Effect of N2/O2 inclusion on polymer ablation and spallation phenomena from polyamide during thermal plasma irradiation

Effect of N_2/O_2 Inclusion on Polymer Ablation and Spallation Phenomena from Polyamide During Thermal Plasma Irradiation

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***Abstract*—This paper reports enhancement effect of N_2/O_2 gas addition in thermal plasma irradiation on the spallation phenomena from polyamide-66 (PA66) specimens with water absorption. The polyamide materials are widely used, for example, in low-voltage circuit breakers and arcing horns as ablation material. In such devices, the polymer is often contacted with arc discharges to be ablated, which increases the arc current interruption ability of the circuit breakers. In our previous experiments, not only ablation but also spallation phenomena had been found to occur from PA66 specimens with water absorption by Ar thermal plasma irradiation. The present work was conducted to investigate effect of N_2/O_2 inclusion in the irradiating thermal plasma on the occurrence of spallation phenomena because the air circuit breaker was used in air. Relative oxygen admixture ratio to N_2 was changed from 0% to 100% with a fixed heat flux irradiated to PA66 specimens. Results indicated that O_2 inclusion effectively promotes the frequency of spallation particle ejection from PA66 specimen with 3 wt% water absorption.**

***Index Terms*—spallation particle, polyamide material, polymer ablation, induction thermal plasma, circuit breaker, arcing horns**

I. Introduction

Polymer materials are widely used for an electrical insulation or a gas flow nozzle in low-voltage or high-voltage circuit breakers. In a current interruption process, an arc plasma is formed between the electrodes in the circuit breaker. The arc plasma may contact the polymer materials, inevitably involving polymer ablation. Ablated vapor originating from polymer ablation can generate a pressure rise and then strong gas flow, which can cause cooling and shrinkage of the arc plasma. Effective utilization of such polymer ablation is expected to enhance the arc interrupting capability of the circuit breaker. However, the interaction between polymer materials and the arc plasma is much complicated involving a large exchange in mass, momentum and energy between them.

In our previous works, an Ar induction thermal plasma was directly irradiated to seven kinds of polymer materials such as polytetrafluoroethylene (PTFE) and polyamide-66 (PA66) to fundamentally study the interaction between the thermal plasma and the polymers [1], [2]. A high-speed video camera was used to observe the dynamics of ablated vapor from the polymers. As a result, we had found out that not only ablated vapor but also "spallation particles" were ejected from water-absorbed polyamide materials surface [1], [2]. Such spallation particles may possibly penetrate the arc discharge core deeply, and then they will be ablated there to decay the arc temperature. This may enhance the interruption ability of the circuit breakers. In addition, we found from another our experiments that the occurrence of spallation phenomena from PA66 specimen was much related with water absorption amount [3].

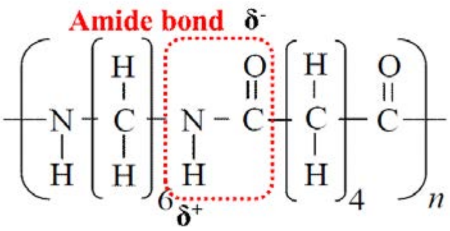


Fig. 1. Structural formula of polyamide-66 (PA66).

The present paper reports experimental results on effect of N_2/O_2 inclusion in the thermal plasma on the spallation phenomena from PA66 specimens with 3 wt% water absorption. The Ar ICTP with N_2/O_2 was used to be irradiated to the PA66 specimens because the ICTP technique is useful to control the experimental condition in detail. The effect of N_2/O_2 inclusion on spallation phenomena was investigated since the actual low voltage circuit breakers or arcing horns are used in air. Oxygen admixture ratio to N_2 was changed as a parameter to understand a role of the oxygen gas. As a result, it was found that O_2 inclusion effectively promoted the frequency of spallation particle ejection from PA66 specimens with a fixed 3 wt% water absorption.

