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ELECTRONIC TREATMENT OF COMPLEX STRUCTURES IN A TORCH VOLUMETRIC ELECTRIC DISCHARGE

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ARTICLE INFO	ABSTRACT
Article history *Received:2025-10-22* *Received in revised form:2025-10-22* *Accepted:2025-10-31* *Available online* *Keywords:* *torch discharge;* *corona discharge;* *adhesion;* *carbon-filled plastics;* *wetting angle.* *JEL classification: L60, L64,O33,C63*	*The influence of torch discharge treatment on carbon-filled plastics with epoxy binder and carbon-filled plastics with cloth layer on the surface was explored. Was elaborated the configuration of potential electrode for getting the stable torch discharge in positive half-period and corona in negative half-period of AC. The limiting wetting angle of materials surface after an activation by torch discharge was measured. Was shown an increase of adhesion between metal coating and treated surface. Was detected a big effect of electrical treatment in static regime when the electrical discharge influence on the surface is summed-up by the action of electron-ion components and active gaseous products action.*

1. Introduction

Exposure to no equilibrium electrical discharges in gases can alter the physicochemical properties of the surface layer of materials, including increasing surface energy, which improves adhesion [1]. One interesting form is the torch discharge, which occurs in electronegative gases, including air, in non-uniform fields of a specific configuration [2] at interelectrode distances of 2-20 cm. It consists of a sequence of cathode-directed streamers and, in terms of its development, is intermediate between a corona discharge and a spark discharge. Like any transient form, the torch discharge is unstable, and its stabilization requires current limiting measures, for example, by using limiting resistors or creating a special field configuration.

In devices implementing a torch discharge [2,3], a metal "pin" serves as the anode, and a "plane" serves as the cathode. Conditions in the gap at a sufficient distance from the anode have little effect on the formation and stability of the torch discharge, as streamers are generated and formed in the region of high field strength near the anode. This characteristic creates the physical prerequisites for using torch discharge to modify the surface of products with a wide range of shapes, sizes, and electrical properties. For example, in [3], it was shown that an increase in adhesion properties after treatment in a torch discharge at a constant voltage is observed for wool fibers, fluoroplastic, and polyethylene threads.

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At the same time, using torch discharge at a constant voltage to modify the surface of solid dielectric materials is difficult, even if a thin dielectric layer is located on a conductive substrate, since charge accumulation on the dielectric surface leads to "locking" of the discharge.

With alternating voltage, a torch discharge is ignited during each positive half-cycle, and an avalanche corona during each negative half-cycle of the applied voltage. The accumulated positive charge on the dielectric surface during the torch discharge is neutralized by the negative corona.

2. Methodology and experimental part

This study examined the effect of a torch discharge in air on the surface of composite materials-carbon fiber reinforced plastics with or without fiberglass sublayers. Experiments with electric discharge processing were conducted using the setup (fig. 1), where HVS is the high-voltage source; kV is a kilovoltmeter, Rlim and R are the limiting and measuring resistances; DG is the discharge gap; D_1 and D_2 are diodes and ELO is the electronic oscilloscope.

A refractory (molybdenum) “pin” electrode with a diameter of 1.5 mm and a cone-shaped end was used as the torch-forming device [4]. The cylindrical portion of the “pin” was covered with a dielectric nozzle. The working end of the “pin” faced the samples, which were positioned on a flat surface. The other end was attached directly to a limiting resistor (KEV-5) with a value of 10-20 Mom.

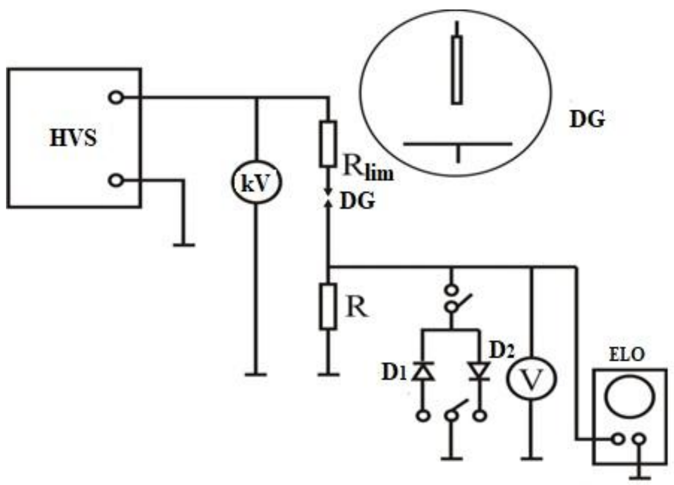

Fig. 1 Schematic diagram of the experimental setup for processing samples in a torch discharge

To determine the stable combustion mode of the torch discharge, geometric parameters characterizing the degree of influence of the dielectric nozzle on the field were varied: the distance to the work piece (2-10 cm) and the depth of the electrode insertion into the nozzle end (0-3 mm). As a result, an optimal anode design was experimentally determined that ensured a stable torch discharge during the positive half-cycle of alternating voltage at industrial frequency. A stable corona was ensured during the negative half-cycle. With a distance between the electrodes of L=4 cm, the torch wetting spot had a diameter of ~1.5 cm.

