DOI: 10.3901/CJME.2011.04.***, available online at www.cjmenet.com; www.cjmenet.com.cn

# Experimental Analysis on the Variable Polarity Plasma Arc Pressure

JIANG Yi[1, 2, *], XU Binshi[1], LU Yaohui[1], LIU Cunlong[1], and LIU Ming[1]

1 *National Science and Technology on Remanufacturing Laboratory, Academy of Armored Force Engineering, Beijing 100072, China*
2 *Naval Flying Academy of China, Huludao, 125101, China*

Received August 24, 2010; revised April 7, 2011; accepted April 29, 2011; published electronically May 12, 2011

**Abstract:** Arc pressure is one of the key factors for variable polarity plasma arc(VPPA) and welding pool formation. In this paper, VPPA pressure is measured by pressure transducer and U-tube barometer methods, and advantages and disadvantages of the two methods are compared. The effects of welding parameters, including with straight polarity(SP) current, reverse polarity(RP) current, time ratio of SP to RP, plasma gas flow rate, on VPPA pressure are investigated by using an orthogonal design. The experimental results indicate that the influencing degree of the welding parameters are in the order of plasma gas flow rate, SP current, time ratio of SP to RP, RP current. These results are important to researches of VPPA welding process and its mechanism. The physics behavior of VPPA is taken into account when the above influence mechanisms are analyzed: Firstly, according to the mechanism of the cooling compression to the arc, the compression to VPPA is enhanced with the increase of plasma gas flow, so the VPPA pressure would increase obviously; Secondly, although the temperature of VPPA is as a function of the welding current, the radius of VPPA is also enhanced. So the effects of SP current on VPPA pressure are inferior to the effects of plasma gas flow; Thirdly, VPPA pressure increases as a function of time ratio of SP to RP because the frequency of welding current influences the arc pressure to the some degree; Finally, the RP intervals are farther less than the SP intervals, so the influence to the pressure is minimal.

**Key words:** variable polarity plasma arc, arc pressure, orthogonal experiment

## 1 Introduction

Variable polarity plasma arc (VPPA)[1–2] welding, as an efficient and cost-efficient welding technology, has been widely applied to aircraft components manufacture, especially aluminum alloy components[3-4]. In the phase of straight polarity (SP, also called direct current electrode negative, DCEN), the fusion zone and heat-affected zone(HAZ) are reduced remarkably due to high energy input of plasma arc, and high quality weld is attained. During reversed polarity time intervals (RP, also called direct current electrode positive, DECP), oxide film on the weld surface is cleaned out due to cathodic cleaning, meanwhile, loss of tungsten electrode decreases. In the keyhole mode of VPPA welding, four forces determine the formation of the keyhole within the weld pool. They are arc pressure, surface tension, buoyancy, and electromagnetic force[5-6]. Arc pressure and surface tension belong to surface force, while buoyancy and electromagnetic force belong to body force. These four forces determine the formation of the keyhole within the molten metal during the welding. Therefore, arc pressure is one of the most important factors to VPPA welding, especially to the welding of the keyhole mode. DAI, et al[7], applied the orthogonal experiment to discuss the effect of welding parameters on the pressure of direct current(DC) plasma arc with a pressure transducer, the experimental results showed that the welding current is prior to the arc pressure in all of the tested welding parameters including with the welding current, gas flow rate, tungsten set-back and nozzle stand-off. JIA, et al[8], measured the radial distribution of the arc pressure of gas tungsten arc welding(GTAW) with a U-tube barometer, and concluded that the arc pressure of GTAW is not the Gaussian distribution, but the exponential distribution. FAN, et al[9] , used a novel two-liquid U-tube barometer to measure the arc pressure of GTAW， and discussed the

* Corresponding author. E-mail: qaz54809@sina.com
This project is supported by Key Project of Natural Science Foundation of China (Grant No.50735006), National Basic Research Program of China(973 Program, Grant No. 2007CB607601), and General Project of Natural Science Foundation of China (Grant No.50675223).

influence of tungsten shape, argon flow rate and welding current on TIG arc pressure. There are many reports on experimental and theoretical analysis about arc pressure of GTAW and DC plasma arc welding. But few researchers pay their attention to studying VPPA pressure. HAN, et al[10], discussed the effects of tungsten set-back, plasma gas flow rate, welding currents and welding frequency on VPPA pressure with the pressure transducer, but the influence of these parameters was not compared. Therefore, in order to know more details about VPPA pressure, experimental analysis is a significant research for VPPA welding.