II. Polyamide 66

We have found that the polymamide with water absorption emits spallation particles as well as ablated vapor during the thermal plasma irradiation from our previous works. This work thus focuses on the polyamide 66 (PA66). The polyamide material 66 is one of thermosoftening plastics, and is well-known as nylon-66. It is widely used as engineering plastics for electrical insulation, textile, etc. Figure 1 shows the structural formula of PA66 $[-CO(CH_2)_4CONH(CH_2)_6NH-]_n$. Chemical elements included are carbon, hydrogen, nitrogen, and oxygen. The PA66 contains repetitive monomer units with amide functional group [-CO-NH-] with electrical polarity. The high water absorption coefficient of this

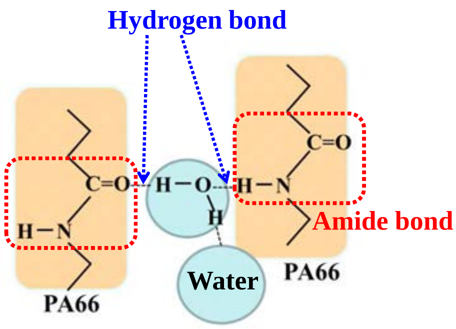


Fig. 2. Image of water absorption in PA66.

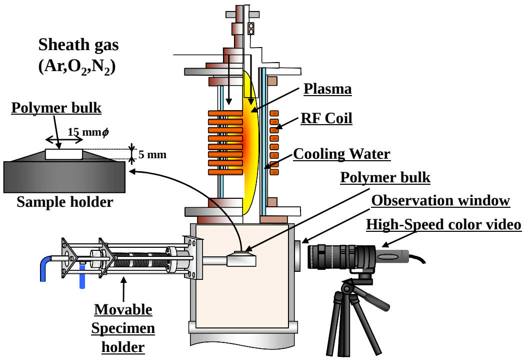


Fig. 3. Inductively coupled thermal plasma system for irradiation.

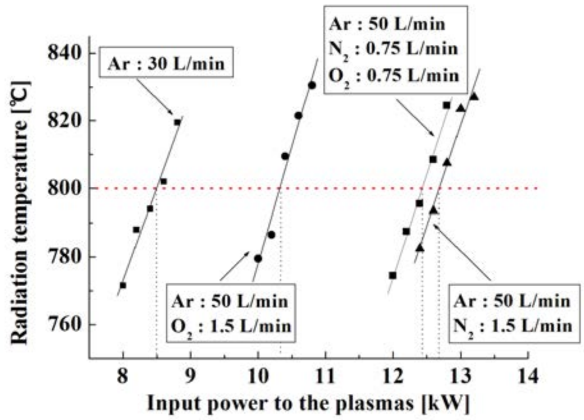


Fig. 4. Dependence of surface temperature of a TiO_2 specimen on input power.

TABLE I

GAS FLOW RATES AND INPUT POWERS

Gas condition	Ar [L/min]	N_2 [L/min]	O_2 [L/min]	Input power [kW]
97%Ar+3%N_2	50	1.5	0	12.8
97%Ar+2%N_2+1%O_2	50	1.0	0.50	12.6
97%Ar+1.5%N_2+1.5%O_2	50	0.75	0.75	12.4
97%Ar+1%N_2+2%O_2	50	0.50	1.0	12.2
97%Ar+3%O_2	50	0	1.5	10.3
100%Ar	30	0	0	8.5

material originates from this amide group, which causes hydrogen bonds with H_2O as indicated in Fig. 2.

