

Surface materials processing with DC laminar plasma jets

W.X. Pan*, W. Ma, and C.K. Wu

Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080, China.

ABSTRACT DC laminar plasma jets of stable flow conditions were generated. This kind of plasma has a flow field of concentrated temperature distribution in the radial direction and reduced temperature and velocity gradients in the axial direction, because of the greatly reduced mixing of the jet flow with the surroundings atmosphere. These characters of the jet flow are favorable for enhancing the process controllability in surface materials processing. Fine YSZ powder was sprayed by low-pressure laminar plasma-jet, to obtain coatings of fine microstructure and low surface roughness. Laminar plasma cladding at atmospheric pressure was conducted by melting the steel surface to form a small molten pool and pouring the Ni+YSZ powder along the jet into the pool simultaneously. This makes the cladding layer bonded metallurgically to the substrate. This method is also suitable for phase transition hardening, remelting hardening, and forming a functional gradient layer.

KEY WORDS: Laminar DC plasma jet, flow character, low pressure plasma spraying, plasma cladding

1. INTRODUCTION

The exceedingly high energy intensity of a dc plasma jet could heat materials to very high temperatures and bring about rapid processing speed^[1]. Conventionally used dc plasma jet at atmospheric pressure is usually operated in turbulent flow. The fluctuating character of a turbulent jet leads to a rapid mixing of the jet flow with the surrounding atmosphere and results in a short arc jet with very high temperature gradient in the axial direction^[2], causing difficulties in the process control^[3-4]. A stable jet flow condition with favorable temperature and velocity distributions is really important to improve the controllability for materials processing.

In the present work, laminar plasma jets of good flow stability were generated under different gas feeding rate and input power conditions. Dependence of jet length and thermal efficiency on the generating conditions, and pressure distributions with the jet impinging on a flat plate were measured. Effects of the jet characters on materials surface processing were discussed.

2. CHARACTERISTICS OF DC LAMINAR PLASMA JETS

2.1 Experimental methods

A torch with an inter-electrode insert, principally the same as in the previous work^[4], was used to generate non-transferred dc plasma jets of laminar flow at atmospheric pressure. Pure argon and a mixture of Ar with N₂ were used as the plasma working gases at a feeding flow rate of 90-250 cm³/s.

The jet power was evaluated by passing the jet flow through a water-cooled annular space. Temperature changes of the cooling water of a certain flow rate were measured with a thermocouple. The enthalpy increase of the cooling water was calculated and the value was considered to be equal to the jet power. Then, the thermal efficiency for the jet generation was evaluated as the ratio of jet power to the input power.

Pressure distributions of the jet flow impinging on a flat plate were measured with a water-cooled copper plate of 120 mm in diameter with a $\Phi 0.5$ mm hole at the plate center. The small hole was led to a micro manometer with its other side open to the atmosphere. Thus, recorded pressure data

* Corresponding author. Professor. Address: Institute of Mechanics, Chinese Academy of Sciences, 15 Zhong-guan-cun road, Beijing 100080, China. Tel: +86-10-62554541; Fax: +86-10-62561284; E-mail: wxpan@imech.ac.cn

indicate the differential value of impinging pressure and atmosphere, and it was called gage pressure here. The plate was set perpendicular to the jet axis at different distance from the torch nozzle, and moved step by step to record the stable pressure value point by point.

2.2 Results

2.2.1 Jet length and thermal efficiency

Laminar plasma jets of different length and power could be generated. Figure 1 (a) shows the relationship between Ar plasma jet length and gas feeding rate, at constant arc current of 200 A. Plasma jets were kept in stable long length and silent flow condition, when gas feeding rate was lower than $210 \text{ cm}^3/\text{s}$, and the jet length of laminar plasma reached a maximum value of about 550 mm at gas feeding rate of near $180 \text{ cm}^3/\text{s}$. Increasing gas feeding rate over $210 \text{ cm}^3/\text{s}$, the jet flow transferred to turbulent state, showing a dramatically reduced jet length with expanded radial dimension and very high noise. Figure 2 is typical appearances of the long laminar and short turbulent plasma jets at gas feeding rate of $180 \text{ cm}^3/\text{s}$ and $220 \text{ cm}^3/\text{s}$ respectively. The ratio of the jet length to its diameter of the laminar jet in figure 2 is over 70.

