid and 100 cc alcohol for 30 s at room temperature, and then characterized by cross-sectional optical microscope (OM) observations.

The micro-structures in three zones, including the central zone, the bonding zone and substrate, at the top surface of the cladding coating and the LSPed cladding coating were characterized by using a JEM-2100 transmission electron microscope (TEM) operated at a voltage of 200 kV. The plane-view thin foils of the surface layer were obtained first by polishing the surface layer from the surface underneath until the sample reaches about 30 μm thickness, and then perforated by ion milling apparatus to make it suitable for TEM observations.

3. Results and discussions

3.1 Effects of LSP treatment on micro-hardness distributions of the cladding coating

Massive LSP treatment has a significant influence on the micro-hardness distributions at different depths from the top surface of the cladding coating. Sixty micro-hardness values are

measured along Line 1 in the top surface of the cladding coating. Fig. 2(a) shows micro-hardness distributions along Line 1 in the cladding coating without and with LSP, and the plane at the depth of 0.7 mm from the LSPed top surface. Whereas, Fig. 2(b) shows the in-depth micro-hardness distributions of Point 3 and Point 4 at Line 1 with and without LSP.

From Fig. 2(a), it can be seen that the average value in micro-hardness of the cladding coating is about 227 HV, which those in the LSPed cladding coating and the plane at a depth of 0.7 mm from the LSPed cladding coating are 372 HV and 305 HV, respectively. It is noted that the micro-hardness gradually increases from 227 HV to a higher value in the side bonding region which is in the range of the LSP affected depth. In-depth micro-hardness distributions of Point 3 and Point 4 at Line 1 in the LSPed cladding coating are shown in Fig. 2(b), and there are similar curves for both cases in depth direction. For the cladding coating, the average value in micro-hardness is about 227 HV, whereas there is a maximum of 372 HV at the top surface of the LSPed cladding coating, and micro-hardness decreases with increasing depth away from the top surface. It is noted that micro-hardness decreases to 227 HV when the depth away from the top surface is about 1.6 mm, indicating that the affected depth of massive LSP treatment on the cladding coating is about 1.6 mm. Cross-sectional micro-hardness profile of the plane perpendicular to the top surface along Line 1 of the cladding coating and the LSPed cladding coating are presented in Fig. 3(a) and Fig. 3(b). It can be seen that this cross-sectional micro-hardness uniformly distributes for the cladding coating, and its value ranges from 221 HV to 232 HV, as shown in Fig. 3(a). For the LSPed cladding coating, there is a significant change in cross-sectional micro-hardness profile of the plane perpendicular to the top surface along Line 1 in the cladding coating. At the LSPed top surface, micro-hardness is distinctly improved from 227 HV to 370 HV, which that is increased from 227 HV to 298 HV in the range of the LSP affected depth. By comparing with the average micro-hardness in the underside bonding zone, both micro-hardness values are increased by 62.9% and 31.3%, respectively.

Similarly, Fan *et al.* investigated the micro-hardness distribution of the welded joint after ultrasonic

peening treatment (UPT), the results indicated that the hardness values on the surface of welded joint before and after UPT were about 340 HV and 1388 HV, respectively. The hardness values after UPT increased by 308% comparing with that before UPT[19]. Hence, massive LSP treatment causes an obvious increment in micro-hardness at the top surface of the laser cladding coating, and this phenomenon may be attributed to the dynamic strain hardening by laser shock wave. Similar results can be seen in previous publication [6], in which laser peening without coating can be used to improve the micro-hardness of welding zone in the friction stir welded A6061-T6 aluminum alloy.

