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Feasibility of laminar plasma-jet hardening of cast iron surface

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Abstract

Nontransferred DC laminar plasma jets of stable flow and low impinging pressure acting on the substrate were used to heat W–Mo–Cu cast iron for phase transfer hardening of the surface layer. Substrates were heated in multipass with or without overlapping or heated with only single-pass. Surface morphologies of the molten trace and microstructure of the cross-section were observed, and the hardness distribution of the treated surface layer was examined. The surface layer of single-pass-heated specimen has an average hardness of about 900 $HV_{0.1}$, while the specimen treated with multipass shows an average hardness of about 700 $HV_{0.1}$, because of the heat effect from the neighboring pass treating, compared with the substrate hardness of about 300 $HV_{0.1}$. The results demonstrate the stable and favorably controlled heating of the laminar plasma jet on the substrate surface and feasibility of using it as a tool for surface hardening of cast iron.

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Keywords: Laminar plasma jets; Stable heating; Surface hardening; Cast iron

1. Introduction

Surface properties are often a decisive factor affecting the performance and service life of a workpiece, and there are various kinds of surface treatment techniques for structural materials. As a high energy–intensity heating source, nontransferred DC plasma jet is widely used for spraying coatings on a material's surface to improve the wear and corrosion resistance or thermal barrier properties [1–3]. This kind of plasma jet is actually an extremely high-temperature gas flow usually possessing a power density of 10^8 W/m^2, which allows rapid heating of almost every kind of solid material to its melting or evaporating point. The heating efficiency of the thermal plasma jet could be much higher and processing cost can be much lower than a laser beam heating of material surface. Nevertheless, much less attempt has been made on metal surface strengthening by using transferred DC arc [2,4], and even less work was conducted with nontransferred plasma jet [5], compared with the laser cladding, glazing and remelting strengthening.

In a process using transferred arc, the treated piece is usually working as the anode which generally moves relative to the torch cathode. Thus, treatment parameters, such as arc current, distance and moving speed between workpiece and cathode, and original physical properties and surface morphology of the piece will all affect the arc root attachment and motion characteristics on the workpiece surface, hence affect the treatment result and uniformity [2,4]. In the case of using nontransferred plasma jet, the cathode and anode are all set in the torch, apart from the treated workpiece, and the material surface is heated by the high temperature jet-flow from the torch nozzle. The turbulent flow condition of serious fluctuation [6,7] could be the essential reason that makes it hardly applied for materials surface processing except for spray coatings. At the same time, the turbulent flow mixes easily with the surrounding atmosphere and causes a rapid energy dissipation of the jet flow, bringing about a short jet length with high axial-temperature gradient. This temperature gradient

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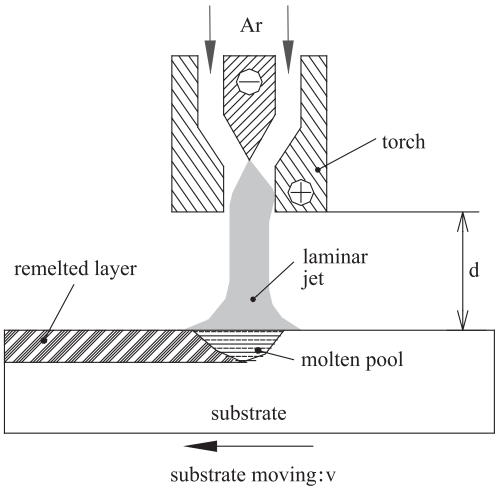

Fig. 1. Schematic drawing of the laminar plasma heating of the cast iron.

generally exceeds 200 K/mm in the useful high-temperature region when it is considered as a steady flow [6], but the large amplitude energy fluctuation can be over 50% of its average value [8,9]. Accordingly, it is difficult to obtain a controlled uniform heating of the material surface with a turbulent plasma jet.

