Atmospheric pressure Ar plasma jet excited by high-voltage pulse source and the treatment of SMC material

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Abstract: Sheet molding compound (SMC) material has been widely used in switch cubicle due to its electrical performance and mechanical properties. The effect of the atmospheric pressure Ar plasma jet on the surface of SMC material has been studied. In this paper, the Ar plasma is generated by the ring-needle electrode in a dielectric tube and the argon gas is used as the feed gas. After treated by Ar plasma jet, the water contact angle of SMC material increase apparently. From the SEM results, the impurities on SMC material are cleaned and the surface roughness increases a lot. The FTIR results show that the C-O and C=O chemical bonds increase because of the treatment of high-energy particles associated with oxygen. Furthermore, the XPS results show that after treated by Ar APPJ, the O increase while the C decrease.

Keywords: SMC material, Ar plasma jet, water contact angle, SEM, FTIR, XPS

1. Introduction

Sheet molding compound(SMC) material has attached considerable attention due to its electrical performance, mechanical properties, heat resistance, chemical resistance and dimensional stability. Tsutao Katayama *et al.* [1] studied the expansion history of the specimens caused by the material internal pressure in curing in order to develop and design the curing system applied the SMC roll-shaped curing oven. Sarah Boylan *et al.* [2] discovered that Overall the tensile strength of SMC increases as the fiber length increases. The research of Li Jian presents the best conditions for the LPMC molding process [3]. In electrical field, SMC has been widely used in switch cabinet as the insulating cell.

Atmospheric pressure plasma jet(APPJ) has received increasing attention for its potential in applications such as medical treatment and surface modification [4-6]. The reactive species such as oxygen generated by the plasma are considered to be the main component that make the APPJ hot in these applications. The plasma can be generated by the ring-needle electrode in a dielectric tube and the noble gas such as He or Ar is used as the feed gas.

To data, many experiments and simulations have concentrated on the atmospheric pressure plasma jet [7-10]. Ruoyu Zhou *et al.* [11] studied the plasma length of different applied voltage and rising time of pulse power. They concluded that higher voltage and shorter rising time results in an increase of plume length. Tao Shao *et al.* [12] discovered that the surface flashover voltage of PMMA increase after treated by Ar plasma. A. Van Deynse *et al.* [13] found that a plasma jet working at atmospheric pressure can successfully enhance the wettability of LDPE foils. However, few studies concentrate on the SMC surface modification by the Ar plasma jet. Here we present the results of our experiment.

2. Experimental setup

The experimental arrangement is shown in Fig.1, which is consist of a pulse power supply, APPJ unit and measuring devices. The voltage amplitude is 3.2kV with a frequency of 10kHz, the pulse width is $1\mu s$ and the rising time and falling time are 50ns. A nanosecond pulse power supply (HV-2015, Lingfeng, Xi'an, China) is used to generate the discharge. The APPJ unit contains a quartz tube, a copper needle and a copper ring. The inner radius of the tube is 4mm and the outer radius is 5mm. The copper ring is 6mm wide and is wrapped around the tube. The distance between the needle tip and the ring is 6mm. The needle is connected with the anode while the ring is connected with the cathode. The plasma jet has two parts: the dielectric barrier discharge (DBD) part and the plasma plume outside the tube. Our working gas is argon (purity: 99.9%) with a flow rate of 3slm.

The measuring device contains a oscilloscope (Tektronix MDO3034), a high-voltage probe (Tektronix P6051A), a current monitor (RXN18001),a digital camera (Nikon D5100) and water contact angle tester (JGW-360A, Chenghui, Shandong, China). The SMC material is placed 1cm away from the tube vertically. The thickness of SMC material is 3mm.

3. Experimental results and discussion

A. Electrical characterization

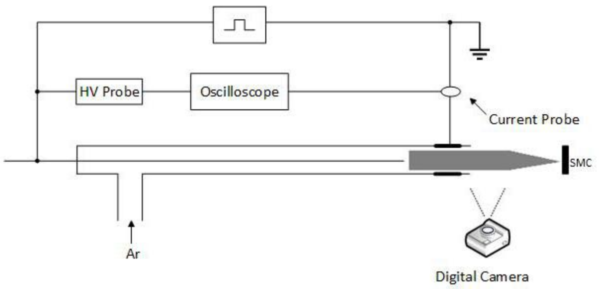

Fig.1. Schematic of APPJ setup.