In this study, VPPA pressure with different welding parameters was measured by using U-tube barometer in comparison with the results determined by the pressure transducer; the orthogonal design was used to investigate the effects of SP current, RP current, time ratio, plasma gas flow on the arc pressure. And the results were discussed in detail.

## 2　Experimental Instruments and Procedure

A VPPAW-500A power system developed in *National Science and Technology on Remanufacturing Laboratory* (Fig. 1.) was used for the measurement of the VPPA pressure. The power system includes a pilot-arc power and a main arc power. In fact, the pilot-arc power is a small DC power which a positive pole “+” and a negative pole “–” joined with the nozzle and the tungsten electrode of welding torch, respectively. The two poles of the main arc power are in circuit with the tungsten electrode and the water-cooled copper plate. Firstly, non-transferred arc is stricken by the pilot-arc power through the high-frequency striking-arc mode; secondly, the main arc power works, meanwhile, pilot-arc power is shut off. Once VPPA is stricken, the measurement of the pressure could begin.

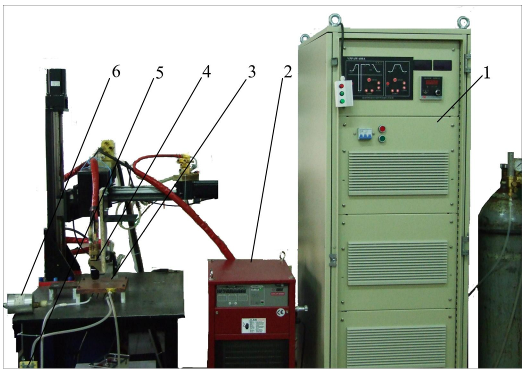
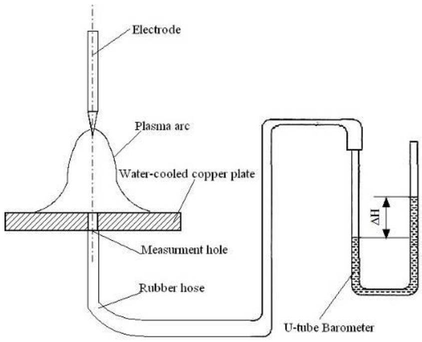


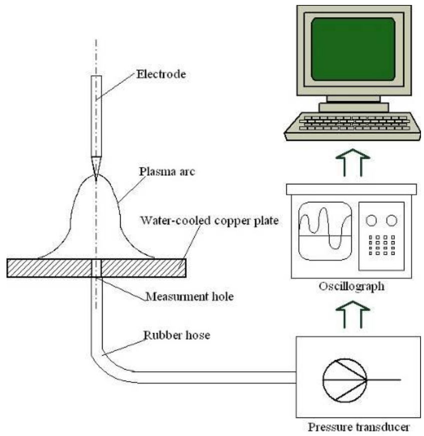

Fig. 1.　Experimental apparatus of VPPA pressure

1.VPPAW-500A power system; 2.water-cooling system; 3.plasma torch; 4.copper plate; 5.U-tube barometer; 6.YB005-01 transducer

For measuring the arc pressure with nonconsumable electrode, two approaches were used: pressure transducer method and U-tube barometer method (Fig. 2.). Moreover, in 1970s, Russian researchers tried to apply the balance to measure the arc pressure. There are many advantages of pressure transducer in the measurement of VPPA pressure, for example, high analysis speed, rapid response, high sensitivity and automatic recording, and so on. Unfortunately, corresponding disadvantages exist, such as low anti-interference, high deviation of the result due to the relative delay of experimental apparatus. However, the U-tube barometer method has many advantages, for example: simple apparatus and principles, high anti-interference, recording experimental data conveniently. But the response of U-tube barometer is insensitive[8-9]. It can only record the average value because the VPPA pressure fluctuates in the range of millisecond. In this paper, the experiments focused on the influence of four welding parameters to VPPA pressure, so average pressure used was enough.