III. Ar+N_2+O_2 Induction Thermal Plasma Irradiation Experiment

A. Experiment setup

Figure 3 shows the experimental setup used in the experiment. This system has a thermal plasma torch, an induction coil, a specimen holder and a reaction chamber. The plasma torch is composed of two coaxial quartz tubes. Between the tubes, cooling water flows to keep the wall temperature around 300 K. Around the quartz tube, an eight-turn induction coil is wound. The coil is connected with an RF power source with a fundamental frequency of 450 kHz. Supplying RF coil current to this coil produces electromagnetic field and then an inductively coupled thermal plasma (ICTP) inside the plasma torch. Argon gas with swirl was supplied along the inner wall of the inner quartz tube from the top of the plasma torch as a sheath gas. It prevents the thermal plasma from contacting the quartz wall, and also stabilizes the thermal plasma.

Downstream of the plasma torch, a specimen holder was installed in the reaction chamber. On the specimen holder, a polymer specimen with a diameter of 15 mm and a thickness of 5 mm was located to be irradiated by the thermal plasma. The polymer is generally ablated by the high heat flux from the thermal plasma. The dynamic behavior of ablated vapor was observed by a high-speed color video camera from an observation window as indicated in Fig. 3. Note that the polyamide material can emit spallation particles as well as ablated vapor according to our previous experiments[3].

The ICTP irradiation test instead of the arc plasma irradiation test has some advantages as follows: (i) The ICTP has essentially no contamination and impurity from electrodes. (ii) The ICTP can be formed in a steady state with a stability. (iii) The ICTP can include different gas species like molecular gases and others to test their effects on the polymer ablation. In this paper, N_2 and O_2 were included to Ar plasmas to measure the effects of them.

B. Preparation of PA66 with water absorption

We have found from our previous experiments that the water absorption amount in PA66 specimen markedly affects the occurrence and frequency of spallation particles ejection [3]. In this work, the water absorption amount was controlled to have the same percentage of 3 wt% for all PA66 specimens by the following procedure. First, PA66 specimens were dried using silica-gel in a desiccator in two weeks. Then, the specimens were soaked in boiling water to absorb water in three hours. The 3 wt% water absorption which is enough to be expected to eject spallation particles was confirmed from the weight difference before and after this procedure.

C. Experiment conditions

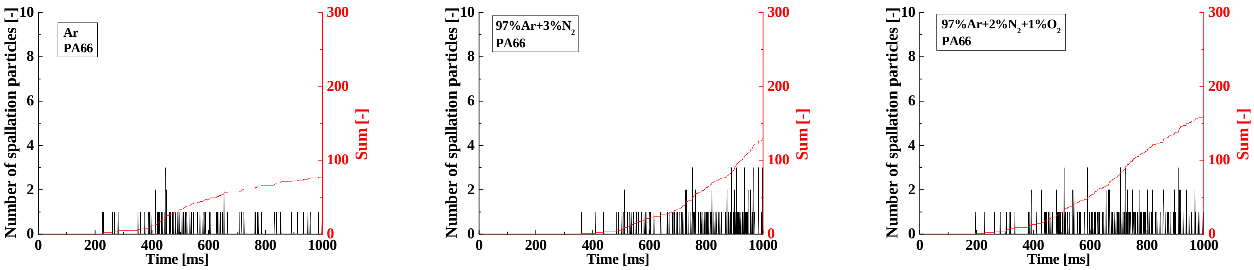
The experimental conditions were set as follows: Table I summarizes the experimental conditions adopted. The pressure inside the chamber was fixed at atmospheric pressure 760 torr. The total gas flow rate was 50 L/min (liters per minute). A 97%Ar ICTP with 3% additional molecular gases was irradiated including N_2 and/or O_2

