Preliminary Studies of Practicability of Laminar Plasma Surface Treatment Process*

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Abstract The basic remelting and cladding tests with laminar plasma technology on metals have been conducted in order to demonstrate the possibility of the technology applied in material surface modification. The experimental results show that the properties of the modified layers of the cast iron surface can be improved notably by the remelting treatment and those of the stainless steel by the cladding treatment. The related results are also verified by microscopic studies such as scanning electron microscopic (SEM) observations, energy dispersive spectra (EDS) analysis and the Vickers hardness measurements of the surface modified layers.

Keywords: remelting, cladding, laminar plasma technology, surface modification, microscopic studies

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1 Introduction

Recently laser method has become one of the most promising techniques in the areas of material welding and surface modification due to its conveniently controlling operation and good working environment [1~4]. However, the thermal efficiency of the laser beams is rather low compared to that of plasma arcs. The amount of the laser energy absorbed by treated materials is less than 50% [5]. Also, the costs of operating the laser equipment are very high. Therefore, it is necessary to develop new methods with higher thermal efficiency. The advantages of laminar plasma jets include: stable flow state with low fluctuation, convenient production at relatively low input powers, notable reduction of the entrainment of impurities, low axial temperature gradient and less environment pollution [6~8]. So it is expected that the laminar plasma technique will become a useful tool in surface treatment. The aim of the present work is to develop the laminar plasma process and to further explore its potential applications in heat treatment of metals. To this end, three metal remelting and cladding tests have been conducted by using the technique to investigate the effects of the processing parameters and the material thermal properties of the modified surface layers. The experimental results demonstrate that the laminar plasma technique can improve the material's surface properties when it is used in the remelting and cladding treatment of the metals with a poor thermal conductivity and high melting points. However, it has little effect on the surface properties of the materials with a good thermal conductivity and low melting points.

2 Experimental procedure

In order to determine the proper processing conditions so far remelting tests on 1Cr18Ni9Ti stainless steel, HT 100 cast iron and Al-Si alloy as well as cladding tests on stainless steel with Al_2O_3 ceramic powder and Al-Si alloy with SiC ceramic powder have been carried out. The sample geometries are stainless steel of 80 mm × 20 mm × 3 mm, cast iron of 120 mm × 80mm × 20 mm and Al-Si alloy of 80 mm × 40 mm × 10 mm. Their thermal conductivities and melting points are 28 W/m· K, 41 W/m· K and 168 W/m · K and 1400 °C , 1130 °C and 580 °C respectively. The additives used for the cladding tests are Al_2O_3 and SiC ceramic powders with particle sizes of 25 μm to 75 μm and 20 μm to 40 μm, respectively.

The related processing conditions are that plasma arc power is in the range of 5 kW to 7 kW; the flow rate of the working gas at 50 cm^3 to 120 cm^3/s, arc current at 110 A to 140 A, the substrates' preheat temperature at 350 °C to 420 °C and the feeding rate of the powder at 3 g/min to 5 g/min in the cladding tests. The length and diameter of the laminar plasma jets are 400 mm and 8 mm respectively. Argon is chosen as the plasma working gas and the powder carrier gas. Before the test the sample surfaces were rubbed with sand papers of 300 μm to increase surface roughness.

Metallographic samples for the microscopic investigation were prepared following standard mechanical polishing procedures. The microstructures and morphologies of the surface modified layer were examined by scanning electron microscope (SEM). The concentration of Al_2O_3 ceramic particles appearing in the stainless steel clad layers were examined through the energy dispersive spectra (EDS) analysis. Vickers hardness along the depth direction of the modified layers was

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measured under both a test load of 200 grams and an acting time of 10 seconds.