3.2 Effects of massive LSP treatment on residual stress distributions of the cladding coating

Fig. 4 shows the surface residual stress distributions of Line 1 and Line 2 in the cladding coating and the LSPed cladding coating. For the cladding coating, both two surface residual stress curves in the central region and the side bonding region fluctuate between 38 MPa and 81 MPa, as shown in Fig. 4(a). After massive LSP treatment, tensile residual stress with an average value of 56 MPa in the central region is turned into high-level compressive residual stress with an average value of -424 MPa, as shown in Fig. 4(b). Hatamleh et al. [20] presented the residual stress distributions of the friction stir welded (FSW) Aluminum Alloy (AA) 2195 joints before and after LSP, the results shown that LSP can result in high amplitude compressive residual stress in the central zone of the welding, and the residual stresses in the longitudinal and transverse directions did not vary by an appreciable amount. Two-dimensional map of the measured residual stresses in the FSW sample for AA 2195 and AA 7075 before and after LSP were also presented. The LSPed samples processed with a single layer showed significant regions of compressive residual stress near the surface and compensating subsurface tensile residual stress, and the LSPed sample with six layers showed increased levels of compressive and tensile residual stress compared with the single layer processing [21]. According to the above researchs, cross-sectional residual stress profiles of the plane perpendicular to the top surface along Line 1 in the cladding coating and the LSPed cladding coating are presented in Fig. 5(a) and Fig. 5(b). It can be seen that this cross-sectional residual

stress uniformly distributes for the cladding coating, and its value fluctuates between 38 MPa and 81 MPa, as shown in Fig. 5(a). For the LSPed cladding coating, there is a significant change in cross-sectional residual stress profile of the plane perpendicular to the top surface along Line 1. In the surface layer of the cladding coating, tensile residual stress with an average value of 56 MPa is completely turned into compressive residual stress with an average value of -183 MPa by massive LSP treatment. In the upper half of the transition zone, tensile residual stress is also eliminated, and there exists in the state of compressive residual stress with a range from 0 to -153 MPa after massive LSP treatment. It is noted that tensile residual stress with an average value of 56 MPa in the side bonding region is turned into the compressive residual stress with an average value of -215 MPa, as shown in Fig. 4(b) and Fig. 5(b).

It is also interesting to find that residual stress only has a smaller fluctuation in any section parallel to the top surface, as shown in Fig. 5(b), and similar result can be seen in Fig. 3(b) in Section 3.1. These results suggest that massive LSP treatment with 50% overlapping rate is a good choice to obtain uniform residual stress field and micro-hardness distribution at any plane with a given depth.

3.3 Typical microstructure observations of the cladding coating along depth direction

Based on the microstructure features observed in various zones with different strains and strain rates in the plastic deformation layer, four elemental states are involved during massive LSP treatment: columnar structure, acicular structure, equiaxed grain, and cellular microstructure.

Fig. 6 shows the typical cross-sectional microstructure in four different zones of the cladding coating. Fig. 6(a) exhibits the cross-sectional OM morphologies at the top surface of the cladding coating, and Fig. 6(b) is the magnified image of the quadrangle [A] in Fig. 6(a). It can be seen that a large number of columnar structures can be found in the top surface of the cladding coating, and the average size of these structures is $8\text{--}12\text{ }\mu\text{m}$. As shown in Fig. 6(a), these columnar structures are arranged in the surface layer with a depth of about 0.2 mm. Fig. 6(c) shows the cross-sectional OM

morphologies in the side bonding zone of the cladding coating, and Fig. 6(d) is the magnified image of the quadrangle [B] in Fig. 6(c). It can be seen that this region is full of parallel acicular structures with a length of 50–90 μm, and the space of the adjacent structures is about 3–5 μm, as shown in Fig. 6(d). Fig. 6(e) shows the cross-sectional OM morphologies in the underside bonding zone of the cladding coating, and Fig. 6(f) is the magnified image of the quadrangle [C] in Fig. 6(e). This region is characterized also with parallel acicular structures with a length of about 30 μm, and the space of the adjacent structures is about 3–5 μm, as shown in Fig. 6(f). Fig. 6(g) presents the cross-sectional OM morphologies in the transition zone of the cladding coating at the depth of 1 mm from the top surface, and Fig. 6(h) is the magnified image of the quadrangle [D] in Fig. 6(g). A large number of smallish columnar structures with a size ranging from 5 μm to 20 μm are found in this zone. Similar distribution can be found in the previous publication [22], and the results showed that acicular structures existed at the bottom and in the middle of laser cladding coating, while columnar structures were found at the top of the coating.

After massive LSP treatment, the structure evolution process may be signed by the micro-structure characteristics (with different strain rates and strains) at different depths when the strain decreases from maximum (up to 10^7 s^{-1}) at the top surface to zero at the depth of more than 1.5 mm from the top surface of the cladding coating. Detailed cross-sectional microstructural observations are carried out in order to systematically understand the effects of massive LSP treatment on the micro-structures along depth direction in different zones of the cladding layer.