(a) U-tube barometer method




(b) Pressure transducer method

Fig. 2.　Schematic of two measurement methods of arc pressure

VPPA pressure was measured using by YB005-01 transducer, which is manufactured by *Institute of System Engineering, China Academy of Engineering Physics*, measurement range of 0.05 MPa. The oscillograph applied to capture the waveform is MS-6034A manufactured by Agilent Technology. The range of U-tube barometer is from –3kPa to +3 kPa. Argon was applied to plasma gas. SER #376 Plasma Torch is used as the VPPA welding torch; the stand-off between the torch and the copper plate is 4mm; the diameter of the orifice is 3.2 mm. The diameter and the setback of the tungsten-$La_2O_3$ electrode is 4mm and 3mm respectively.

## 3 Orthogonal Experimental Results

VPPA pressure is influenced by many welding parameters such as welding currents, plasma gas flow rate, and time ratio of SP to RP, and so on. In order to evaluate the most important factors, an orthogonal design is used to analyze the effects of some factors to VPPA pressure, as shown in Table 1. According to actual VPPA welding parameters, there are four parameters in Table 2: A is SP current（$I_{SP}$）, B is RP current （$I_{RP}$）, C is time ratio （$t_{SP}$:$t_{RP}$）, D is plasma gas flow rate($q$).

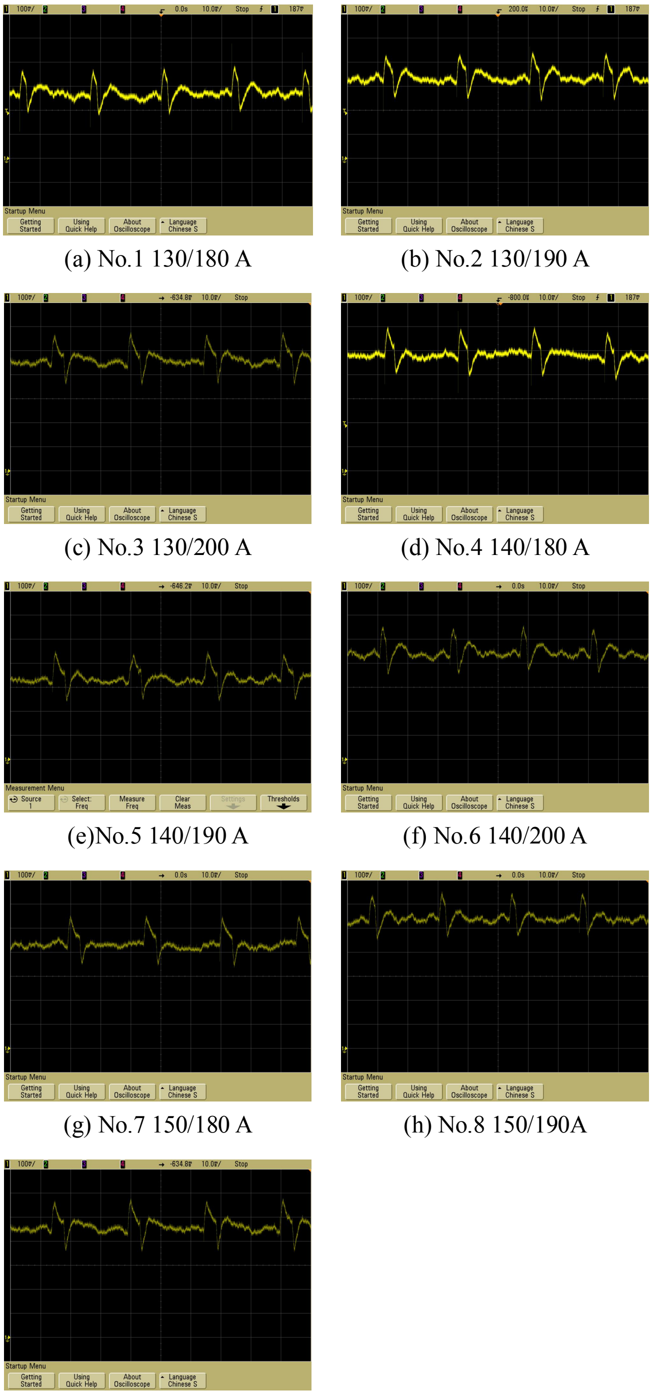
**Table 1 Experimental design of VPPA pressure**

