CHEMICAL ENGINEERING TRANSACTIONS

VOL. 46, 2015

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Peiyu Ren, Yancang Li, Huiping Song

ISBN 978-88-95608-37-2; **ISSN** 2283-9216

DOI: 10.3303/CET1546017

Surface Modification of Stainless Steel Using an Atmospheric Pressure Plasma Arc Driven by an External Transverse-Alternating Magnetic Field

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An experimental cleaning system for surface modification was developed. It consisted of a plasma torch with a DC power supply to generate an atmospheric pressure plasma arc, two field coils with an AC power supply to generate an external transverse-alternating magnetic field, a moving system for the plasma arc cleaning stainless steel samples. The external transverse-alternating magnetic field was applied to the atmospheric pressure plasma arc to widen its cross section and uniform its energy density distribution. Effects of process parameters, such as arc currents, gas flow rates, distances from the torch nozzle to the substrate, scanning velocities, and magnetic flux densities on the cleaning quality were investigated. The experimental results demonstrate that it is feasible to improve cleaning quality of the atmospheric pressure plasma arc with the external transverse-alternating magnetic field, which can expand the cleaning area and uniform the energy density distribution upon the substrates. As well as, the experimental results show that the cleaning region and cleaning quality of plasma arc are significantly influenced by the process parameters.

1. Introduction

Atmospheric pressure plasma arc (APPA) in a non-transferred type is used widely as a convenient method to material processing (Mandilas, et al. (2013); Yin, et al (2007); Sarani, et al. (2012)), such as welding, surface quenching, surface conditioning and surface cleaning, etc. APPA cleaning is a novel cleaning means and has the advantage of the environment, cost and operation (Meng, et al. (2008)). Compared to traditional cleaning methods such as mechanical cleaning by sand blasting (Pal and Kumar (2011)), chemical cleaning using organic or inorganic solvents (Howard, et al. (2013)), ultrasonic cleaning and vacuum plasma cleaning (Jüschke and Koch (2012); Fuchs, et al. (2012)), APPA cleaning is easier to set-up and operation (Asad, et al. (2009); Moon, et al. (2006)) than vacuum plasma arc cleaning. This cleaning method is also friendly to the environment.

In this method, APPA focuses on the substrate surface and generates energy enough to bring about reactions, including physical shock, thermal spalling and chemical activation decomposition. Contaminant such as the oxide or organic compound on the sample surface is heated, decomposed and evaporated by the plasma arc spots. The contaminant layer is completely cleaned without melting the substrate surface, by choosing proper process parameters. Since the density of reactive species such as charged particle, functional group is high, APPA for surface cleaning is used to improve the hydrophilic surfaces on metals, polymers, plastics (Chen, et al. (2015)). Wettability is one of the most significant properties of hydrophilic or hydrophobic surfaces (Chen, et al. (2008)). In this field, the contact angle is used to investigate a high degree of cleaning quality of APPA (Yuan and Lee (2013)).

Because of electro-magnetic and thermal contraction effects, energy concentration of APPA is confined in a narrow region. Though this property can obtain high temperature for welding or cutting, it is not convenient for material surface cleaning using APPA. APPA cleaning required a uniform and broad plasma arc. In order to obtain a desired plasma arc for material surface cleaning, some methods were carried out to expand the heating area and control the distributions of energy density in the cross-section of the plasma arc by an external magnetic field. Akiho, et al. (2014) succeeded in controlling the area of the plasma arc by applying an

Please cite this article as: Dong X.J., Meng J.B., Wei X.T., Liu W.H., 2015, Surface modification of stainless steel using an atmospheric pressure plasma arc driven by an external transverse-alternating magnetic field, Chemical Engineering Transactions, 46, 97-102 DOI:10.3303/CET1546017