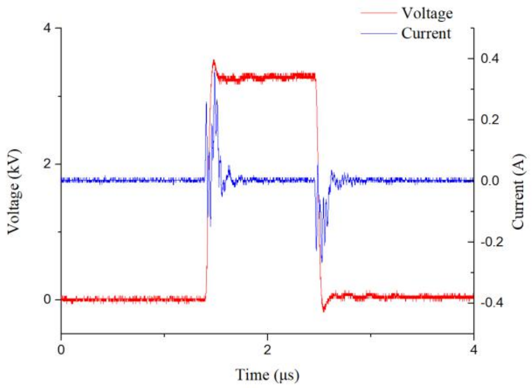

Fig.2. Voltage and current waveforms.

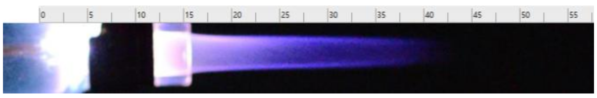

Fig.3. Discharge image of Ar plasma jet

When the applied voltage amplitude is 3.2 kV, the frequency is 10kHz, the distance between the tube orifice and SMC is 1cm and gas velocity is fixed at 3 L/min, the voltage current waveform and current waveform of Ar plasma jet discharge are shown in Fig.2. From the picture we can see that in the rising edge of the voltage there is a positive current peak in the falling edge there is a negative current peak. The value of the positive peak of current is 364mA and the negative current peak is 268mA. The negative peak is caused by the reverse electric field from the accumulated charge in the quartz tube [11].

The discharge image of atmospheric pressure Ar plasma jet is displayed in Fig.3. The colour of the plasma is purple and the length of the jet is about 42mm. The shape of the plasma is stable because in low voltage the mode of discharge is glow discharge.

B. Water static contact angles

The water static contact angles of untreated and treated SMC material are shown in the Fig 4. They are measured by the water contact angle tester. From Fig.4, The water contact angle of untreated SMC is 59.9° while the angle of treated SMC is 29.94°. The water contact angle decrease significantly after treated by Ar plasma jet. There are two reasons for the increase of SMC hydrophilia: first of all, the Ar plasma is consist of many energetic particles. SMC is etched by the plasma and the surface of SMC becomes more rough. Secondly, the atmospheric pressure Ar plasma contains many active oxygen groups, which are highlyhydrophilia groups. These will be confirmed by the subsequent results.

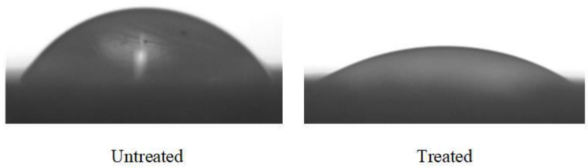

Fig. 4. Water Static contact angles of untreated and treated SMC material.

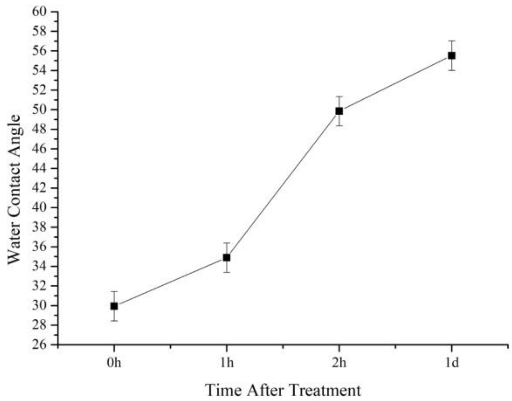

Fig.5. The water contact angles of different time (0h, 1h, 2h,1d) after treated by Ar plasma