| No. | A | B | C | D |
|---|---|---|---|---|
| | $I_{SP}$/A | $I_{RP}$/A | $t_{SP}$:$t_{RP}$ | $q$/(L • min$^{-1}$) |
| 1 | $A_1$(130) | $B_1$(180) | $C_1$(19:02) | $D_1$(2.0) |
| 2 | $A_1$(130) | $B_2$(190) | $C_2$(19:03) | $D_2$(2.3) |
| 3 | $A_1$(130) | $B_3$(200) | $C_3$(19:04) | $D_3$(2.8) |
| 4 | $A_2$(140) | $B_1$(180) | $C_2$(19:03) | $D_3$(2.8) |
| 5 | $A_2$(140) | $B_2$(190) | $C_3$(19:04) | $D_1$(2.0) |
| 6 | $A_2$(140) | $B_3$(200) | $C_1$(19:02) | $D_2$(2.3) |
| 7 | $A_3$(150) | $B_1$(180) | $C_3$(19:04) | $D_2$(2.3) |
| 8 | $A_3$(150) | $B_2$(190) | $C_1$(19:02) | $D_3$(2.8) |
| 9 | $A_3$(150) | $B_3$(200) | $C_2$(19:03) | $D_1$(2.0) |

In most of the welding processes, time ratio of SP to RP is about 19:4. RP current with 30-80 A is higher than that of SP current. For each measured welding parameter, there are three level values, which are selected on the base of the actual VPPA welding process.

### 3.1 Experimental results of pressure transducer

The waveform graphs of arc pressure measured by the oscillograph are shown in Fig. 3. It could be seen that waveforms rise with increasing of plasma gas flow rate and the welding current. Furthermore, in RP time intervals, arc pressure increases sharply firstly, and then declines rapidly. However, to the best of our knowledge, arc radius expands and arc pressure would drop off in RP time intervals. According to measurement range of the pressure transducer, 100 mV in waveform graphs means to 1 kPa. After treatments to these waveforms, the measurement results are input to the orthogonal analysis. The results are shown in Fig. 4 and Table 2.



(a) No.1 130/180 A (b) No.2 130/190 A

(c) No.3 130/200 A (d) No.4 140/180 A

(e)No.5 140/190 A (f) No.6 140/200 A

(g) No.7 150/180 A (h) No.8 150/190A

(i) No.9 150/200 A

Fig. 3. waveform graphs of arc pressure measured by the oscillograph

**Table 2. Orthogonal analysis for transducer experiments**

| Analytical items | Results of transducer experiments $p$/kPa | | | |
|---|---|---|---|---|
| | A | B | C | D |
| $T_1$ | 8.859 | 9.271 | 9.970 | 7.511 |
| $T_2$ | 9.090 | 9.490 | 9.517 | 9.401 |
| $T_3$ | 10.295 | 9.482 | 8.756 | 11.331 |
| $m_1$ | 2.953 | 3.090 | 3.323 | 2.504 |
| $m_2$ | 3.030 | 3.163 | 3.172 | 3.134 |

| | | | | |
|---|---|---|---|---|
| $m_3$ | 3.432 | 3.161 | 2.919 | 3.777 |
| $R$ | 0.479 | 0.073 | 0.405 | 1.273 |

In Table 2, $T_i$ is the experimental results of different levels to each factor, and mi is the average. $R$ is the range of each factor,$R$=max{$m_i$}–min{$m_i$}. $R$ reflects the effect of each factor on VPPA pressure.