Laminar flow jets of nontransferred DC plasma were generated [7,10]. It is characterized to be a stable flow of much lower fluctuation, which results in much less mixing with the surrounding atmosphere, low axial-temperature gradient and long region of high temperature, reduced material oxidation and very low working noise, compared with a turbulent jet. These characteristics make the laminar plasma jet worth investigating on its usage for material surface strengthening.

In the present work, W–Mo–Cu cast iron used as the cylinder liner of diesel engines was heated with the argon laminar plasma jet rapidly at atmospheric pressure to temperatures around its melting point. Surface morphology of the melting trace and microstructure of the cross-section were observed. Hardness and its distribution on the treated surface layer were examined and the process feasibility was discussed.

2. Experimental detail

The special torch structure and working parameters for the laminar plasma jet generation was described in our previous work [10]. The pure argon DC plasma jets were injected into atmosphere for the substrate heating. The maximum gas temperature of the laminar plasma jet at the centre of torch exit can exceed 17 000 K with an axial temperature gradient lower than 60 K/mm [11]. The jets are very stable and the impinging pressure is quite low compared with those of a turbulent plasma jet [7].

Table 1
Process parameters of laminar plasma heating for cast iron

Substrate dimension (mm)	150×150×15
Substrate moving speed: *v* (m/min)	0.03–0.3
Torch-substrate distance: *d* (mm)	5–15
Plasma working gas	Ar
Gas flow rate (cm^3/s)	75–220
Arc current (A)	180–200
Arc voltage (V)	46–48

Fig. 1 shows the schematic drawing of the plasma heating system. The cathode and anode are all in the torch which keeps the heated substrate apart from the electrodes. The treated substrate was set at a certain distance from the torch nozzle and moved across the laminar plasma jet. The main process parameters are listed in Table 1. Pure argon was used as the plasma working gas. As-cast iron pieces of the composition 1.9%W, 0.8% Mo, 1.2% Cu, 0.8% Mn, 3.3% C, 2.0% Si and balanced Fe were used as the treated substrates with the dimension of 150×150 mm area and 15-mm thick.

As shown schematically in Fig. 2, the substrates were treated in three ways. One is heating the substrate to form only single trace; the second is heating the substrate in multiple passes (pass by pass with a space about 10 mm) but without overlapping; and the third way is multipass heating with an overlapping of about 50% on the former trace, forming a relatively wide treated area.

Macro surface morphology of the treated substrates was observed. Microstructure of the cross-section near the surface layer was observed by using an optical microscope. The hardness distribution of the surface layer was measured with a micro Vickers hardness meter with a load of 100 g and a keeping time of 15 s, on matrices except the graphite of a polished cross-section without corrosion.

3. Results and discussions

The parameter range in Table 1 was employed in the test; and results show that surface roughness increased considerably and large pores formed at the bottom of molten pool after solidification when the arc current is over 195A or when the substrate moving speed is very low. Under such conditions, and with flow velocity of the jet and impinging pressure on the substrate increasing with the gas flow rate,

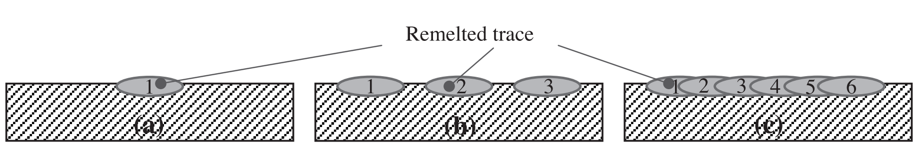

Fig. 2. Schematic drawing of the substrate cross section for the three treatment ways: (a) the single-trace heating; (b) the multipass heating without overlapping; and (c) the multipass heating with an overlapping of about 50% on the former trace. Numbers in the drawing indicate the heating sequence.

Fig. 3. Surface morphology of the turbulent-jet heated specimen.

the blowing jet would break the molten pool. Thus, the treatment condition was then fixed at: torch nozzle to substrate distance, 9 mm; substrate moving speed, 0.1 m/min; gas flow rate, 150 cm^3/s; and arc current, 180–195A for the later describing and discussions. The arc voltage takes its value as the change of arc current here when torch structure and gas flow rate are fixed.