Fig. 7 shows the typical cross-sectional microstructure in four different zones of the LSPed cladding coating. Fig. 7(a) presents the cross-sectional OM morphologies at the top surface of the LSPed cladding coating, and Fig. 7(b) is the magnified image of the quadrangle [A] in Fig. 7(a). A large number of equiaxed grains are found in the top surface of the LSPed cladding coating, and the average size of these structures is about 5 μm. These equiaxed grains are arranged in the surface layer with a depth of about 0.2 mm, as shown in Fig. 7(a). Fig. 7(c) shows the cross-sectional OM

morphologies in the side bonding zone of the LSPed cladding coating, and Fig. 7(d) is the magnified image of the quadrangle [B] in Fig. 7(c). It can be seen that this region is full of parallel acicular structures with a length of about 30 μm , and the space of the adjacent structures is about 3–5 μm . By comparison with the acicular structure in Fig. 6(d), it is interesting to observe that most of acicular structures are broken into cellular microstructures with a size of 2–3 μm (as shown in Fig. 7(d)), which may be attributed to the fact that these acicular structures in the side bonding zone are refined by the mechanical effect of the ultra-strong laser shock wave. Fig. 7(e) shows the cross-sectional OM morphologies in the underside bonding zone of the LSPed cladding coating, and Fig. 7(f) is the magnified image of the quadrangle [C] in Fig. 7(e). This region is characterized also with parallel acicular structures with a length of about 30 μm , and the space of the adjacent structures is about 3–5 μm , as shown in Fig. 7(f). Unlike the acicular structure in the side bonding zone, these parallel acicular structures are not broken after massive LSP treatment, which suggests that massive LSP treatment has no direct influence on microstructure in this zone. Fig. 7(g) presents the cross-sectional OM morphologies in the transition zone of the cladding coating at the depth of 1 mm from the top surface, and Fig. 7(h) is the magnified image of the quadrangle [D] in Fig. 7(g). Similar to the microstructure in the cladding coating, a large number of smallish columnar structures with a size ranging from 5 μm to 20 μm are found in this zone. However, it is noted that these columnar structures in the transition zone are much larger than the equiaxed grains at the top surface of the LSPed cladding coating.

3.4 Typical TEM observations in three zones of the cladding coating and the LSPed cladding coating

Considering the effect of laser shock wave on the microstructure in the top surface in the laser cladding coating of 316L stainless steel, the typical TEM images in different zones at the top surface of the cladding coating without and with LSP treatment were characterized by TEM observations, in Fig. 8. Fig 8(a) shows schematically the distributions of the TEM observation locations and three

zones of the cladding coating. It can be seen that a whole cross-section of the cladding coating is presented, and the left half is the laser cladding coating without LSP treatment whereas the right half is the LSPed cladding coating. At the top surface of the cladding coating, TEM microstructures in [Locations\[b\], \[d\], \[f\]](#) and [Locations\[c\], \[e\], \[g\]](#) were characterized to investigate the effects of laser shock wave on three zones of the cladding coating, respectively. [Fig 8\(b\)](#) shows the typical TEM image in inter-diffusion zone at the top surface of the cladding coating whereas [Fig. 8\(c\)](#) is that of the LSPed cladding coating. It can be seen that a complete grain can be found in the inter-diffusion zone of the cladding coating and the grain size is about 5–6 μm . After massive LSP treatment, a large number of dislocation lines (DLs) can be found in the grain, as shown in [Fig. 8\(c\)](#). [Fig. 8\(d\)](#) shows the typical TEM image in the bonding zone at the top surface of the cladding coating without LSP treatment. A thin and long grain can be found in [Fig. 8\(d\)](#), which is corresponding to the acicular structures in [Fig. 6\(d\)](#). After massive LSP treatment, a large number of DLs and some dislocation tangles (DTs) exist in the coarse grain of the bonding zone. Furthermore, some obvious dislocation blocks (DBs) can be found adjacent to the grain boundary (as shown in [Fig. 8e](#)), which can be explained by the fact that the dislocation movement is hindered by grain boundary and then a large number of dislocations are piled along the grain boundary [\[23\]](#). Finally, for the substrate of 316L stainless steel, the average size of the original grain in the substrate is more than 8 μm , as shown in [Fig. 8f](#). After massive LSP treatment, a large number of twin matrix lamellas (T–M lamellas) can be found in [Fig. 8\(g\)](#), and the average width of these T–M lamellas are about 150–200 nm. Furthermore, in the interior of the T–M lamellas, some stacking faults (SF) can be observed clearly.