alternating magnetic field with a sinusoidal wave. They investigated the plasma arc driven by the external magnetic field, and found that the heating area of plasma arc decreased with the increase of the swirling motion. Yamamoto, et al. (2014) succeeded in applying an alternating magnetic field to drive a transferred arc movement and to heat a larger metal surface. Then, they developed a theoretical model on the plasma arc driven by an alternating magnetic field. This practical model was useful to predict energy densities with various flux densities of the alternating magnetic field. Matsumoto, et al. (2010) applied a transverse magnetic field to a DC plasma arc, carried out theoretical and experimental investigations. They found that the heat flux density of the driven plasma arc increased with the decrease of the magnetic flux density. Meanwhile, the result showed that the distribution of the energy density varied with various types of electric currents, such as triangular and sinusoidal wave forms. Authors (Meng, et al. (2013); Dong, et al. (2014)) supplied an external transverse-alternating magnetic field for a combined plasma arc to investigate the movement of plasma arc. Theoretical and experimental investigations both showed that the movements and energy density distributions were affected considerably by process parameters, such as arc currents, gas flow rates, magnetic flux densities. The oscillatory region and energy density of the combined plasma arc varied with parameters. For example, the oscillatory region reduced with the increase of gas flow rates and working arc currents. Increasing gas flow rates or working currents were to flatten the energy density of the combined plasma arc on the sample surface.

In this paper, a cleaning system of APPA is developed. In this system, an external transverse-alternating magnetic field is introduced into APPA to generate an oscillatory movement. This oscillating plasma arc can be considered as a uniform heat source for cleaning a large metal surface. Since wettability is an important obtained properties of cleaned metal surface, cleaning quality can be obtained using water contact angle measurement machine. This study is intended to reveal the relationship between contact angles and the process parameters, such as arc currents, gas flow rate, magnetic flux density, and the distance from the nozzle outlet to the sample surface. This relationship is quite significant for the application of external transverse-alternating magnetic field to control the heating area and the energy density distribution of APPA.

2. Experiments

2.1 Experimental setup

As shown in Figure 1, a cleaning system of APPA driven by an external transverse-alternating magnetic field is presented. The experimental system consists of a non-transferred arc generator with a tungsten cathode, a DC power supply to generate APPA, a generator with two field coils, two magnetic irons, and an AC power supply to generate a magnetic field. The magnetic field is imposed perpendicularly to APPA. The current of DC power supply is constant. The AC power supply is operated in a triangular wave current. The frequency of AC power supply is 50 Hz, and the coil current can be supplied from 0.4 A to 1.2 A. The width and thickness of magnetic irons are 4 mm, 6 mm, respectively. Ar is a typical gas to provide relatively uniform and large plasmas for APPA. However, the temperature in Ar plasma arc is high. Oxygen is a gas for producing chemical reactive particles and often used in surface modification. Consequently, a mixed gas (Ar, O_2) is fed into the plasma arc generator at various gas flow rates. Samples used in this cleaning experiment are commercial available stainless steel (SUS304) samples covered lubricants.

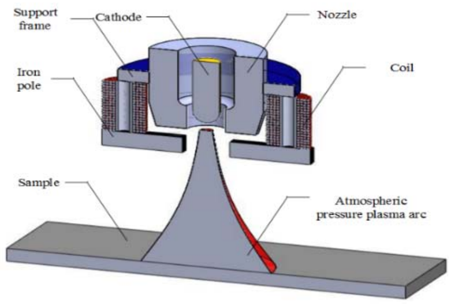

Figure 1: Schematic illustration of the cleaning system

2.2 Experimental conditions

The cleaning experiments are carried out using APPA driven the external transverse magnetic field. In order to measure the cleaned surface, deionized water is introduced, and contact angles are measured using a commercial optical contact angle meter. A following Descartes coordinate system is used for this measurement. SUS304 plate serving as the cleaned samples expands in the x-y plane. The coordinate origin is located at the center of SUS304 samples. In addition, the movement of the whole cleaning system is parallel to the y axis.