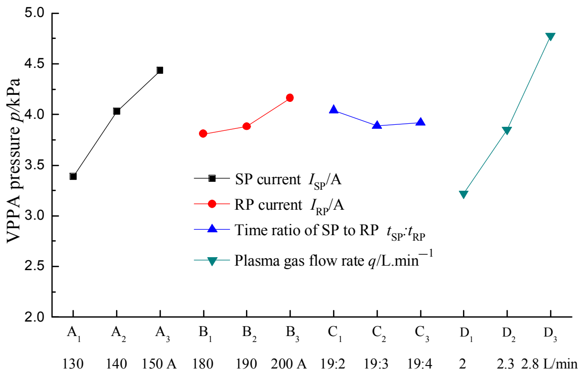



Fig. 4.　Relationship of arc pressure with four factors (results from YB005-01 pressure transducer)

The data curves of $m_i$ of each factor are shown in Fig.4, it could be concluded that the effects of four factors on VPPA pressure in turn are: $q$, $I_{SP}$, $I_{SP}$, $I_{RP}$, and $I_{RP}$. From the range($R$) analysis in Table 2, the same conclusion can be made.

The results by pressure transducer are inaccurate because of relatively high measurement range of the transducer (0−0.05 MPa), low anti-interference, moreover, the average treatments to the waveform would bring errors. In order to obtain more accurate results, VPPA pressure was measured by U-tube barometer.

### 3.2　Experimental results of U-tube barometer

VPPA pressure was measured three times by U-tube barometer. After averaging treatment of these experimental data, the results were input to the orthogonal analysis. The orthogonal results are shown in Table 3 and Fig. 5.

**Table 3.　Orthogonal analysis for U-tube barometer experiments**

| Analytical items | Results of transducer experiments $p$/kPa | | | |
|---|---|---|---|---|
| | A | B | C | D |
| $T_1$ | 8.420 | 9.360 | 10.080 | 7.600 |
| $T_2$ | 9.400 | 9.620 | 9.580 | 9.460 |
| $T_3$ | 10.740 | 9.580 | 8.900 | 11.500 |
| $m_1$ | 2.807 | 3.120 | 3.360 | 2.533 |
| $m_2$ | 3.133 | 3.193 | 3.193 | 3.153 |
| $m_3$ | 3.580 | 3.207 | 2.967 | 3.833 |
| $R$ | 0.773 | 0.0867 | 0.393 | 1.300 |

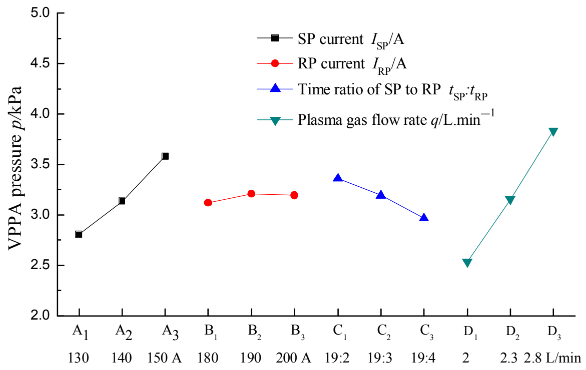



Fig. 5.　Relationship of arc pressure with four factors (results from U-tube barometer)

Comparing results of pressure transducer and U-tube, measurement results are similar. Without regard to errors in experiments, the measurement data of VPPA pressure is convictive.

## 4　Results and Discussion

From Table 2 and Table 3, it can be seen that the range ($R$) of parameters is in the order of $q$, $I_{SP}$, $t_{SP}$:$t_{RP}$, and $I_{RP}$. The results indicate that the influencing degree of four factors on arc pressure in the range of experimental design is as following: $q > I_{SP} > t_{SP}:t_{RP} > I_{RP}$.