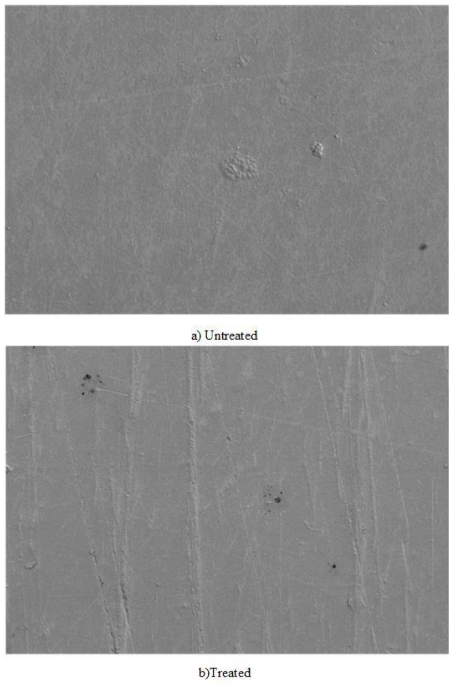

Fig.6. SEM results of untreated and treated SMC

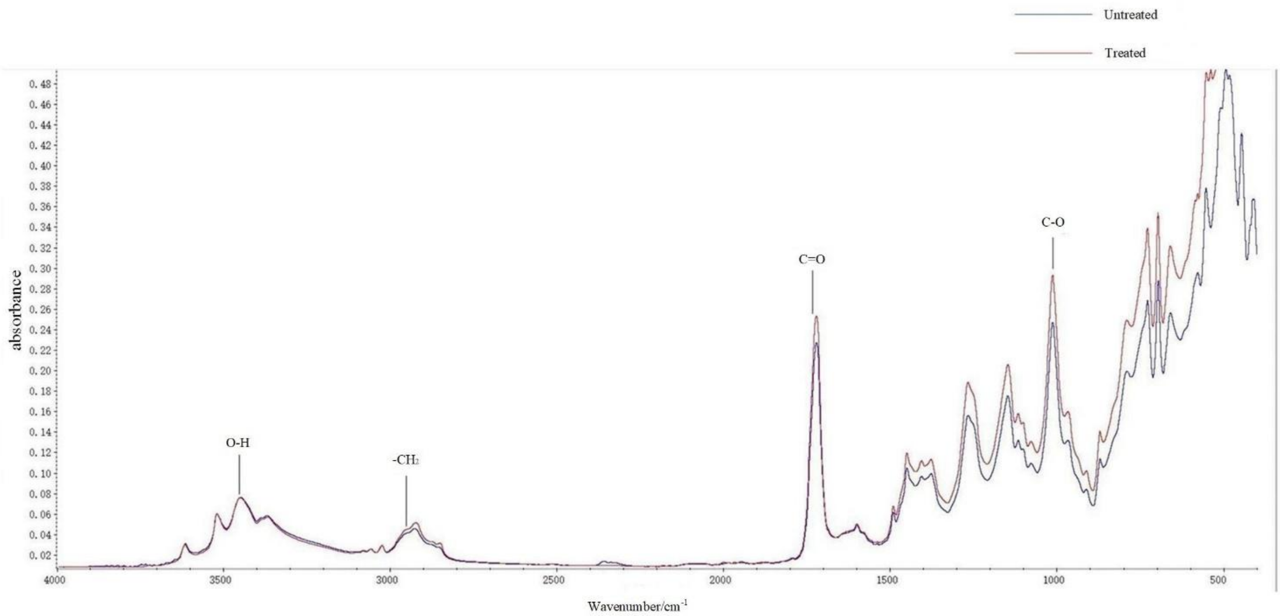

Fig.7. FTIR results of untreated and treated SMC material

The water static contact angles of different time after treated are shown in Fig.5. From Fig.5 we can see that as time goes on, the contact angle recovers gradually. And when the time comes to 1 day after treated by the Ar plasma, the contact angle rises to 55.2°. The water contact angle recovers because when the treated material is placed in the air, its surface properties will degrade to some extent, which is called "aging effect" [14]. The water contact angle recovers about 25° because the treatment time of our experiment is short and the surface composition is not particularly stable.

C. Surface morphology analysis

The surface properties of solid materials are mainly determined by the chemical composition and physical structure of the surface. Therefore, in the process of Ar plasma jet modifying SMC surface and increasing its hydrophilicity, the chemical composition and physical structure of SMC surface will inevitably change accordingly. Therefore, SEM, FTIR and XPS were used to study the changes of surface morphology and chemical composition of SMC before and after surface modification by atmospheric pressure Ar plasma jet.

SEM observation results of SMC surface before and after treatment are shown in Fig.6. Before treated by the Ar plasma, the surface of untreated SMC is relatively smooth and homogenous, and there are some impurities on the surface. After treatment, the surface is full of irregular protrusions. Impurities on SMC surface are cleaned and the surface roughness increases a lot, which is caused by plasma etching and sputtering on SMC surface.

D. Changes in surface chemical composition

While studying the chemical changes of SMC surface before and after surface modification, we used FTIR and XPS to analyse the changes of chemical bonds, chemical groups and chemical components on SMC surface before and after the surface treatment. The results of FTIR were shown in Fig.7.

From the results, SMC material has several characteristic peaks: The O-H peak from 3150cm^{-1} to 3650cm^{-1}, C-H peak at 2800-3100cm^{-1}, C=O peak associated with COOH at 1740 and C-O peak of alcohols and ethers at about 1100cm^{-1}. As we can see, the O-H peak and C-H peak change little after treated by the Ar plasma. However, the C=O and C-O increase obviously comparing