(a) 100%Ar (b) 97%Ar+3%N_2 (c) 97%Ar+2%N_2+1%O_2 (d) 97%Ar+3%O_2

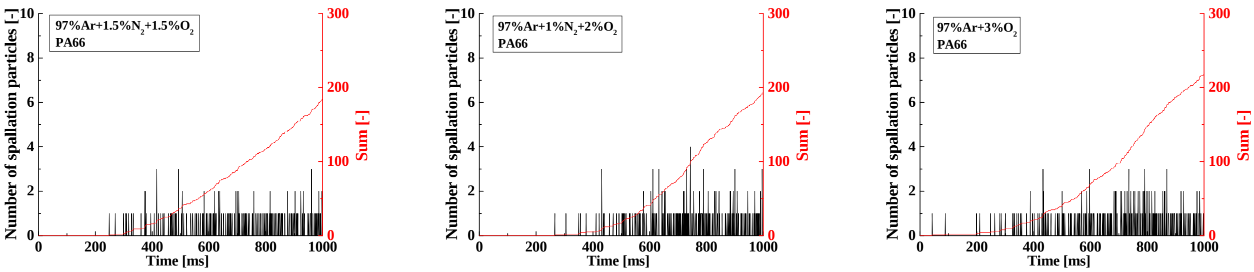
Fig. 5. High-speed video camera captures of thermal plasma irradiated on PA66 specimens with different N_2/O_2 gas mixture ratio.

(a) 100%Ar (b) 97%Ar+3%N_2 (c) 97%Ar+2%N_2+1%O_2 (d) 97%Ar+3%O_2

Fig. 6. Accumulated images from high-speed video camera images for Figs.5(a)-(d), respectively.



(a) 100%Ar (b) 97%Ar+3%N_2 (c) 97%Ar+2%N_2+1%O_2



(d) 97%Ar+1.5%N_2+1.5%O_2 (e) 97%Ar+1%N_2+2%O_2 (f) 97%Ar+3%O_2

Fig. 7. Instantaneous and accumulative number of spallation particles injected from PA66 specimens irradiated by thermal plasmas.

with different gas admixture ratios in thermal plasma irradiation tests. For these conditions, the input power to the ICTP was regulated for different conditions, as indicated in Tab. I. This regulation was done to provide the same heat flux irradiation on the specimen surface. The same heat flux condition was determined by Fig. 4 which depicts the dependence of the surface temperature of a TiO_2 specimen instead of polymer specimen on the input power to the thermal plasma for different gas conditions. The input power for the same heat flux condition was determined from the same surface temperature 800 °C of a TiO_2 specimen. In this case, the irradiated heat flux was estimated to be around 550 kW/m^2 from a help of the numerical simulation. As a reference, 100%Ar ICTP with 30 L/min gas flow rate was also irradiated for comparison.

High-speed video camera measurements were conducted with the exposure time of 50 μs and the frame rate of 1000 fps.

IV. Results and Discussions for Ar+N_2+O_2 ICTP Irradiation on PA66 Bulk

A. *High-speed video camera observation results*

Figures 5(a)–5(d) show the observed pictures of the different conditions by the high-speed video camera. Irradiation of the Ar ICTP with different gas mixtures provides quite different aspect of PA66 ablation. In case of

100%Ar ICTP irradiation, ablated vapor from PA66 emits white-bluish light. This is mainly attributed to strong spectral intensity from C_2 Swan system at wavelengths around 450–570 nm according to our previous work [3]. The 97%Ar ICTP with 3%N_2 offers the similar color ablated vapor but also with purple around the PA66 surface. The color purple comes from the high intensity of CN Violet spectra at wavelengths around 350–400 nm [3]. On the other hand, inclusion of O_2 in the Ar ICTP involves orange color in ablated vapor. This arises from the continuous spectra by the black-body radiation according to spectroscopic measurement [3]. This seems due to combustion reaction of carbon particles in ablated vapor.

In addition to ablated vapor, "spallation particles" can be observed to be emitted from PA66 specimens for any six conditions of gas mixtures. Figures 6(a)–6(d) present four images produced by accumulating 100 consecutive video captures from 900 ms to 1000 ms after ICTP irradiation. These figures were created to clarify the presence of spallation phenomena happening intermittently. As seen in these figures, the spallation occurrence is clearly promoted by increasing O_2 admixture ratio to N_2.