From these experimental data, it can be found that massive LSP treatment has a significant influence on the microstructure in three zones. Under the effect of mechanical effect generated by massive LSP treatment, dislocation movement obviously increases to form DL, DT and T–M lamellas in the coarse grains of three zones. Combining with microstructural observations in Section 3.3, it can be inferred that the coarse grains in three zones of the cladding coating are obviously refined by massive LSP treatment.

3.5 Schematic illustration of massive LSP treatment on microstructure and properties of the cladding coating

The effects of massive LSP treatment on microstructure and mechanical properties in different zones of the cladding coating are schematically illustrated in Fig. 9. Typical microstructures can be obviously identified in different zones of both coatings, respectively.

As discussed in Section 3.1 and Section 3.2, micro-hardness is distinctly improved from 227 HV to 370 HV in the surface layer of the cladding coating after massive LSP treatment, and tensile residual stress with an average value of 56 MPa is completely turned into compressive residual stress with an average value of –183 MPa. This phenomenon can be explained by the fact that columnar structure with a length of 8–12 μm is turned into equiaxed grain with a size of about 5 μm in the surface layer by massive LSP treatment, and this process is schematically illustrated as Region (I) and Region (I') in Fig. 9, as shown in Fig. 6(a) and Fig. 7(a). According to the TEM images described in Section 3.4, it can be found that after massive LSP treatment, three zones of laser cladding coating are treated by laser shock wave. Severe plastic deformation and high strain result in broken grain boundary and the dislocation movements, reflecting in a significant accumulation of DL and the formation of high density dislocations. Hence, when dynamic plastic deformation occurs in the surface layer, dislocation is accumulated and the sub-boundary forms, and then the coarse grain is refined. The mechanism governing deformation-induced grain refinement is believed to be

dominated by dislocation activities in this process. Hence, it can be demonstrated that laser shock wave is effective to refine the cladding coating of 316L stainless steel. Similar results can be found in the previous publication [24], Wang *et al.* investigated the grain refinement mechanism of LSPed 7075 aluminum alloy laser welded joints, and the results showed that with the inhomogeneous heat, the microstructure of weld was composed of coarse columnar crystals and acicular structures. Under the effect of laser shock wave, the dislocation was accumulated and the subcrystal boundaries was formed, then the coarse grain was refined into equiaxed grain and cellular microstructure. The micro-structural evolution of ANSI 8620 carbon steel subjected to multiple LSP impacts can be found as the following steps [25]: (i) the parallel lamellar pearlites are broken into bitty pearlites, and dislocation activities simultaneously lead to the formation of DLs and DTs in original grains, (ii) with further decreasing depth, bitty pearlites are all broken into Fe₃C granules with high carbon content, and dislocation movement make Fe₃C granules disperse near subgrain boundaries, which leads to subgrain boundaries separating individual cells, and (iii) evolution of the continuous dynamic recrystallization in subgrain boundaries is refined to grain boundaries.

For the side bonding zone of the cladding coating, tensile residual stress with an average value of 56 MPa is completely eliminated and turned into compressive residual stress with an average value of −183 MPa after massive LSP treatment. This phenomenon has a relation with the fact that parallel acicular structures with a length of 50–90 μm are broken into cellular microstructures with a size of 2–3 μm by ultra-strong laser shock wave, and this process is schematically illustrated as Region (II) and Region (II') in Fig. 9, as shown in Fig. 6(c) and Fig. 7(c). For the transition zone of the cladding coating, a large number of smallish columnar structures with a size ranging from 5 μm to 20 μm are not broken after massive LSP treatment, which suggests that massive LSP treatment has no direct influence on microstructure in this zone. This process is schematically illustrated as Region (III) and Region (III') in Fig. 9, as shown in Fig. 6(e) and Fig. 7(e). For the underside zone of the cladding coating, there is no obvious change in micro-hardness, residual stress and

microstructure after massive LSP treatment, which is schematically illustrated as Region (IV) and Region (IV') in Fig. 9, as shown in Fig. 6(g) and Fig. 7(g). This experimental data indicate that massive LSP treatment has no direct influence on the underside zone of the cladding coating.

