On Pulsed Electric Strength of Gaps with Broad-Area Stainless-Steel Electrodes in Vacuum[1]

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Abstract – The paper describes the results of study of pulsed electric strength of vacuum insulation of gaps formed by plane-parallel broad-area electrodes made of stainless steels. Comprehensive statistical data were collected as a result of experiments with mechanically polished and electron-beam treated electrodes. Breakdown experiments were accompanied with anode-scanning technique allowing one to recognize emission sites on plane cathodes. This approach revealed electrical and spatial correlations between pre-breakdown emission sites and breakdown events at nanosecond-range voltages. Cathode emission sites were found experimentally to be responsible for electrical breakdown at hold-off electric field essentially below 1 MV/cm. In a case of better insulating ability of a vacuum gap, the anode becomes more influencing on electrical insulation of a gap.

1. Introduction

Electrical breakdown of broad-area vacuum gaps is a complex phenomenon since there are a lot of aspects being responsible for it [1]. As a result, easy-to-understand model notations describing electrical breakdown of point-to-plane vacuum gaps fail adequate description of hold-off voltages in a case of broad-area gaps.

Vacuum insulation at pulsed voltages, especially of nanosecond-range durations, seems to be easier for understanding since just cathode emission sites are considered to be dominant reason [2] of breakdown. Puzzling with the nature of cathode emission sites, one chooses spatial mapping of them as an uncontested approach. It gives an opportunity for meticulous study of sites characteristics [3] as well as of spatial and electrical correlations between electron emission sites and breakdown events [4]. The latter was studied for dc and microsecond pulsed voltages. We have set to ourselves a task of studying the correlations in nanosecond range of pulse durations. Doing this, we shifted the focus of study upon large-area gaps for the reason of rapprochement of the experiment and applications.

Our anode-probe scanning experiments have answered some of questions arising in analysis of data on vacuum breakdown of gaps with polished electrodes. Polishing techniques of two kinds were involved in the experiments. The first one is traditional fine-grade mechanical polishing and the second one is electron-beam enhancing surface treatment (EBEST). The latter technique is being developed for a long time at IHCE for the application to vacuum insulation [5].

2. Techniques and Methods

A. Experimental conditions

All the experiments were performed in conditions of high oil-free vacuum of about 5×10^{-7} mBar. A couple of 8-cm-diameter electrodes formed a plane-parallel gap. Manipulations with electrodes and their installation into the chamber were performed in dust-free environment provided by the air-filtering equipment based on HEPA H13 air filters. The use of dust-free clothes and mask and powder-free gloves was obligatory condition in manipulation with electrodes. Electrodes transportation between set-ups was carried out with using once-through clean boxes.

B. Electrodes performance and preparation

All the electrodes were shaped as plane cylinders of 8-cm diameter and 1.25-cm thick with Chang-profiled edges to provide the uniform electric filed in a gap. The electrode materials were stainless steels 304L, 316L SCQ, and 12X18H10T (steel 321 equivalence). Some of electrodes were annealed in hydrogen (HVFF). Electrodes were either mechanically machined or EBEST treated in the mode of thin-layer surface melting in oil-free vacuum.

Before the installation in the vacuum chamber, each electrode was wiped with lint-free cloth and high-purity-grade acetone.

C. Breakdown test procedure

On a set-up intended for high voltage tests, which was used at IHCE [5], a quasi-rectangular voltage pulse of amplitude ~220 kV and FWHM 50 ns

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produced by a Marx generator was applied to a vacuum gap formed by electrodes of diameter 8 cm. The electric field between the electrodes was varied by *in situ* varying the width of the vacuum gap. Tests were started at fields that certainly would not result in breakdown. Then the electrodes were gradually brought closer to each other with step not over 100 μm, and a high voltage pulse was applied to the gap at each step until a first breakdown took place. The following high voltage pulses were applied to the same gap until there occurred a series of five pulses without breakdown. In this case, the electrode separation was decreased by one step and the procedure was repeated. The conditioning of the gap ceased as the breakdown voltage increased to some value as a result of the initiation of a high-current arc. The arc caused a significant erosion of the electrodes resulting in a decrease in electric strength.