3.1. Surface morphology and process stability

Fig. 3 shows the specimen surface heated by a turbulent-flow plasma jet. Separate cavities formed along the heating trace, which indicates that the molten pool was broken by the high impinging pressure of the jet flow on the specimen surface. The intermittent cavities suggest the nonuniform heating in large scale for the specimen surface because of the serious fluctuation of the turbulent jet flow.

Fig. 4 is the surface morphologies heated by the laminar plasma jets generated at arc current of 180–195A, in which panels (a)–(c) were heated in multipass fashion without overlapping in the remelting order of 195, 190 and 185A, panels (d)–(f) were those of only single-pass heating on one substrate and panel (g) was heated at 182A with the overlapping of about 50%. All of the laminar plasma-heated specimen shows continuous and uniform solidified trace, and the molten pool was not broken by the impinging pressure due to the relatively low velocity of the laminar jet flow. Specimens heated in multipass fashion seem to have reached higher temperatures than the single-pass-heating specimen when the arc current is at the same value. The specimen surface shown in Fig. 4(d), single-pass heating,

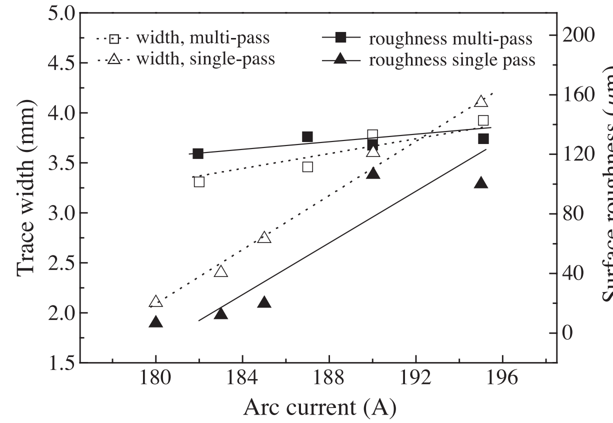

Fig. 5. Trace width and maximum surface roughness of remelted specimens change with the arc current.

was heated to a temperature just around its melting point, and the trace surface shows lowest roughness. Width and surface roughness of the single-pass-remelted trace increased essentially with increasing arc current, as shown in Fig. 5, when the substrate roughness is assumed as zero. However, the width and surface roughness of the multipass-treated specimens without overlapping show almost no apparent difference because they were heated in the order from high arc current to low one; that is, the first trace was heated at 195A, second at 190A and last at 183A. This could be caused by the heat effect of the former passes which provide preheating for the substrate when the later pass is made.

It was found that distance variation within 4 mm from the torch nozzle to the substrate surface did not cause apparent change of the trace morphology of the melting pool, in the case of the laminar plasma heating. This distance changes corresponding to about 220 K change of the gas temperature on the specimen surface, according to the axial temperature gradient of about 55 K/mm for the laminar jet [11]. That is,