Fig. 4 and Fig. 5 show the effects of four characteristic parameters on VPPA pressure. VPPA pressure increase as a function of $q$, $I_{SP}$, $t_{SP}$:$t_{RP}$, and $I_{RP}$,.but the increasing degree caused by different parameters is different obviously. The influence of four factors is the same with the range analysis in Table 2 and Table 3.

Plasma arc is compressed by hydro cooled copper nozzle. During compression process, plasma arc is influenced by three kinds of compressions [11]: mechanical compression, thermal compression and magnetic compression. To arc pressure caused by magnetic compression ($P_r$), some empirical formulas show that $P_r$ is proportional to the square of the ratio of welding current to arc radius[12]:

$$P_r \propto \frac{I^2}{r^2} \tag{1}$$

where $I$ is welding current and $r$ is arc radius. It is obvious that arc pressure increases as function of welding current.

In fact, the mechanical compression and thermal compression are commonly considered as “cooling compression”. The outside temperature of plasma arc column drops because of cooling compression, then the current doesn’t circulate in this part. Therefore, the current density increases with decrease of arc radius, and the action of cooling compression is strengthened as function of plasma gas flow rate. The effects of the plasma gas flow rate on the arc pressure are greater than those of current density.

As the most important factors of plasma arc, pressure and temperature primarily are determined by plasma arc radius, while arc pressure and temperature are influenced by heat flux potential. Some researchers, such as PHILLIPS[13] and WU, et al[14, 15], investigated the dynamic characteristics of alternating current(AC) arc and some conclusions are presented as following. With the increase of current frequency, the fluctuation of heat flux potential in AC arc axis and arc radius decrease. And this tendency strongly affects the arc pressure.

The status of VPPA is similar to AC arc. Therefore, VPPA pressure increases with the increasing of time ratio. The effect of time ratio is even similar to $I_{SP}$. During RP time intervals, the arc pressure drops significantly because of different arc production mechanism and the expanding of arc radius. However, due to relatively time shortage, effect of $I_{RP}$ on arc pressure is the smallest factors.

It is noted that the above analysis on VPPA is different to DAI's researches about the DC plasma arc pressure[7]. DAI concluded that the effect of principal factors on DC plasma arc pressure is the order of welding current and plasma gas flow rate. There are some reasons of difference between DAI's analysis and authors' results in this paper. Firstly, the effects of $I_{SP}$, $I_{SP}$, $t_{SP}$:$t_{RP}$, and $I_{RP}$ on VPPA decrease because of the distortion from RP intervals; Secondly, in the orthogonal design, the variation of $q$ is wider than that of $I_{SP}$.

## 5 Conclusions

(1) VPPA pressure is measured by pressure transducer and U-tube barometer method as well. Although experimental errors exist, however, the results of two methods are similar. Therefore, the experimental data of VPPA pressure is convictive.

(2) Orthogonal design is used to investigate the effects of four characteristic parameters on arc pressure and the data treatments. The influencing degree of four welding parameters on arc pressure is the order of plasma gas flow rate, SP current, time ratio, RP current.

(3) The experimental results above are analyzed. Firstly, cooling compression is strengthened as a function of plasma gas flow rate, which results in the increase of arc pressure. Secondly, arc temperature and radius increase as a function of welding current, so the increasing tendency with plasma gas flow is greater than that of SP current. Furthermore, time ratio of SP to RP is important to heat flux potential (or temperature field), so it can influence the arc pressure. The effects of RP current on the arc pressure are the smallest because RP intervals are less than SP intervals.

### References

[1] JENNEY C L, O'BRIEN A. Welding handbook. Volume 1, Welding science and technology [M]. *American Welding Society*, 2001.

[2] BAYLESS E O. *Variable polarity arc welding*[R]. USA Huntsville : Marshall Space Flight Center, 1991.