The set-up used at SNL [6] allowed investigations of the electric strength of a vacuum insulation with electrodes of greater diameter. The high voltage pulse generated with the help of a special circuit based on the TG 70 cable generator had a $(1 - \cos\omega t)$ waveform, an FWHM of ~160 ns, and amplitude controllable within the limits of 150–260 kV. The controllable voltage amplitude made it possible to vary the electric field in a vacuum gap of fixed length. The step of increase of the field was 30–50 kV/cm.

D. Anode-probe scanning technique

Figure 1 shows the diagram of the anode-probe scanner.

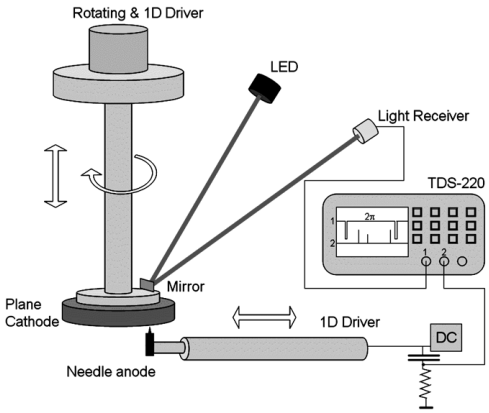

Fig. 1. Schematic diagram of the anode-probe scanning technique

The technique for surface emission scanning is based on measuring dark currents of a vacuum gap formed by a plane cathode and a needle anode. Herewith, an anode is moved along the rotated cathode surface, which could produce an emission sites map of a surface under study. Herewith, the 1D driver scale produces the radial coordinate, and the phase shift between a light receiver pulse and an emission current pulse produce the angular coordinate. Besides, the technique allows one to get current-voltage characteristics of separate emission sites and electric field of pre-breakdown emission switching, E_{onset}, as well. In turn, the treatment of I–V characteristics of emission sites could optionally produce the local field enhancement factor, β, [1].

The accuracy of emission current measurements is mainly determined by beats of the cathode under rotation. The beating amplitude in the experiment was typically about 3 μm, while the scanning gap was within 100 to 200 μm. This produces 3–6% instability in electric field strength under scanning.

After the scanning procedure followed by the pulsed breakdown test, either cathode was examined *ex situ* with the light microscope to recognise emission sites appearance.

3. Results and Discussion

A. Breakdown electric fields

Analysis of all the data on breakdown study of 8-cm-diameter plain-parallel gaps gave unexpected result that breakdown electric field, E_{br}, depends basically on electrode roughness while dependence on material purity seems to be less noticeable. Fig. 2 contains dependence of E_{br} on electrode roughness for various-grade electrode materials at either mechanical or EBEST polishing. Note plots behave very similar but the plot for EBEST electrodes corresponds to higher electric fields. The latter reflects intrinsic positive effect of electron-beam treatment on hold-off electric field.

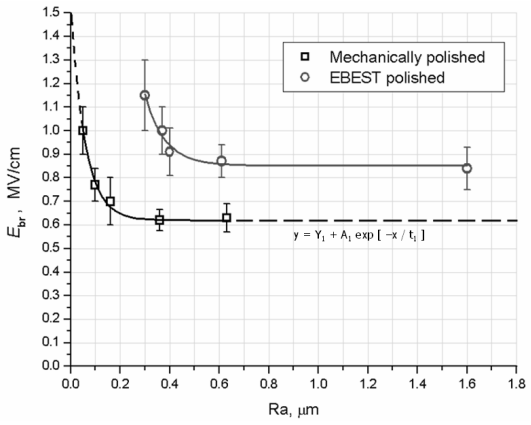

Fig. 2. Dependence of breakdown electric field on electrode roughness for plane-parallel 8-cm-diameter gaps with stainless steel electrodes. Extrapolations are plotted with dashed curves

Fitting of the plot for mechanically polished electrodes with the formula of $E_{br} = E_0 + A\ \mathrm{Exp}(-\mathrm{Ra}/R_0)$, where E_0, A, and R_0 are fitting parameters, gives reasonable limit of E_{br} for $\mathrm{Ra} \to 0$, which is of about 1.5 MV/cm. Similar fitting for a case of EBEST polished electrodes gives the limit of about order of magnitude higher. Nevertheless, such a speculation doesn't take into account a difference in relief features of mechanically polished and EBEST treated surfaces.