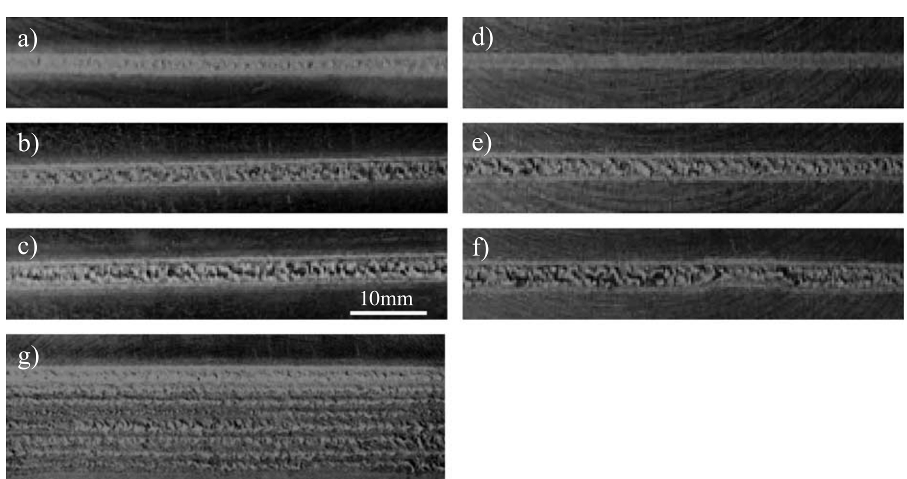

Fig. 4. Surface morphologies of the laminar plasma-heated specimens. Panels (a)–(c) were heated in multipass without overlapping and (d)–(f) were heated only single-pass on one substrate, at arc current of 185A for panels (a) and (d), 190A for panels (b) and (e), and 195A for panels (c) and (f). Panel (g) was heated at 182A with the overlapping.

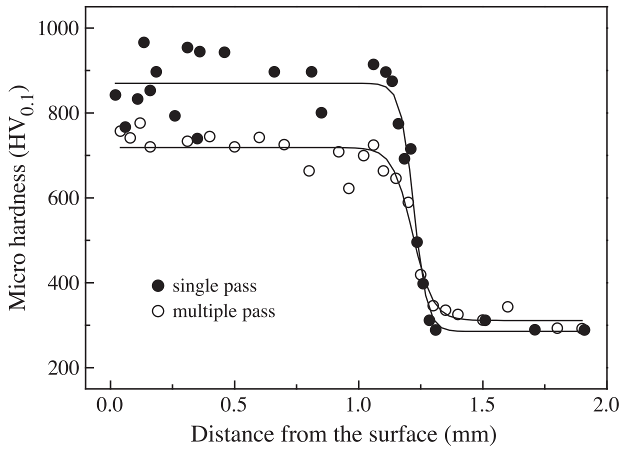

Fig. 6. Hardness distributions at the surface layer of laminar-jet treated specimens at arc current of 190A.

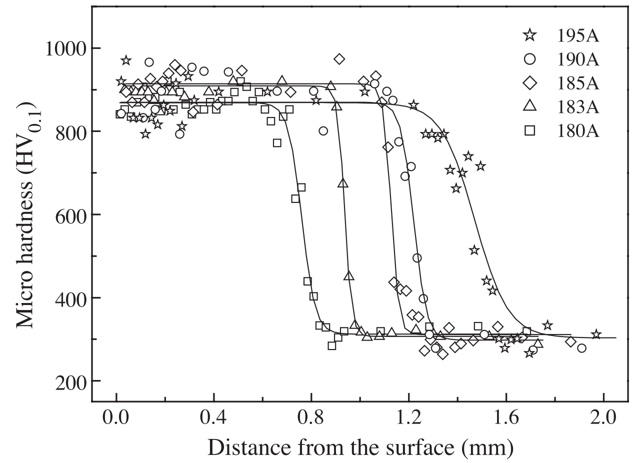

Fig. 8. Hardness distribution at the surface layer of single-pass-treated specimens at different arc currents.

gas temperature change in this range could not appreciably affect the specimen heating.

In brief, the above results show the favorably controlled heating of the laminar plasma jet for metal surface treatment.

3.2. Hardening effects

Fig. 6 is the hardness distribution of the specimen surface layer treated by the laminar plasma jet at arc current of 190A, corresponding to the specimens with surface morphologies shown in Fig. 4(b) and (e). The specimen treated in multipass fashion shows an average hardness of about 700 $HV_{0.1}$, and the specimen of single-pass heating has an average hardness of about 900 $HV_{0.1}$, while the substrate hardness is about 300 $HV_{0.1}$. The fluctuation of the measured hardness data could be caused by the complex matrix phases and their distribution (shown later in Fig. 10). Again, heat effects of the former and later pass heating could be the reason of the relatively lower hardness value, as in the case of multipass heating. The former heating could cause substrate preheating and reduce the cooling rate of the molten trace, and the later pass could cause a tempering effect. Fig. 7 is the linear hardness distribution across the heating trace at 0.3 mm beneath the free surface of the overlapped specimen. Its average hardness is at the same level of the multipass-treated specimen without overlapping.