3 Results and discussion

3.1 Remelting tests

The results of the remelting tests with three metals, shown in Fig. 1, demonstrate that the plasma technology can create obvious effects on the surface modified layers. Because of the influence of the flow state of the plasma jets the remelting tracks on various, even on the same, metal substrates exhibit quite different macroscopic uniformities. Generally there are two typical flow states of the plasma jets which can be classified into turbulent and laminar regimes based on the internal flow structure of the plasma jets. The flow structure in the laminar regime is characterized by motion in layers of the plasma gas particles, i.e., there is no macroscopic mixing of the adjacent plasma flow layers. Usually the laminar plasma jets with long plumes can maintain relatively steady flow states, which suggests a constant output of the thermal energy of the plasma arcs and a relatively steady interaction between the plasma jets and the surface substances of the substrates. Therefore, the remelting tracks with the uniform surface appearances can be easily developed by using the remelting process (Fig. 1a-c). However in the turbulent regime the flow structure of the plasma jets is characterized by a random, three-dimensional motion of the plasma gas particles superimposed on the averaged motion. In this case, the surging and whipping phenomena of the plasma plumes due to the non-regulation of the anode arc root motion generally create a large difference in the temperatures in the axial direction of the plasma jets that is accompanied with an unsteady output of the plasma thermal energy. Hence when the turbulent plasma jets are chosen as the heat sources to be used in the heat treatment for material surface modification, both the output of the thermal energy of the plasma jets and the exchange of the thermal energy between the plasma jets and the substrate substances will show a sharply pulsatile variation with time, which will result in a rather irregular thermal energy absorption of the substances of the surface modified layer. It is this fact that creates the uneven surface appearance of the stainless steel track (Fig. 1d) and even the discontinuous appearance of the cast iron and Al-Si alloy tracks (Fig 1e,f). The experimental results indicate that there is perhaps a more extensive perspective for the laminar plasma remelting technology in the application to metal surface modification compared to the turbulent plasma technology.

The remelting tracks produced by the laminar plasma technique on different metal substrates demonstrate quite different surface traits. The stainless steel track exhibits a deep groovy surface shape as in Fig. 1a while the cast iron track shows a very smooth surface seen in Fig. 1b. The Al-Si alloy track displays a wide profile with some dimples shown in Fig. 1c. Apparently the track surface traits are closely associated with the thermal properties of the substrate materials. The poor heat conductivity of the stainless steel makes a less dissipation of thermal energy in the remelting procedure. So the pool substance can get sufficient thermal energy and reach a very high temperature of about 3000 °C [10]. Under the impact of the plasma gas pressures some pool liquid substance is blown away to both sides of the remelting tracks and forms the uneven surface, due to the sharp decrease in its viscosity as shown in Fig. 1a. Since cast iron has good heat conductivity and a high melting point the thermal energy of the plasma arcs can be rapidly transferred into the solid phase. Thus the pool liquid substance can maintain relatively low temperature and sufficient viscosity so that the plasma gas pressure cannot make the liquid substance move rapidly, which eventually produces a relatively smooth track surface (Fig. 1b). Ai-Si alloy has the best heat conductivity and lowest melting point. In the remelting process most of the plasma thermal energy is dissipated through the heat conduction process and only the surface layer, heated directly by the plasma jets, is molten so that some dimples are formed as shown in Fig. 1c.