Fig. 3 presents typical appearance of surfaces in a light microscope. In the figure, the drawings below are speculative surface profiles for the images above. It is seen that EBEST surface roughness contains two components which are short-scale and long-scale ones. It seems that short-scale components of those surface fragments are similar one another while total roughness is different. Short-scale component of roughness is probably most responsible for hold-off.

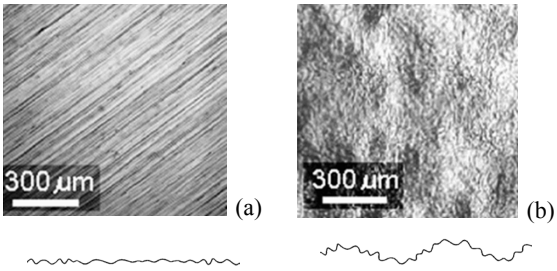

Fig. 3. Electrode surface appearance and speculative surface profiles corresponding to images. (a) Mechanically polished Ra = 0.1 μm surface and (b) EBEST treated Ra = 0.4 μm surface

Finally, in spite of the fact that mechanical polishing could provide rather high hold-off, the EBEST treatment has obvious benefit ensured by simultaneous carrying out of smoothing and surface cleaning as a result of cyclic re-melting of thin surface layer in vacuum [7]. Furthermore, EBEST technique allows one to treat electrodes of complex shapes.

B. Correlations between pre-breakdown emission sites and breakdown events

Anode-probe scanning experiments answered partially the question why surface roughness is so much important in the breakdown mechanism.

The anode-probe scanning of a cathode surface revealed emission sites being evenly distributed on a surface under scan. Emission I–V characteristics produce quasi-straight lines in coordinates of Fauler-Nordhein equation, so, calculation of β was suitable.

Examination of surfaces under scan with the light microscope revealed big-sized surface irregularities on local areas corresponding to emission sites. Fig. 4 shows typical images of sites. The probability of observation of such irregularities under examination was about 90%. In the rest of the cases, surface irregularities causing pre-breakdown emission were in dimensions beyond the optical resolution of the microscope.

The final goal of any pre-breakdown study is prediction of a breakdown place and breakdown electric field. In current experiments, the 70-% probability of co-occurrence of emission sites and breakdown places was found. This correlates well with results [4] obtained in another experimental conditions. Furthermore, breakdown electric fields correlated also with fields of emission switching, and first were almost equal to second for all the electrodes used.

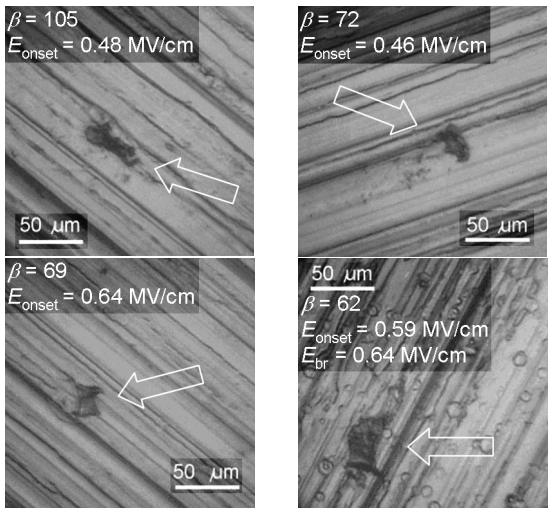

Fig. 4. Typical cathode surface images corresponding to emission sites at a machined surface and their parameters

Pre-breakdown emission sites on EBEST cathode surfaces were detected only in a case of 12X18H10T steel containing essentially more impurities in comparison with 304L and 316L steels. I–V characteristics were highly instable, which failed calculation of β. Moreover, they manifested hysteresis just as described elsewhere [1]. Microscope examination reviled specific appearance of emission sites on EBEST surfaces. They look like either pores associated often with craters or cracks (Fig. 5).