The results in Fig. 8 indicate that arc current regulation did not cause apparent hardness change at the hardened surface layer, but appreciably affects the thickness of the hardened layer. Fig. 9 shows the thickness of the hardened surface layer increasing from about 0.6 to 1.6 mm with the arc current increasing from 180 to 195A, whether the specimen was treated in multipass or only single-pass. This result means that the depth of molten pool increases as the increase of energy intensity of the jet flow because the laminar jet-flow temperature increases with the arc current [11]. When the specimen is heated at arc current of 180A, its surface just melted slightly; that is, the pool depth is almost zero, but the thickness of the hardened layer is over 0.6 mm

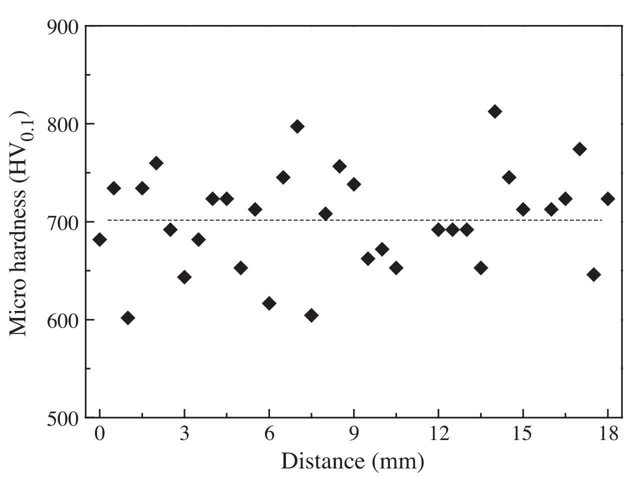

Fig. 7. Hardness distribution (◆) of 0.3 mm beneath the free surface at the direction across the heating trace of the overlapped specimen remelted at 182A.

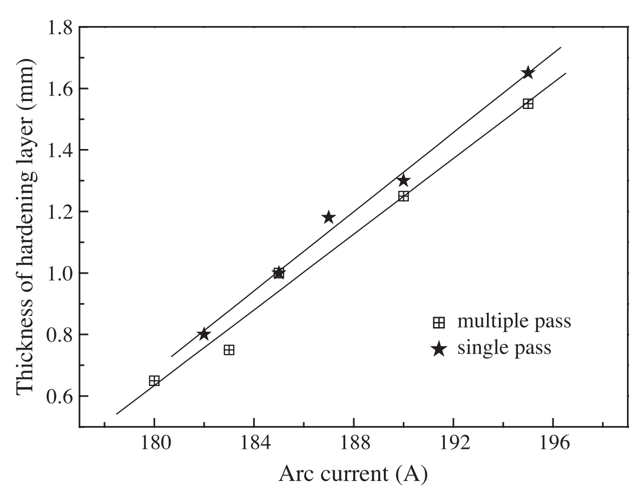

Fig. 9. Thickness of the hardening layer increased with the increasing arc current.

as shown in Fig. 9. This indicates the thickness of the hardening layer is that added by the pool depth and solid-phase transfer region of about 0.6 mm thick.