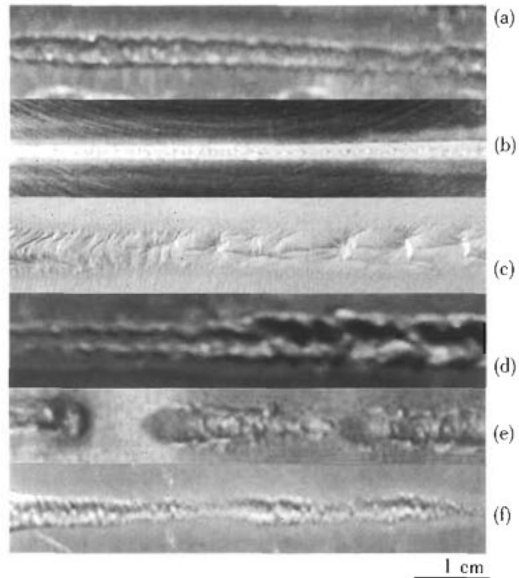

Fig.1 The macroscopic profiles of the remelting tracks on the stainless steel surface (a) cast iron surface (b) and Al-Si alloy surface (c) produced by laminar plasma technology; the macroscopic profiles of the remelting tracks on the stainless steel surface (d); cast iron surface (e) and Al-Si alloy surface (f) produced by turbulent plasma technology

Metal remelting is a rapid heating and cooling procedure that is accompanied by a material phase transformation. Usually the solidification rates and the cooling rates of the pool substance, which determine the crystal growth rates and further influence the microstructure of the material modified layers, are closely associated with the plasma jet scanning velocity in the remelting procedure [9]. A finite element simulation [10] shows that the laminar plasma jets can create the cooling rates of the pool substance reaching up to about 10^3 °C/s and the solidification rates to 10^0 to 10^1 mm/s. These thermally physical properties are sufficient to cause the occurrence of the phase transformation of the metal as cast iron with phase transformation point. When cast iron undergoes the remelting treatment the heat can be expediently transfered into the solid phase by heat conduction process and develop the heat-affected zone with a larger area. From Fig. 2, it can be found that the entire heat-affected zone consists of two parts: one is the solidifying phase transformation layer and the other is the quenching phase transformation zone. It is known that the quenching phase transformation of the cast iron occurs in the range of 727 °C to 738 °C and the solidifying phase transformation occurs in the range of 1143 °C to 1154 °C. It can be seen that zone a in Fig. 2 is developed through the remelting treatment of the pool substance, so the solidifying phase transformation causes the improvement of material properties in this zone. But the temperature in zone b only reaches the quenching level so the quenching phase transformation causes a change in the material properties. The microscopic observation indicates that the austenite phases and sheet graphite morphologies have developed in the remelting phase transformation zone and the cementite, ledeburite phases and discrete graphite phases have grown in the quenching phase transformation zone. Moreover the fact that the hardness of the surface modified layers increases obviously(Fig. 3) suggests that the remelting process really improves the surface properties of cast iron. The investigation on the microstructure of the surface modified layers of both the stainless steel samples and the Al-Si alloy samples shows that no clear molten pools or heat-affected zones develop on the substrate surface in the remelting process. Also the hardness of the modified layer does not improve evidently. These facts suggest that for the kinds of metals with non-phase transformation point in the circumstance of heat treatment, the laminar plasma remelting process cannot improve the material properties of the surface modified layers. Whereas the application of the cladding process is perhaps practicable in resolving the problems technically.

3.2 Cladding tests

In the cladding process the additive powder particles are injected into the high temperature core of the plasma jets. They obtain the thermal energy there from the plasma source and are heated by the plasma jets until deposited on the pool surface. Thus on the one hand the plasma thermal energy is consumed to heat the additive powders to melt them and the substrate surface to create the pool respectively, which will result in a

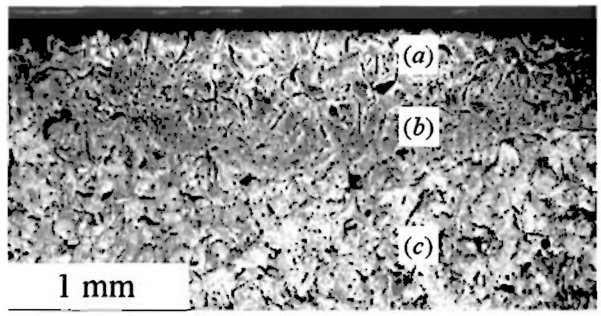

Fig.2 The microscopic observations of the remelting cross-section of the cast iron. (a) remelting modified phase transformation layer, (b) quenching phase transformation zone and (c) non-phase transformation substrate