The thermal efficiency shown in figure 1 (b) increased simply with the increasing gas feeding rate, when the arc current was kept at a constant of 200 A. The jet power of laminar plasma could reach 3.7 kW with a thermal efficiency of about 40%, at gas feeding rate of $210 \text{ cm}^3/\text{s}$. The thermal efficiency changed smoothly in the transition of the jet flow from laminar to turbulent state, although it displayed a dramatic change in the jet length with the transition as shown in figure 1(a).

The working system used here is very simple and easy to operate and maintain^[4], and at the same time, the jet power and the thermal efficiency is higher than the reported work^[5].

2.2.2. Impinging pressure on a flat plate

Figure 3 shows the axial gage pressure changes on the plate surface at different gas feeding rate of $95 \text{ cm}^3/\text{s}$ and $160 \text{ cm}^3/\text{s}$ of laminar jets and $240 \text{ cm}^3/\text{s}$ of turbulent jet. The pressure decreased with the increasing distance from nozzle exit to the plate, in both laminar and turbulent cases. In the case of the turbulent jet, the pressure decreased quickly along the jet axial direction. The peak pressure value of the laminar jet at low gas flow rate could be one order lower than that of the turbulent jet at the position near the torch exit and reduced slowly along the axis. On the other hand, gage pressures of the turbulent jet fluctuated irregularly in large scale during the measurement, and values shown in figure 3 was only the estimated average ones. The pressure of the laminar jet showed quite stable value in the measuring. The measured pressures would be directly proportional to square of the flow velocity in the axial direction. Thus, the results suggest the rapid reduction of the flow velocity in the axial direction and serious flow fluctuation of the turbulent plasma jet. And the flow conditions of a laminar plasma jet could be characterized as a stable gas flow with relatively slow velocity and low reduction gradient in the axial direction.

3. APPLICATIONS OF LAMINAR PLASMA JETS FOR MATERIALS PROCESSING

The different power and gas flow rate of laminar jets correspond to different maximum temperature and maximum velocity at the torch exit. And changes of jet length indicate the different temperature and velocity distribution characters of the flow fields, even at the same jet power or gas feeding rate. This could provide a wide selecting possibility for different materials processing, such as

particle heating, coating, hardening, and cladding etc.

3.1 Plasma remelting and cladding

Gas flow velocity of a turbulent jet is generally very high in the useful high temperature region as suggested in figure 3. This makes it difficult to be used for cladding and remelting treatment of metal surface, because the high impinging pressure caused by the high flow velocity could break up the molten liquid. The relatively low flow velocity of the laminar jet could reduce the impinging pressure on material surface. Fast remelting tests of cast iron and stainless steel surface were conducted. Figure 4 shows surface morphologies of fast remelted cast iron. It shows a uniform remelted trace in figure 4 (a) by the laminar plasma jet. The turbulent jet heated the iron surface with great fluctuation as shown in figure 4 (b), even keeping parameters unchanged such as the arc current, gas flow rate, distance from the torch nozzle to the plate surface, and moving speed of the plate across the jet.

Figure 5 shows a microstructure of cladded layer of Ni+30%ZrO₂ on stainless steel surface by the laminar plasma jet. It was conducted by melting the steel surface with the laminar jet to form a small molten pool and pouring the Ni+30%ZrO₂ powder along the jet into the pool simultaneously. This makes the cladding layer bonded metallurgically to the substrate, resulting in favorable interface conditions and adhesive properties.