The whole cleaning system of APPA driven by the external transverse magnetic field can be divided into a plasma arc generator and a magnetic field generator. In this consideration, the external transverse magnetic field is imposed along the x direction. When the DC power supply is supplied for the nozzle and tungsten cathode, and the mixed gas is fed into the generator, APPA is to be generated. Then the external transverse magnetic field brings out the oscillatory movement of APPA upon the surface of stainless steel sample. The shape of APPA driven by electro-magnetic forces is like a bell. In addition, coil diameter and its length are 44, 38 mm, respectively. The time t of plasma from the nozzle to the sample surface can be obtained from D/v_0, where v_0 is the plasma velocity along z direction. If a half period of the magnetic field is much greater than t, the external transverse-alternating magnetic field can be assumed constant. From previous study of authors (Meng and Dong (2011)), it can be found that T is less than 0.68 ms, and accord with the relation of $t \ll 1/2f$, where f is the frequency of transverse-alternating magnetic field. Therefore, the oscillatory movement of APPA is independent of the magnetic field frequency in this paper.

3. Experimental results and discussion

3.1 Effects of plasma arc currents on contact angles

Under the same operating conditions (Q=6 L/min, D=7 mm, v=60 mm/s), experiments are carried out. In these experiments, four different arc currents are inputted (I=10, 15, 20, 25 A). Figure 2 shows the distributions of contact angles upon the cleaned sample surfaces with and without the external transverse-alternating magnetic field (B=0, 15 mT), respectively.

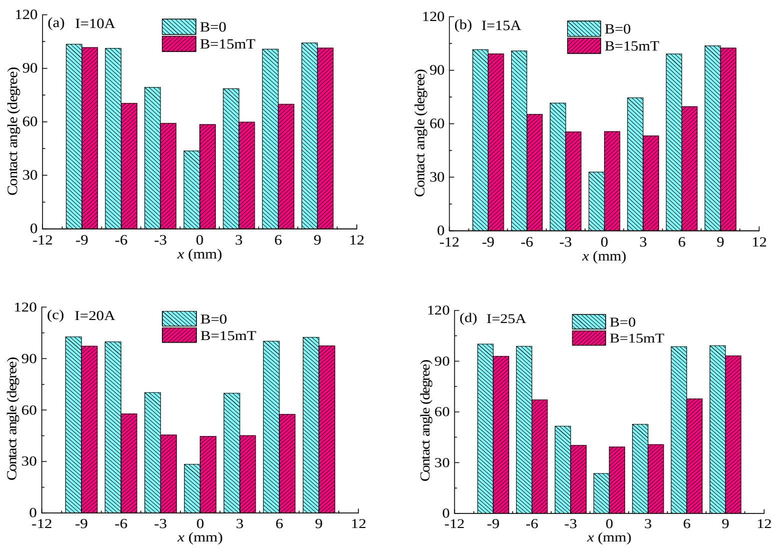

Figure 2: Contact angles distributions along x direction with different plasma arc currents

As shown in Figure 2(a-d), the contact angles' distribution near the centre of APPA is more uniform than that of cleaned surfaces with no external magnetic field. Contact angles on the centre of plasma arc decrease with the increase of the plasma arc current. This reason is that Lorentz force increases with the increase of the plasma arc currents, and improves the oscillating movement of APPA driven by the external transverse magnetic field. As expected, the energy density distribution is wider. Therefore, the distributions of measured contact angles are more uniform. On the other hand, increasing the arc currents, the energy densities at the center of the plasma arc are more concentrated. The contaminants at the sample surface are more prone to be cleaned by APPA. Consequently, the contact angles measured on the centre of the sample surface decrease with the increase of plasma arc current.

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3.2 Effects of mixed gas flow rate on contact angles

Under the same operating conditions (I=15 A, D=7 mm, v=60 mm/s), experiments are carried out. In these experiments, four different mixed gas flow rates are imposed (Q=4, 6, 8, 10 L/min). Figure 3 shows the distributions of contact angles upon the cleaned sample surfaces with and without the external transverse-alternating magnetic field (B=0, 15 mT), respectively.