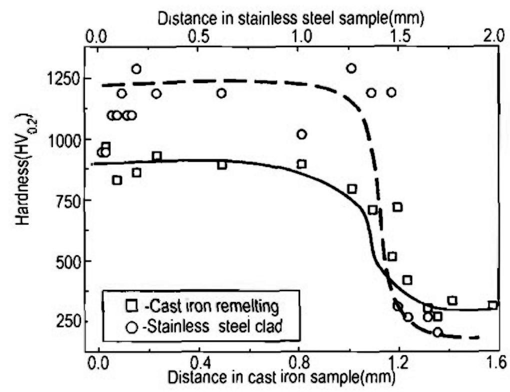

Fig.3 The hardness profile along the depth direction of the surface processed layers: the square symbols correspond to the cast iron sample processed by remelting treatment and the circle symbols to the stainless steel sample processed by cladding treatment

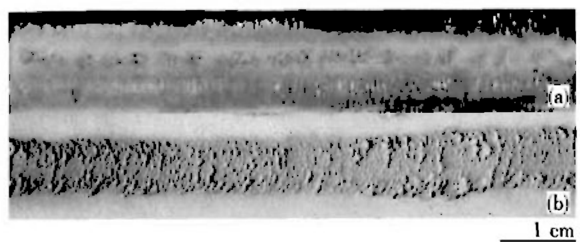

Fig.4 The macroscopic pictures of the cladding tracks on the stainless steel surface (a) and Al-Si alloy surface (b) produced by laminar treatment

decrease in the temperature of the pool substance and an increase in the fluid viscosity. On the other hand, the carrier gas flows and the injected powder streams reduce the plasma gas pressures impacting the pool substance, which greatly diminish the kinetic velocities of the high temperature fluid particles in the pools. Therefore the surface appearances of the cladding tracks change greatly compared to that of the remelting tracks. The picture shown in Fig. 4 demonstrates that the cladding track of the stainless steel shows a quite uniform surface shape bulging outwardly and that of the Al-Si alloy has a fine surface fluctuation instead of the remelting dimples.

SEM photograph of the cross-section of the clad layer of the stainless steel sample is shown in Fig. 5a. There

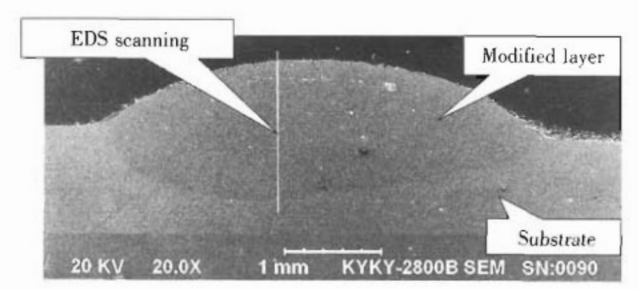

Fig.5a The SEM observation of the cross-section of the cladding track of the stainless steel

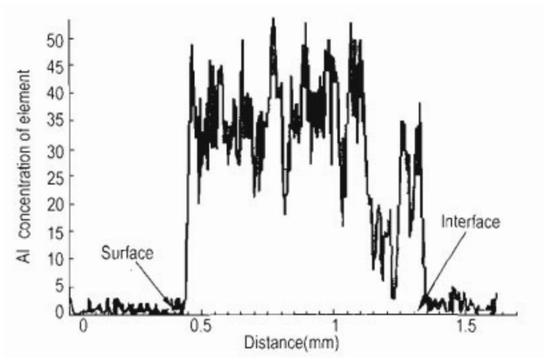

Fig.5b The result of the EDS line-scan analysis of element Al in the clad layer of the stainless steel samples