[3] SAAD E, WANG H J, KOVACEVIC R. Classification of molten pool modes in variable polarity plasma arc welding based on acoustic signature[J]. *Journal of Materials Processing Technology*, 2006, 174(1–3) : 27–136.

[4] NUNES A C. Variable polarity plasma arc welding on space shuttle external tank[J]. *Welding Journal*, 1984, 63(4): 27s–35s.

[5] TANAKA M, TERASAKI H, USHIO M, et al. A unified numerical modeling of stationary tungsten-inert-gas welding process[J]. *Metallurgical and materials transactions A*, 2002, 33A(7): 2 043–2 052.

[6] TANAKA M, USHIO M, LOWKE J J. Numerical study of gas tungsten arc plasma with anode melting[J]. *Vacuum*, 2004, 73(3–4): 381–389.

[7] DAI Dashan, SONG Yonglun, Zhang Hui, et al. Study on arc force in plasma welding[J]. *Transactions of China Welding Institution*, 2002, 23(2): 5l–54 (in Chinese).

[8] JIA Changshen, XIAO Kemin, YIN Xianqing. Plasma flow force of welding arc[J]. *Transactions of the China Welding Institution*, 1994, 15(2): 101–105. (in Chinese).

[9] FAN Honggang, SHI Yaowu, HUANG Yong, et al. Experimental analysis of the effect of TIG welding arc force[J]. *Welding Technology*, 1995, 24(5): 3–5 (in Chinese).

[10]HAN Yongquan, LU Yaohui, CHEN Shujun, et al. Study on the mechanical characteristic of the VPPAW[J]. *Electric Welding Machine*, 2005, 35(2): 54–57.

[11]NIU Jitai, GUO Wei, GUO Mianhuan, et al. Plasma application in thermal processing of materials[J]. *Vacuum,* 2002,65(3-4): 263–266.

[12]GUO Zengyuan, ZHAO Wenhua. *Arc and thermal plasma*[M]. Beijing: Science Press, 1985 (in Chinese).

[13]PHILLIPS R L. Theory of the non-stationary arc column[J]. *British Journal of Applied Physics, 1967*, 18(1): 65–78.

[14]WU H M, CAREY G F. Numerical Simulation of AC Plasma Arc Thermodynamics[J]. *Journal of Computational Physics*, 1994, 112(1): 24–30.

[15]WU H M, CAREY G F. Nonlinear convective effects on moving boundary AC plasma arcs[J]. *IEEE Transactions on Plasma Science*, 1992, 20(6): 1 041–1 046.

### Biographical notes

JIANG Yi, born in 1978, is currently a PhD candidate at *National Science and Technology on Remanufacturing Laboratory, Academy of Armored Force Engineering, China.* He received his bachelor degree in 2001 from *China University of Petroleum, China.* His research interests include the key techniques of remanufacturing engineering.
Tel: +86-10-66718541; E-mail:qaz54809@sina.com

XU Binshi, born in 1931, is an academician of *Chinese Academy of Engineering* and a professor at *Academy of Armored Force Engineering, China.* His research interests include remanufacturing engineering and surface engineering.
E-mail: xubinshi@vip.sina.com

LU Yaohui ，born in 1970, is an associate professor at *National Science and Technology on Remanufacturing Laboratory, Academy of Armored Force Engineering, China.*. He received his PhD degree from *Beijing Universtiy of Technology, China*, in 2003. His research interests include the plasma arc welding techniques.
E-mail: yaohui.lv@163.com

LIU Cunlong, born in 1980, is a lecturer at *National Science and Technology on Remanufacturing Laboratory, Academy of Armored Force Engineering, China*. He received his master degree in 2009 from *Academy of Armored Force Engineering, China*. His research interests include the plasma arc cladding technique.
E-mail: liucunlong@sina.com

LIU Ming, born in 1979, is a lecturer at *National Science and Technology on Remanufacturing Laboratory, Academy of Armored Force Engineering, China*. He received his master degree in 2007 from Academy of Armored Force Engineering, China. His research interests include the supersonic plasma spraying technique.
E-mail: lmsrpay@sina.com