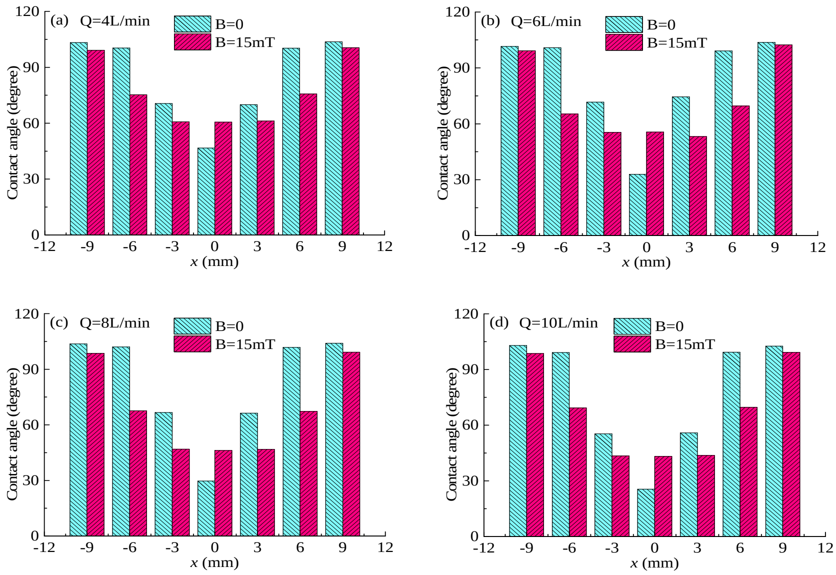

Figure 3: Contact angles distributions along x direction with different mixed gas flow rates

From Figure 3(a-d), it can be found that the contact angles distribution on the cleaned sample surface along x direction is more uniform than that of atmospheric pressure plasma arc with no external magnetic field. Increasing mixed gas flow rates, the contact angles at the centre of the plasma arc are to decrease. This reason is that the plasma velocity across the external magnetic field is accelerated by the mixed gas flow rate. It causes the time of plasma passing through the magnetic field to be shortened, and reduces the amplitude of the arc oscillating movement. Compared with the energy density distribution of plasma arc with no magnetic field, that of APPA with *B*=15 mT is more uniform. In addition, increasing the arc currents, the plasma arc is so stable that it is difficult to be flattened. As a result, with the increase of plasma arc current, the energy density is more concentrated, and the contact angles measured on the centre of the sample surface decrease.

3.3 Effects of the distances between nozzle and sample surface on contact angles

Under the same operating conditions (*I*=15 A, *Q*=6 L/min, *v*=60 mm/s), experiments are carried out. In these experiments, four different distances from the nozzle to the sample surface are imposed (*D*=5, 6, 7, 8 mm). Figure 4 shows the distributions of contact angles upon the cleaned sample surfaces with and without the external transverse-alternating magnetic field (*B*=0, 15 mT), respectively.

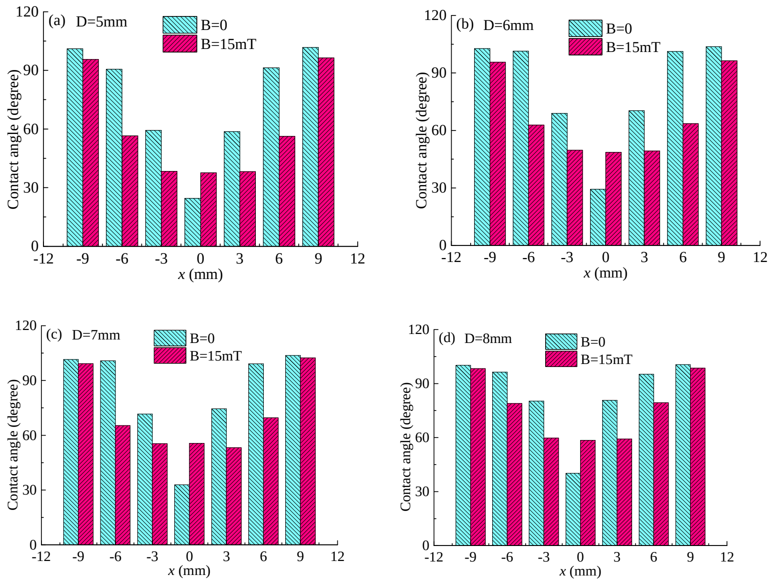

Figure 4 Contact angles distributions with different distances from the nozzle to sample surface

Figure 4(a-d) show a comparison of the contact angles' distribution under *B*=15 mT with the measured that of APPA cleaning under *B*=0 mT. It can be seen that the former is more uniform than the latter. Furthermore, the contact angles at the centre of the plasma arc decrease with the increase of the distances from the nozzle to the sample surface. This reason is that the increasing distances result in more passing time of plasma through the external magnetic field. It means to increase the oscillating region and to expand the diameter of the energy density distribution. Consequently, the energy flux at the centre of the plasma arc is spread into the whole cleaning region. As a result, with the distances increasing, it is much easier to flatten the energy density of APPA driven by the external transverse-alternating magnetic field, and to uniform the measured contact angle distributions along x direction.