are no cavities and decohesion in the viewing field, which indicates that the laminar plasma cladding process can produce high quality modified layers and good metallurgical bonding between the clad layer and substrate. The EDS line-scan analysis shown in Fig. 5b demonstrates the increased concentration of the Al element distributed in the clad layers. This fact suggests that the process can clad the powder materials with high melting points such as the refractory Al_2O_3 ceramic powders on the stainless steel substrate surface. A further amplifying SEM observation of the cross-section microstructure, as in Fig. 6, indicates that the Al_2O_3 ceramic phases in the modified layer are principally precipitated at the boundaries and the boundary triple junctions between the crystals. The shape changes of the ceramic phases from the original spherical structure of the powder materials to the needle-shape structure reveal that the Al_2O_3 powders have been fully molten in the cladding procedure. The diameters of the needle-shape ceramic phases are in the sub-micrometer scale and the lengths are in a range of the 5 μm to 10 μm. The numerical simulation [10] of the transient thermal physical properties of the pool substances in the melting/solidifying procedure demonstrates that the growth directions of the Al_2O_3 ceramic phases are closely associated with the solidification rates of the pool substances. In the top central part of the clad layer the direction of the ceramic phase growth is perpendicular to the view plane in Fig. 6 which corresponds with the cooling rates above 2500 °C/s and the solidification rates of about 10 mm/s to 12 mm/s in the solidifying procedure. Near the interface region the direction of

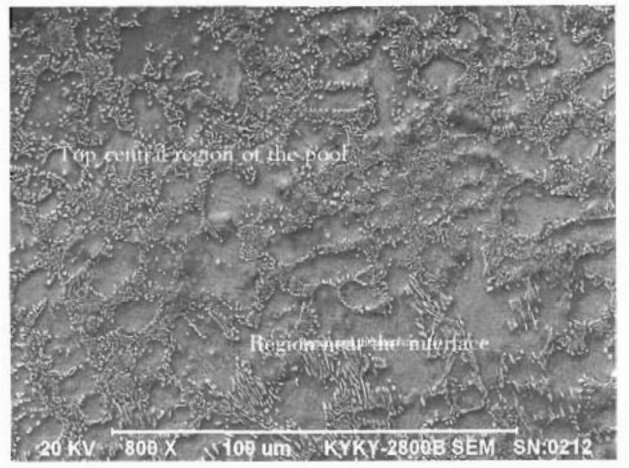

Fig.6 High magnification metallograph of the cross-section in the clad layer of the stainless steel sample. (a) microstructure of the needle-shape ceramic phases, (b) cross-section observation of the needle-shape ceramic phases

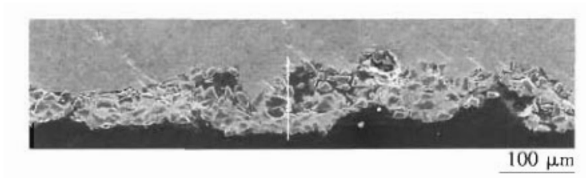

Fig.7a SEM cross-section image of the clad layers of the SiC ceramic powder on the Al-Si alloy substrate

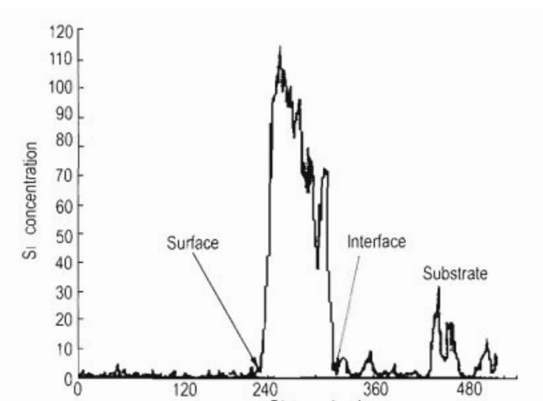

Fig.7b The result of the EDS line-scan analysis of Si element in the clad layer on the Ai-Si alloy substrate

the ceramic phase growth is parallel to the view plane and that the related cooling rates are below 1000 °C/s. Because of the rapid cooling a refined microstructure of the ceramic phases segregates out in the clad layers. This results in the high hardness with a value of about $HV_{0.2}$ 1100 as shown in Fig. 3. Since the poor heat conductivity of the stainless steel produces an evident temperature difference between pool liquid phases and the solid phases, only a very thin heat-affected layer between them develops. Hence, the influence of the cladding treatment on the hardness of the materials is principally limited in the clad layers.