B. Effect of O_2 inclusion to N_2 on the frequency of spallation particles ejection

Next, we estimated the frequency of spallation particles ejected from the PA66 specimens for different six conditions. The bar chart in Figs. 7(a)–7(f) indicates the instantaneous number of particles ejected from PA66 specimen surface for 1000 ms during the ICTP irradiation. These figures also contain their cumulative number of the particles, which refers to the right vertical axis in these figures. For 100%Ar ICTP irradiation, spallation particles were sparsely observed from 200 ms after ICTP irradiation, and finally 80 particles were ejected for 1000 ms. Irradiation of 97%Ar ICTP with only 3%N_2 inclusion on the PA66 specimen slightly increases the frequency of spallation particle ejection. On the other hand, O_2 inclusion in Ar ICTP clearly promotes the occurrence of spallation. In case of 3%O_2 inclusion, total number of spallation particle ejection exceeds 200.

Figure 8 compares the averaged total number of spallation particles ejected in 1000 ms for different six conditions. The averaged total numbers were calculated for three different experiments with the each same condition. The averaged total number of spallation particles for 100%Ar ICTP was estimated to be 105. The 3%N_2 inclusion increases the averaged total number to 135. On the other hand, increasing O_2 ratio to Ar+N_2 ICTP only from 0% to 1.5%, which corresponds to a relative O_2 ratio to N_2 $R_{\mathrm{O/N}}$ from 0% to 50%, remarkably enhances the averaged total number of spallation particles from 135 to 211. This means that O_2 is effective to promote the occurrence of spallation phenomena on the PA66 specimen. Meanwhile, a further increase in O_2 admixture ratio from 1.5 to 3% ($R_{\mathrm{O/N}}$ from 50% to 100%) hardly changes the averaged total number. This result implies

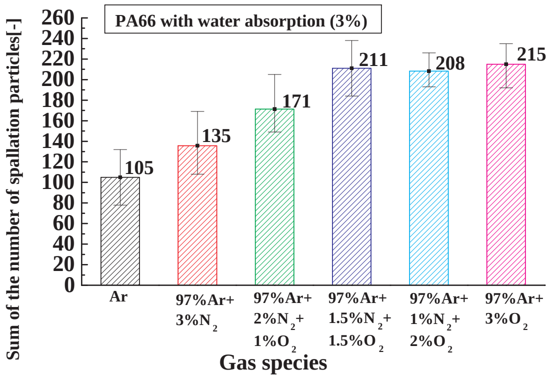


Fig. 8. The number of spallation particles

that spallation phenomena can occur in air, a mixture of 78%N_2 and 22%O_2, with a high frequency.

From the results above, O_2 inclusion was found to extremely enhance the ejection frequency of spallation particles even with the same heat flux. Thus, we infer that it is possible to increase in the spallation particles by chemical reactions mainly with O atom on the PA66 surface. Oxygen atoms from the thermal plasma may break some chemical bonds in PA66 surface to reduce the mechanical strength. On the other hand, high heat flux increases the temperature of water absorbed inside the PA66 specimen to be evaporated. The vaporized water elevates local pressure in the PA66 specimen, and then the elevated local pressure breaks a part of the PA66 specimen surface mechanically-weaken by O atom. As a result, spallation particles may be ejected more frequently from PA66 specimen surface irradiated by O_2 included thermal plasma.

V. Summary

This paper describes experimental results on effect of N_2/O_2 inclusion in the thermal plasma on the spallation phenomena from PA66 specimens with water absorption. The polyamide material with water absorption can be ablated, for example, in low-voltage circuit breakers or arcing horns as a ablation material. It ejects not only ablated vapor, but also spallation particles. The Ar ICTP with N_2/O_2 was irradiated on the PA66 specimen with a fixed 3 wt% water absorption. As a result, increasing relative O_2 admixture ratio to N_2 clearly enhanced the frequency of spallation particle ejection.

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