In addition, due to the higher temperature and extensive plastic deformation caused by massive LSP treatment in the inter-diffusion zone of the cladding coating, the grain size in the inter-diffusion zone of the cladding coating is smaller than that in the bonding zones, which is in agreement with the following investigation. Hatamleh *et al.* have investigated the effects of LSP on mechanical properties in friction stir welded AA 2195 at elevated and cryogenic temperatures, and results showed that elevated temperature and extensive plastic deformation in the weld nugget resulted in fine and equiaxed grain sizes significantly smaller than the original coarse grain [26].

However, in the bonding zone, the coating cooling is faster than the inter-diffusion zone and the temperature in the zone is also relative low. Furthermore, the microstructure in the side bonding zone are looser than that in the inter-diffusion zone of the cladding coating, and there is a relative large space between both adjacent grains. Therefore, the pulse energy of produced by laser shock wave decays rapidly in the side bonding zones, resulting in the plastic deformation in the zones are relative small. Hence, the grain size in the inter-diffusion zone is smaller than that in the bonding zones of the cladding coating.

Although the mechanical and physical properties of all crystalline materials are determined by several factors, the average grain size of the material generally plays a very significant and often a dominant role. Thus, the strength of all crystalline materials is related to the grain size, d , through the Hall-Petch equation which states that the yield stress, σ_y , is given by $\sigma_y = \sigma_0 + k_y d^{-1/2}$, where σ_0 is termed the friction stress and k_y is a constant of yielding [27]. Hence, in the present work, parallel acicular structures with a length of 50–90 μm are broken into cellular microstructures with a size of 2–3 μm by ultra-strong laser shock wave, and as a result of the grain refinement induced by laser shock wave, the LSPed cladding coating is strengthened. Furthermore, according to Amir

Abdullah's research, micro-hardness behavior of peened materials is in correlation with the grain refinement accompanied by strain-induced martensitic, and the grain boundary activities. The generation of mechanical twins and strain-induced martensite give rise to increase in the micro-hardness of the surface coating [28]. Hence, it is obviously that grain refinement generated by LSP treatment is an important factor of improved micro-hardness at the top surface of the laser cladding coating.

High temperature during laser cladding can result in the transformation of austenite to martensite [29]. Furthermore, there was some martensite in the diffusion layer because of the carbon diffusion from Q345R steel to transition layer, and the martensite led to an obvious increase in hardness in the diffusion layer [30]. Similar results can be found in reference [31]. According to these results, it may be inferred that the high temperature results in martensite phase of 304 SS powder and 316L SS during the laser cladding, which effects the distribution of micro-hardness in 316L SS coatings. Furthermore, laser shock wave breaks martensite microstructure into smaller microstructures, which causes the improvement in micro-hardness. Massive LSP treatment has an important influence on micro-hardness, residual stress, and microstructure of the cladding coating, and the affected depth is schematically illustrated as the rectangle full of green in Fig. 9(b). Furthermore, it is interesting to find that the improvement of mechanical properties (including micro-hardness and residual stress) strongly depends on local microstructure in different zones.

According to the above analyses, some inferences can be made: (i) massive LSP treatment is an effective approach to eliminate tensile residual stress and improve the micro-hardness in the surface layer of the cladding coating and the affected depth is about 1.6 mm, (ii) massive LSP treatment brings a transition from columnar structure to equiaxed grain, and at the same time causes grain refinement in the surface layer of the cladding coating, (iii) the refinement of the original grains in the surface layer generated by massive LSP treatment is the cause to increase the interfacial bonding strength between the cladding coating and the substrate, and (iv) the plastic deformation layer in the

surface layer of laser cladding coating mainly consists of DL, DT, DB, T–M lamella and stacking fault.