3.2 Low pressure laminar plasma spraying

Fine particle ZrO₂-8 mol%Y₂O₃ powder of particle size less than 25 μm was sprayed at low pressure of 1.3310⁴ Pa with a Ar laminar plasma of a input power of 6 kW. Figure 6 shows the measured surface roughness results of the low-pressure laminar-plasma sprayed sample and the one by a conventional atmospheric plasma spraying. The results indicate that the sample surface deposited with the fine particle powder possesses a low relative roughness of about 2.7 μm, compared with the high surface roughness of about 7.3 μm by a conventional process.

Figure 7 is a scanning electron microscopy (SEM) image of the cross section of coating layer using the fine particle powder. It showed a fine microstructure with low porosity ratio and small defect size. The thickness of each progressively deposited layer is about 3 μm. Results of X-ray diffraction indicated that the phase structure of the ceramic coatings coincided with that of the powder, which indicates that no apparently component change and thus no phase structure change occurred in the vacuum argon plasma spraying.

4. CONCLUSIONS

1. Atmospheric laminar-plasma of long jet length and low noise were generated at gas feeding rate of 90-240 cm³/s and input power of 2.5-10 kW. The jet length of laminar plasma reached a maximum value of 550 mm, while the jet power reached 3.7 kW with a thermal efficiency of about 40%. The low velocity and stable flow conditions of the laminar jet make it suitable for material surface cladding and remelting hardening.
2. Laminar plasma jet can heat metals with favorable controllability. Laminar plasma cladding of Ni+30%ZrO₂ on stainless steel surface resulted in metallurgical bonding to the substrate and favorable interface conditions and adhesive properties.
3. Fine particle ZrO₂-8 mol%Y₂O₃ powder could be sprayed with low-pressure laminar plasma. The coating layer of fine microstructures, lower surface roughness and porosity could be obtained.

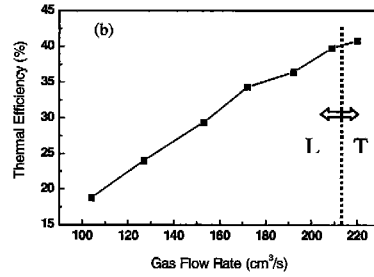
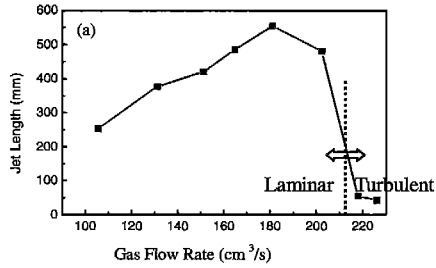


Figure 1. Dependence of jet length (a) and thermal efficiency (b) on the gas feeding rate at arc current of 200 A.

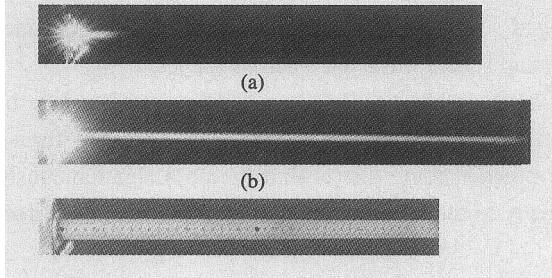


Figure 2. Plasma jet appearances at arc current of 200 A. (a) is a turbulent jet at gas feeding rate of 220 cm³/s and (b) laminar jet at 180 cm³/s.

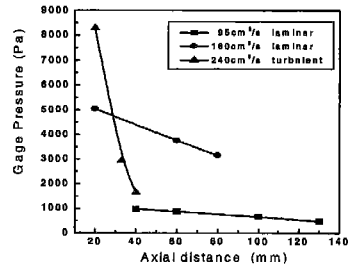


Figure 3. Dependence of gage pressure in jets axis direction at gas feeding rate of 95 cm³/s and 160 cm³/s of the laminar jets and 240 cm³/s of the turbulent jet.