3.4 Effects of the scanning velocities on contact angles

Under the same operating conditions (*I*=15 A, *Q*=6 L/min, *D*=7 mm), experiments are carried out. In these experiments, four different scanning velocity of APPA upon the sample surface are imposed (*v*=20, 40, 60, 80 mm/s). Figure 5 shows the distributions of contact angles upon the cleaned sample surfaces with and without the external transverse-alternating magnetic field (*B*=0, 15 mT), respectively.

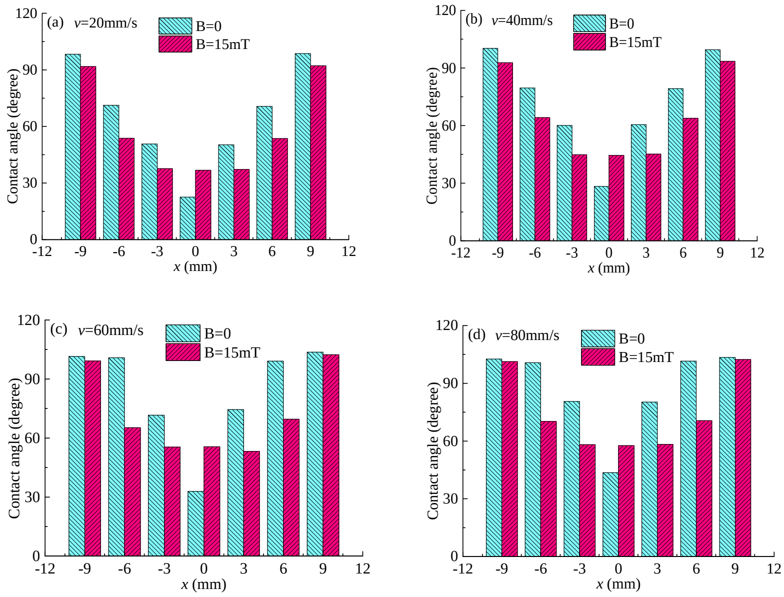

Figure 5 Contact angles distributions with different scanning velocity of plasma arc

As shown in Figure 5(a-d), the contact angles' distribution near the centre of APPA is more uniform than that of cleaned surfaces with no external magnetic field. The contact angles on the centre of the plasma arc increase with the increase of the scanning velocity of APPA. This reason is that the time of plasma arc cleaning the metal sample becomes smaller with the increase of scanning velocities. It leads to less energy flux dispersed throughout the cleaning region of the sample and more residual contaminants staying on the cleaned surface. As expected, decreasing the scanning velocities, the energy flux becomes enough to remove contaminants from the sample surface. Consequently, contact angles measured on the centre of the sample surface increase with the increase of scanning velocity of atmospheric pressure plasma arc.

4. Conclusions

The SUS304 stainless steel substrates were successfully cleaned by APPA. It was efficient to uniform the energy density distribution, to improve the cleaning quality of APPA driven with an external transverse-alternating magnetic field. The region of oscillating movement and the contact angle on the sample surface increases with the enhancement of external transverse-alternating magnetic flux densities. Less arc current or mixed gas flow rates, more distances from the torch nozzle to the sample surface can cause oscillating areas and contact angles to increase. In addition, contact angles measured on the centre of the sample surface increase with the increase of scanning velocity of APPA.

Acknowledgments

Part of this work is supported by the National Natural Science Foundation of China (Grant No. 51205237 and 51375284), the natural science foundation of Shandong Province (ZR2014EEQ019), the young teacher development support plan of Shandong University of Technology, and young college teachers international visiting scholars plan of Shandong Province.

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