The microscopic observation of the Al-Si alloy clad layers as shown in Fig. 7a indicates that the SiC ceramic particles have been implanted, but not molten, into the substrate modified layers. The EDS line-scan analysis of the Si element also clearly demonstrates the concentration increase compared to the original concentration of the substrate materials in Fig. 7b. The good thermal conductivity of the Al-Si alloy greatly promotes the dissipation of the thermal energy of the plasma source from the substrate solid phases. This causes the pool substance temperature to remain below 1100 °C [10], at which to melt the SiC ceramic particles with the melting point above 3400 °C is clearly impossible. Therefore as undergoing the cladding treatment only a weak joint between the non-molten SiC ceramic phases and the Al-Si alloy phase has formed. It is the weak bonding mechanism, that results in the failure of the SiC ceramic phases to play an important part in the strengthening and hardening of the clad modified layers and the failure to improve the properties of the alloy surface.

4 Conclusion

Laminar plasma remelting technique can improve the surface properties of the metal with phase transformation point, such as cast iron. The test results show that not only the hardness of the cast iron surface modified layer increases evidently but also its microstructure refines uniformly. But the remelting technique is not suitable for the surface modification of metals such as stainless steel and Al-Si alloy without phase transformation point.

Laminar plasma cladding technique with adding ceramic powders can produce an evident surface hardening modified layer on some metals without phase transformation point, such as stainless steel. Further microscopic investigation shows that the cladding technique can completely melt the adding ceramic powder particles in the heating procedure and form a good metallurgical bonding between the clad layer and the substrate. These facts are very useful in the improvement of the microstructure of the material surfaces, such as the enhancement of the Vickers hardness. However, the technique, when applied in the cladding treatment of metals such as Al-Si alloy with good thermal conductivity, proves to be quite inefficient even though the SiC particles could be incorporated into the modified layers. Further studies on this issue will be undertaken in the future.

References

1 Markwood A P, Crafer R C. Optics & Laser Technology, 2005, 37: 99 ~ 115
2 Shepeleva L, Medres B, Kaplan W D, et al. Surface & Coatings Technology, 2000, 125: 45 ~ 48
3 Sexton L, Lavin S, Byrne G, et al. Journal of Materials Processing Technology, 2002, 122: 63 ~ 68
4 Kathuria Y P. Surface & Coatings Technology, 2000, 132: 265 ~ 269
5 Li L J, Mazumder K. "A Study of the Mechanism of Laser Cladding Processing", in Laser Processing of Materials, Edited by K. Mukherjee and J. Mazumder, The 113th AIME Annual Meeting, Los Angeles, California, Febuary 26 - March 1, 1984, 35 ~ 50
6 Pan W X, Zhang W H, Zhang W H, et al. Plasma Chemistry and Plasma Processing, 2001, 21 (1): 23 ~ 35
7 Osaki K, Fukumasa O, Kobayashi A. Vacuum, 2000, 59: 47 ~ 54
8 Pan W X, Zhang W H, Ma W, et al. Plasma Chem. Plasma Process, 2002, 22 (2): 271~ 284
9 Krumbhaar H M, Kurz W, Brener E. Phase Transformation in Materials. Ed. Kostorz G. Wiley-VCH, Weinheim: Berlin, Germmary, 2001, 81 ~ 170
10 Wu Bin, Ma Wei. ACTA Heat Treatment of Metals, 2006, 8: 31 (in Chinese) (to be published)

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