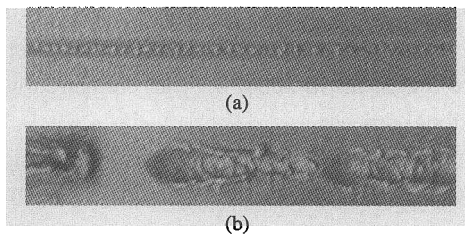


Figure 4. Surface morphologies of cast iron remelted by (a) laminar plasma jet and (b) turbulent jet.

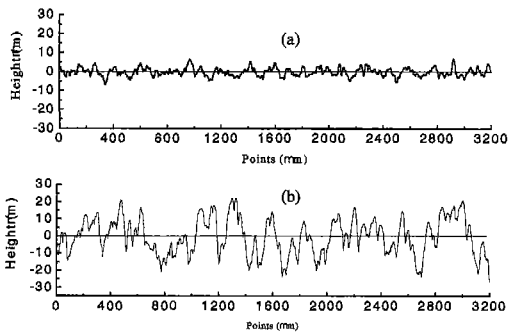


Figure 6. Surface profiles of TBCs fabricated with two types of the powders. (a) with fine ceramic powder in low-pressure laminar jet, and (b) with popular ceramic powder in atmospheric pressure turbulent jet.

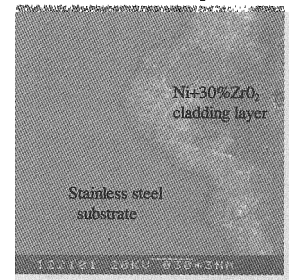


Figure 5. Cross section structure of the surface cladding layer of Ni+30%ZrO₂ on stainless substrate.

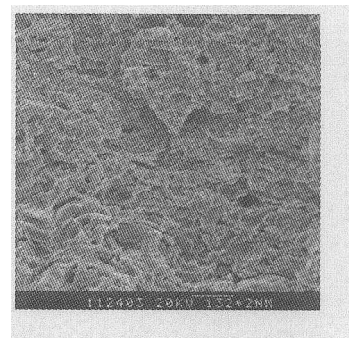


Figure 7. SEM image of the cross section of YSZ coating layer.

ACKNOWLEDGEMENTS

This work was financially supported by Project Nos. 59836220 and 19975064 of the National Natural Science Foundation of China and Institute of Mechanics President's Foundation.

REFERENCES

1. P. Fauchais and A. Vardelle, Thermal Plasmas, *IEEE Trans. Plasma Sci.*, 25(1997), 1258-1280.
2. E. Pfender, Plasma jet behavior and modeling associated with the plasma spray process, *Thin Solid Films*, 238(1994), 228-241.
3. O. P. Soloneuko, State-of-The Art of Thermophysical Fundamentals of Plasma Spraying, *Thermal Plasma and New Materials Technology*, O. P. Solonenko and M. F. Zhukov, eds. Cambridge Interscience Publishing, Cambridge CB2 6AZ, Vol.2, (1995), 7-94.
4. W.X.Pan, W.H.Zhang, W.H.Zhang and C.K.Wu, Generation of Long, Laminar Plasma Jets at Atmospheric Pressure and Effects of Flow Turbulence, *Plasma Chem. and Plasma Process.*, 21(2001), 23-36.
5. K.Osaki, O.Fukumasa, A.Kobayashi, High thermal efficiency-type laminar plasma jet generator for plasma processing, *Vacuum*, 59 (2000), 47-54.

Pan Wenxia, Female, Research Professor, Institute of Mechanics, Chinese Academy of Sciences. Sep.1988 got the Ph.D. at The University of Tokyo, Japan, in materials science. Research experience: Plasma Sintering (Si_3N_4 , SiC, Al_2O_3 , Mo); Thermal Plasma Synthesis of Fine Powder (Si_3N_4 , SiC); Low Pressure Plasma Spraying (Al, Ni, Ti, Ni-Cr, SiC, YSZ); Generation of Laminar DC Plasma Jet at Atmospheric Pressure; High Speed and Large Area Deposition of Diamond Films; Ion Nitriding