The presence of two diodes, D_1 and D_2, in the recording circuit allowed for separate measurement of the effective current values during each half-cycle of the applied voltage. Current during the negative half-cycle was recorded by connecting diode D_1, and current during the positive half-cycle by connecting diode D_2. The current-voltage characteristic of the torch-forming device under alternating voltage is shown in figure 2, where curve 1 corresponds to the effective current value with the diodes disconnected, curve 2 to the positive half-cycle, and curve 3 to the negative half-cycle.

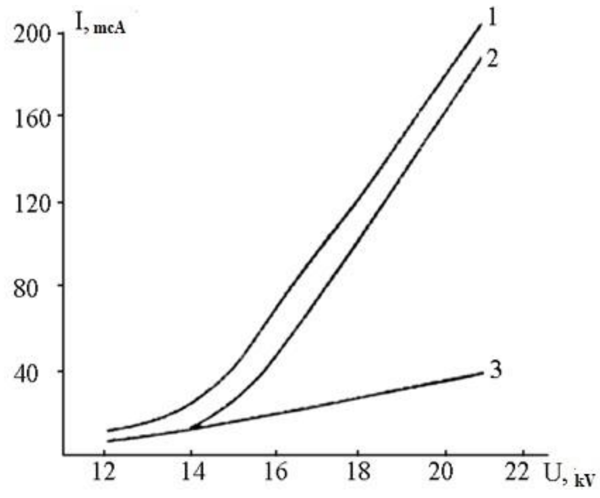

Fig. 2 Current-voltage characteristic of the torch-forming device at alternating voltage

The discrepancy between the total current and the sum of the currents during the positive and negative half-cycles of the alternating voltage is due to the imperfections of the diode characteristics. The appearance of a stable torch during the positive half-cycle is noted, according to oscillograms and visual observation, at U=12 kV. At U > 21 kV, spark channels are observed against the background of the stable torch. When a direct positive voltage of 22 kV is applied to the torch-forming device, a torch discharge is ignited. However, it has been noted that the torch discharge stability at direct voltage is significantly lower than with alternating voltage, and the stable torch currents for the same electrode configuration are lower. The stable torch range is 22-28 kV.

The applicability and effectiveness of torch discharge at direct and alternating voltages was tested when processing carbon fiber reinforced plastic (CFRP) plates and CFRPs with two fiberglass sublayers on each side. Since carbon fiber reinforced plastic (CFRP) is a conductive material, torch treatment can be used to modify its surface with both direct and alternating voltages. The surface of carbon fiber reinforced plastic (CFRP) plates with fiberglass sublayers is nonconductive, so torch treatment with alternating voltage is the only option.

The degree of modification was determined by the change in the wetting angle θ, which is related to the value of the work of adhesion forces by the Dupré-Young relationship:

$$W_A = \gamma(1 + \cos\theta) \quad (1)$$

where γ is the surface tension of the working fluid, θ is the wetting angle (for distilled water γ = 72.75*10-3 N/m or 72.75 mJ/m2).

The average value was calculated based on measurements at three points on the sample. The samples were treated at voltages of 15.5 and 19 kV with torch currents of 32 and 136 μA and negative half-cycle corona currents of 20 and 30 μA, respectively.

At 15.5 kV, the corona and torch currents differ by a factor of 1.5. This treatment of the carbon fiber reinforced plastic surface results in a monotonic increase in adhesion (curve 1, fig. 3). The main increase in adhesion is observed in the first 100 s of treatment, followed by insignificant growth. After 5 min of treatment, adhesion $\cos\theta$=0.82. Treatment of the surface of carbon fiber reinforced plastics with a sublayer also leads to a monotonic increase (curve 2). The main increase is noted in the first 50 s of treatment. Five-minute treatment yields adhesion

$\cos\theta$=0.86. At a voltage of U=19 kV, the torch current exceeds the corona current by four times. In this case, a monotonic increase in adhesion is observed during treatment of both carbon fiber reinforced plastics and CFRPs with a sublayer (curves 3 and 4, respectively). After five minutes of treatment, adhesion $\cos\theta$=0.94 for carbon fiber reinforced plastics and $\cos\theta$=0.95 for carbon fiber reinforced plastics with a sublayer.