4. Conclusions

The effects of massive LSP treatment on micro–hardness, residual stress, and microstructure in different zones of the cladding coating are investigated. Some important conclusions can be made as follows:

(1) Cross–sectional profiles in micro–hardness and residual stress of both coatings are presented by three–dimensional surface fitting algorithm, and massive LSP treatment brings an obvious improvement in micro–hardness and residual stress in the surface layer of the cladding coating. Massive LSP treatment is an effective approach to eliminate tensile residual stress and to improve the micro–hardness in the near surface layer of the cladding coating.

(2) After massive LSP treatment, the improvement of micro–hardness and residual stress strongly depends on local microstructure in different zones of the cladding coating. For example, columnar structure with a length of 8–12 μm is turned into equiaxed grain with a size of about 5 μm in the surface layer of the cladding coating by massive LSP treatment, which results in the improvement of local micro–hardness and residual stress.

(3) The affected depth of massive LSP treatment on the cladding coating is about 1.6 mm, and acicular structures in the side bonding zone are refined by the mechanical effect of the ultra–strong laser shock wave, which is helpful to increase the interfacial bonding strength between the cladding coating and the substrate.

(4) Massive LSP treatment causes the increased microstructural activities, and induces plastic deformation layer in three zones in the surface layer of the cladding coating, which is the direct cause of the improvement in mechanical properties of the cladding coating.

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Underlying mechanism of massive LSP treatment on microstructure and mechanical properties of the cladding coating

Fig. 1 (a) Dimensions of LSPed region and laser cladded region, and insert in (a) is the front photograph of and the cladding specimen, (b) the cross-sectional polished photograph showing the dimensions of the cladding region (Unit in mm), and (c) the partial enlargement drawing of LSPed region schematically showing LSP path at the top surface of laser cladded layer, in which the red arrow represents the LSP path, and 14 blue points at Line 1 and Line 2 are the measurement locations of residual stress.

Fig. 2 (a) Micro-hardness distributions along Line 1 in the cladding coating without and with LSP, and the plane at the depth of 0.7 mm from the LSPed top surface, and (b) in-depth micro-hardness distributions of two measurement points (Point 3 and Point 4 at Line 1) with and without LSP.

Fig. 3 Cross-sectional micro-hardness profiles of the plane perpendicular to the top surface along Line 1. (a) The cladding coating, and (b) the LSPed cladding coating.

Fig. 4 Surface residual stress distributions of Line 1 and Line 2 in (a) the cladding coating and (b) the LSPed cladding coating.

Fig. 5 Cross-sectional residual stress profiles of the plane perpendicular to the top surface along Line 1. (a) The cladding coating, and (b) the LSPed cladding coating.

Fig. 6 Typical cross-sectional microstructure in different zones of the cladding coating. (a) at the top surface of the cladding coating, (b) the magnified image of the quadrangle [A] in (a), (c) in the side bonding zone, (d) the magnified image of the quadrangle [B] in (c), (e) in the underside bonding zone of the cladding coating, (f) the magnified image of the quadrangle [C] in (e), (g) in the transition zone of the cladding coating at the depth of 1 mm from the top surface, and (h) the magnified image of the quadrangle [D] in (g).

Fig. 7 Typical cross-sectional microstructure in different zones of the LSPed cladding coating. (a) at the top surface of the cladding coating, (b) the magnified image of the quadrangle [A] in (a), (c) in the side bonding zone, (d) the magnified image of the quadrangle [B] in (c), (e) in the underside bonding zone of the cladding coating, (f) the magnified image of the quadrangle [C] in (e), (g) in the transition zone of the cladding coating at the depth of 1 mm from the top surface, and (h) the magnified image of the quadrangle [D] in (g).

Fig. 8 Typical TEM images in different zones at the top surface of the cladding coating without and with massive LSP treatment. (a) schematic illustration showing the distributions of the observation locations and three zones of the cladding coating, (b) in the inter-diffusion zone of the cladding coating, (c) in the inter-diffusion zone of the LSPed cladding coating, (d) in the bonding zone of the cladding coating, (e) in the bonding zone of the LSPed cladding coating, (f) in the substrate of the cladding coating and (g) in the substrate of the LSPed cladding coating.

Fig. 9 Schematic illustration showing the effects of massive LSP treatment on microstructure and mechanical properties in different zones of the cladding coating.