3.3. Microstructure change at surface layer

Fig. 10 shows the structures at the cross section of the surface layers observed with the optical microscope. Fig. 10(a) is the typical structure when the specimen is heated by the laminar plasma jet at arc current of lower than 185A, and in this case, the graphite almost keeps its original shape and distribution in the matrix. The arrows in Fig. 10(a) indicate part of the interface between hardened surface layer and original structure. As the arc current increases to over 190A, the molten pool was overheated. The graphite disappeared or dissolved at the top surface and was broken into small sized pieces beneath the top surface (shown in Fig. 10(b), broken graphite like those indicated with number "1"). Fig. 10(c) shows an over eutectic structure at the top surface with large pieces of cementite (long gray light bars such as those marked "A") in the ledeburite matrix (as those marked "B"). This means that the carbon content in the top surface increased from its original subeutectic to the over eutectic level, and the low density of graphite (carbon) could be the reason causing its concentration towards the top layer because of the effect of gravity. When the arc current exceeds 195A, large pores formed near the bottom of the molten pool. However, there are no cracks found in the hardened surface layer in the parameter range of this work.

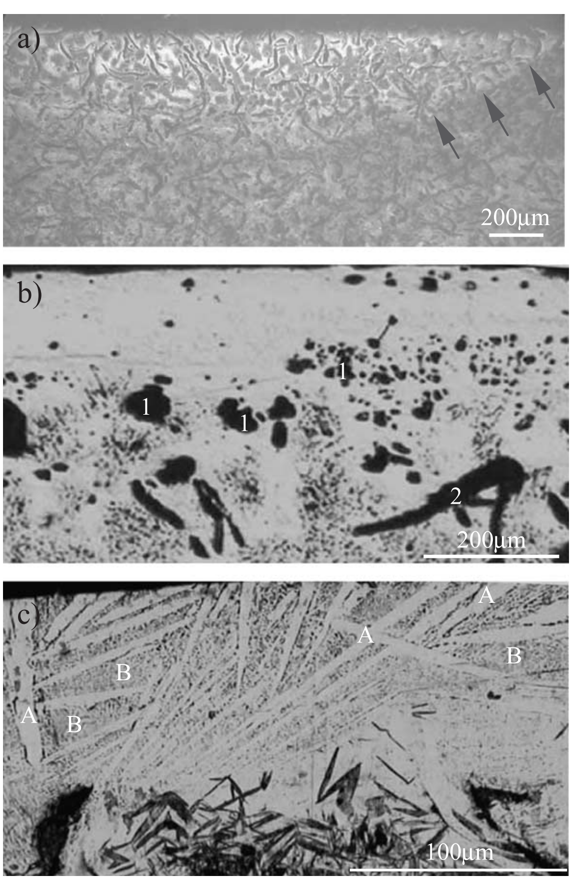

Fig. 10. Microstructures at the cross section of laminar plasma heated specimens. Panel (a) was heated at arc current of 185A and panels (b) and (c) were heated at 190A.

Associated with the results of surface morphology and hardness distribution of the laminar plasma-treated cast iron, although the thickness of hardened layer increased with increasing arc current, the surface roughness and defects in the surface layer increased also with the increasing arc current. Accordingly, suitable heating of the cast iron to the temperature just around its melting point could be favorable for obtaining a well-balanced surface strengthening effect.

4. Conclusions

The results indicate that the laminar plasma jet at atmospheric pressure is a controllable heating source for metal surface treatment to achieve the phase transfer strengthening in a considered region with favorable reproducibility. The impinging pressure of the laminar jet flow on the treated surface can be low enough to avoid the breaking of the molten pool. Surface layer of the W–Mo–Cu cast iron heated in multipass with the laminar plasma jet shows an average hardness of about 700 $HV_{0.1}$, while that of single-trace heating reaches an average hardness of about 900 $HV_{0.1}$ which is about three times the substrate hardness. The thickness of the hardened surface layer increases from about 0.6 to 1.6 mm as the arc current increased from 180A to 195A. A well-balanced surface strengthening effect could be obtained at arc current of 185–190A in this experiment range. Overheating at high arc current could cause increased surface roughness and defects in the surface layer, and temperature control is important to obtain a strengthened surface layer of high hardness and favorite microstructure.

Acknowledgements

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