It was noted that with increasing discharge exposure time, the curves $\cos\theta$(t) reach saturation, which can be explained by the onset of a dynamic equilibrium between the processes of formation and destruction of groups that increase surface adhesion. Since, as the modified layer is removed, deeper layers of the sample will be exposed to the discharge.

When machining carbon fiber reinforced plastic (CFRP) samples with a sublayer, a characteristic peak appears on the dependence curve $\cos\theta$(t), which is reproduced under different machining conditions. This peak may be due to two different mechanisms increasing surface adhesion.

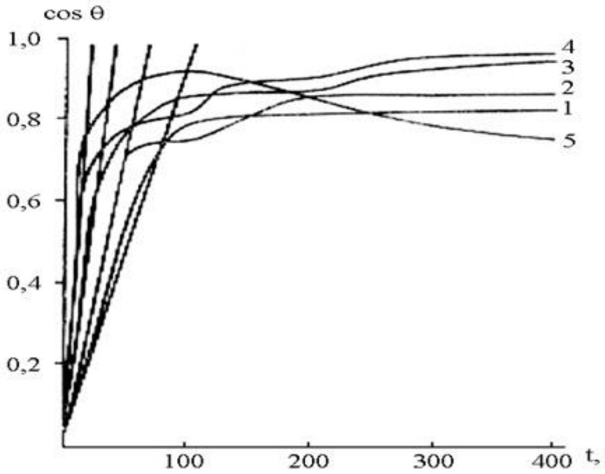

Fig. 3 Dependence of the change in the wetting angle of the surface of carbon fiber reinforced plastics (1, 3, 5) and CFRPs with a fiberglass sublayer (2, 4) on the duration of treatment in a torch discharge: 1, 2 – discharge current 90 μA at alternating voltage; 3, 4 – discharge current 150 μA at alternating voltage; 5 – discharge current 50 μA at constant voltage

Under the first machining condition (U=15.5 kV), the steepness of the initial portion of curve 3 is approximately three times greater than that of curve 1. This suggests that the increased machining effect is attributed to the effect of the torch discharge during the positive half-cycle. It is possible that some of the accelerated modification may also be attributed to the increase in negative corona current.

Under the second condition, at U=19 kV, higher values of adhesion work are achieved compared to the first condition, and the difference in wetting angles at different points on the same sample after machining is small, indicating uniform machining in this condition. Machining samples at U > 19 kV yielded higher average values, but due to the presence of sparks and their localization at certain points on the surface, machining of the samples was uneven. Furthermore, in this case, the appearance of spots on the surface of the carbon fiber reinforced plastics with a sublayer after processing was noted.

Under constant voltage, the carbon fiber reinforced plastic surface was treated at U=27 kV and a torch current of 50 μA. The dependence $\cos\theta$ (t) for the treatment of the carbon fiber surface is shown in figure 3 (curve 5).

It can be seen that the dependence $\cos\theta$ (t) peaks at 100 s ($\cos\theta$ (t)=0.91) and then decreases, indicating that prolonged treatment degrades the previously achieved effect. Compared to treatment of carbon fiber reinforced plastic samples in a torch discharge under alternating voltage, the steepness of the $\cos\theta$ (t) curve under constant voltage is greater. However, the ability to process at higher average currents and achieve better treatment results is an advantage of torch processing under alternating voltage. Furthermore, the use of alternating voltage simplifies the design and operation of the installation.

Experimental results show that a bipolar mode combining a torch discharge with a negative corona may prove optimal for practical use in electrical discharge surface modification of composite materials.

Furthermore, this mode enables surface modification of large dielectrics with equal torch and corona discharge currents, where the positive charge from the torch accumulated on the surface is compensated by the negative charge of the corona. In this case, a longer treatment period is required to activate the surface. However, for small samples, treatment with higher torch currents exceeding the corona current is possible, as this allows the charge to drain from the surface.

Since the effect of an air discharge on the surface of materials involves the action of the electron-ion component of the discharge and active oxygen-containing gaseous compounds (ozone, nitrogen oxides, and atomic oxygen), the objective was to determine which of these factors is decisive when treating the surface of carbon-fiber reinforced plastics and carbon-fiber reinforced plastics with a sublayer using a torch discharge under alternating voltage. To this end, the following experiments were conducted. First, during treatment near a flat electrode, the near-electrode zone was purged with an air flow under an excess pressure of 0.5 atm. This prevented oxygen-containing discharge products from coming into wetting with the sample surface, and only the electron-ion component of the discharge contributed to the surface modification. Treatment was then carried out while simultaneously using a metal mesh in wetting with the flat electrode. It was positioned above the sample surface parallel to their plane. In this case, the samples were exposed only to gaseous discharge products.