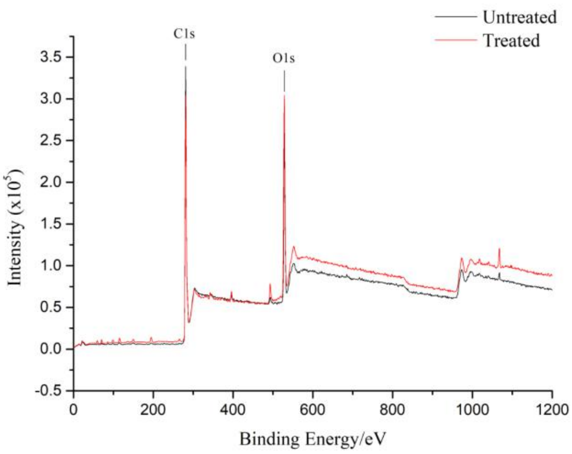

Fig.8. XPS full scan spectra of untreated and treated SMC material

to the untreated SMC material. The reason is that the atmospheric pressure Ar plasma consists of high-energy particles, which break the chemical bonds on the SMC surface and many free radicals exist. Free radicals recombine and form new chemical structure with O on the surface of SMC, which results in the increase of C-O and C=O chemical bonds. And the increase of C-O and C=O chemical bonds lead to the increase of hydrophilicity of SMC.

The chemical composition of SMC surface before and after Ar plasma jet treatment is analysed by XPS. The results of XPS are shown in Fig.8. The SMC material mainly has two peaks: C1s peak and O1s peak. After surface modification, the peak value of C1s on the surface decreased significantly, while the peak strength of O1s increased. Because of the treatment of APPJ, the chemical bonds associated with C are broken by the high-energy particles. The free radicals form new chemical bonds consist of oxygen such as C-O and C=O which leads to the decrease of C and increase of O. The results of XPS is consistent with the results of FTIR.

4.Conclusion

Atmospheric pressure Ar plasma jet has been used for the surface modification of SMC material. The conclusions are as follows:

1. The hydrophilicity of SMC increases obviously. However, the hydrophilicity recovers when the treated material is placed in the air for a long time. The reason is that surface properties of SMC will degrade to some extent in the ambient environment, which is called "aging effect".

2. After the surface modification of Ar plasma jet, the surface properties of SMC material have changed. From the SEM results, the surface is full of irregular protrusions. Impurities on SMC surface are cleaned and the surface roughness increases a lot. The oxygen content on the surface of SMC increases significantly, and active groups containing oxygen are introduced into the surface after APPJ modification.

3. The main effects of plasma on SMC surface are as follows: removing surface impurities, surface etching and forming new chemical structures. The high-energy particles in the plasma break some chemical bonds on the SMC surface so that many free radicals exist. Free radicals recombine and form new chemical structure with O on the surface of SMC such as the C=O and C-O chemical bonds, which results in the increase of hydrophilicity of SMC.

4. References

[1] Katayama T, Hakotani M, Shinohara M, et al. Journal of Materials Processing Technology, **155-156**, 1577-1582 (2004).

[2] Boylan S, Castro J M. Journal of Applied Polymer Science, **90**, 2557-2571 (2010).

[3] J. Li, Z. Huang, K. Zhang. Chinese Journal of Mechanical Engineering, **24**, 452-459 (2011).

[4] R. Jijie, V. Pohoata, and I. Topala, Appl. Phys. Lett. **101**, 144103 (2012).

[5] E. Stoffels, I. E. Kieft, and R. E. J. Sladek, J. Phys. D: Appl. Phys. **36**, 2908 (2003).

[6] K. R. Stalder, D. F. Mcmillen, and J. Woloszko, J. Phys. D: Appl. Phys. **38**, 1728 (2005).

[7] N. Mericam-Bourdet, M. Laroussi, A. Begum, and E. Karakas, J. Phys. D: Appl. Phys. **42**, 055207 (2009).

[8] X. Lu, G. V. Naidis, M. Laroussi, and K. Ostrikov, Phys. Rep. **540**, 123 (2014).

[9] J. P. Boeuf, L. L. Yang, and L. C. Pitchford, J. Phys. D: Appl. Phys. **46**, 015201 (2013).

[10] X. Y. Liu, X. K. Pei, X. P. Lu, and D. W. Liu, Plasma Sources Sci. Technol. **23**, 035007 (2014).

[11] R. Zhou, F. Liu, L. Wang, X. Li and Z. Fang, AIP Advances. **8**, 115004 (2018).

[12] T. Shao, Y. Zhou, C. Zhang, W. Yang, Z. Niu and C. Ren, IEEE Trans. Dielectr. Electr. Insul. **22**, 1747-1754 (2015).

[13] A. Van Deynse, P. Cools, C. Leys, N. De Geyter and R. Morent, Applied Surface Science. **328**, 269–278 (2015).

[14] Z. Hao, S. Ji, Y. Song, Journal of Xi′an Jiaotong University. **48,** 0253-987X (2014).