The wetting angle measurements after torch discharge treatment are presented in the table. The table lists the wetting angle values θ for carbon fiber reinforced plastics and carbon fiber reinforced plastics with a sublayer at various torch discharge treatment times. The first row lists the θ values for static treatment, the second row for blast treatment, and the third row for treatment with a mesh.

It is evident that the strongest treatment effect is achieved in static mode, i.e., with the simultaneous action of the electron-ion component of the discharge and gaseous discharge products. When exposed to the electron-ion component, the modification effect is slightly weaker. Gaseous discharge products have either a very weak effect or no effect at all.

As can be seen from the table, the effect of an electric discharge is determined by the combined action of the electron-ion component of the discharge and active gaseous compounds. A similar conclusion was reached in [5] when studying the electrical aging of polymer films in a barrier discharge.

Wetting angle measurement data for different types of carbon fiber reinforced plastics

Table 1.

Material	Material treatment time, min.		
	1	3	5
	Wetting angle θ		
Carbon fiber reinforced plastic	38	30	22
	41	33	29
	62	57	57
Carbon fiber reinforced plastic with sublayer	38	27	20
	40	35	34
	75	70	70

The role of gaseous discharge products in the modification of carbon fiber reinforced plastics with a sublayer is particularly evident. Since fiberglass is resistant to oxidation initiated by ozone and nitrogen oxides, as can be seen from the table, exposure to gaseous compounds alone does not cause changes in its adhesive properties. Therefore, if the effects of the discharge and its gaseous products are simply cumulative, then the absence of the latter should not affect the adhesion properties of carbon fiber reinforced plastics with a sublayer. However, it turned out that for these materials, the presence of ozone and nitrogen oxides in the discharge zone significantly enhances the change in adhesion properties.

In [6], it was shown that modification of carbon fibers in an ozone environment increases their surface adhesion as a result of oxidation. IR spectroscopy after ozonation of the fibers revealed the appearance of a broad band at 1050 cm-1, caused by the vibration of structural fragments containing single C-O-C bonds. It is likely that during electric discharge treatment, with the combined action of electron-ionic action and gaseous oxidants, adhesion should increase significantly more than that obtained in [6].

8. Discussion of results

To determine the qualitative change in the carbon fiber surface after treatment in a torch discharge, the IR transmittance spectra of the samples were studied. IR transmittance spectra were recorded for powder obtained by scraping from the carbon fiber surface to a depth of 10 µm. Powder, obtained from torch-exposed samples, as well as powder from untreated samples, were sintered into pellets using low-melting chalcogenide glass as the base material. IR spectra were then recorded using a SPECORD-751 setup.

Samples of fiberglass (the basis of the fiberglass sublayer in carbon fiber reinforced plastics with a sublayer) and cured epoxy resin were also pelletized and exposed to a flare discharge. The resulting IR transmittance spectra showed no noticeable changes in the treated fiberglass and epoxy resin samples compared to the untreated ones. This may be due to the fact that exposure to the discharge does not alter the chemical composition of the samples' surfaces.

In [7], no changes were noted in the epoxy resin after electric discharge treatment. In [8], non-stoichiometric oxygen was detected on the surface during glow discharge treatment. It is possible that such oxygen also forms after treatment of the fiberglass and epoxy resin, but IR spectroscopy cannot detect it. In CFRP samples treated in a torch discharge, an intense broad band appears at 1062 cm-1, which can be attributed to C-O vibrations. The observed increase in the work of surface adhesion forces in reducing the wetting angle is associated with oxidation of the CFRP surface and enrichment of the fiberglass surface with oxygen in the torch discharge.

Control and torch-treated CFRP samples and CFRPs with a sublayer were coated with an Al coating ~1 μm thick using thermal sputtering and magnetron methods. Coating adhesion to the surface, measured on a tensile testing machine, was 50-70% greater for the treated samples compared to the untreated ones.

When a metal coating is sprayed onto the sample surface after torch discharge treatment, metal atoms interact with non-stoichiometric oxygen and surface atomic groups, releasing corresponding oxidation energy at the film-substrate interface. This process is accompanied by the formation of valence bonds between substrate atoms and metal atoms through oxygen bridges.

9. Conclusion

A similar conclusion was reached when processing glass in a glow discharge [8], and the increase in adhesion of metals to glass after glow discharge treatment was explained by the formation of an intermediate layer of oxidized condensate. Better results were obtained when treatment in an oxygen-containing environment.

Treatment of carbon fiber reinforced plastics in a torch discharge in air leads to oxidation of the surface, accumulation of non-stoichiometric oxygen in it, which causes an increase in the adhesion of metal coatings applied to them.

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