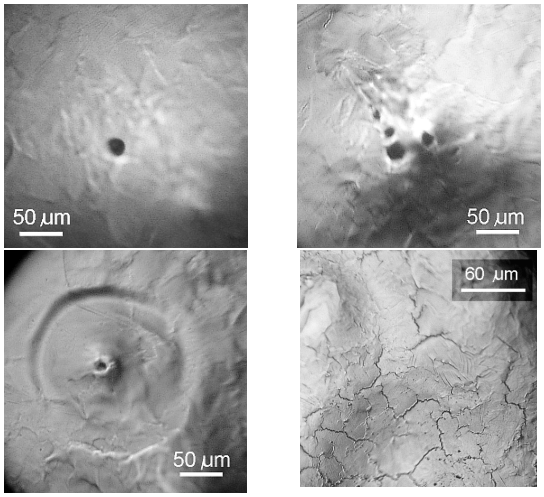

Fig. 5. Typical cathode surface images corresponding to emission sites at EBEST cathode surfaces

Pores (and cracks as well) are known to be a cause of emission according to microdischarge mechanism described elsewhere [8], considering a pore as a hole cathode. This mechanism declares hysteresis in I–V characteristics of a pore-kind emission site, which is in agree with our results.

Experiments on cathodes made of 304L and 316L steels gave absence of emission sites at electric field strength under scan of up to ~1 MV/cm. It is an unexpected result since mean values of first breakdown

electric field strength for electrodes made of those materials were below 1 MV/cm as a rule, i.e. there is no correlation between cathode emission sites and breakdown events. Careful microscopic examination of whole the cathode surfaces did not reveal pores, which explains partially the absence of emission sites. Herewith, the fact of breakdown fields to be lower than fields of switching pre-breakdown emission calls for necessity to recognize direct influence of the anode on breakdown initiation even at nanosecond range of pulse durations.

It has been found in experiments, that solvent surface cleaning with lint-free wipe changes radically emission sites maps. Herewith, appearances of all the observed emission sites under microscope examination rested without changes with every wiping, but some of them become inactive while other ones find activity. This concerns both to machined and EBEST cathodes. Therefore, emission sites observed in the light microscope are mainly traps for some smaller particles which are loosely bound with a surface.

D. Experiment without solvent cleaning of surfaces after EBEST treatment

The purpose of the experiment was research of a degree of the pollution left by the EBEST facility as well as of the nature of contaminants. Doing this, we skipped lint-free wiping of electrodes under experimentation.

Anode-probe scanning revealed essentially higher emission activity of cathodes in comparison with wiped machined cathodes, which manifested itself in higher values of β and lower E_{onset} (Fig. 6).

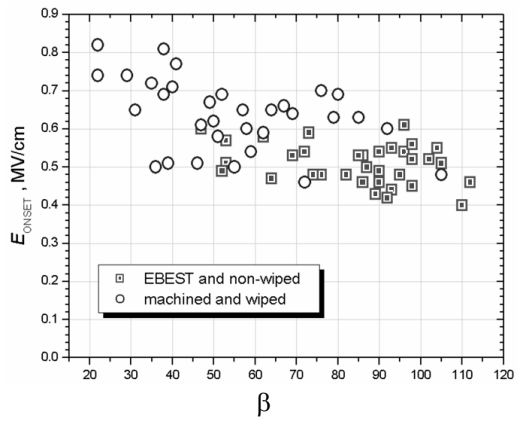

Fig. 6. E_{onset} vs. β for wiped and non-wiped cathodes

Microscopic examination of non-wiped EBEST cathodes didn't reveal observable surface irregularities corresponding to emission sites, i.e. their sizes are beyond the microscope optical resolution. Besides, solvent cleaning of a surface with a lint-free cloth removes most of sites, i.e. those sites are associated with loosely bound particles. In turn, particles are known to be a very unpleasant feature of vacuum technologies [9], and emission activity of particles rises with reduction of their sizes [3].

In this experiment breakdown electric fields correlated also with fields of emission switching as it was found for machined electrodes, and they are almost equal one another.

4. Summary

All the data described here point to the fact that even at nanosecond-range voltages the major cause of electrical breakdown of broad-area gaps is loosely bound particles adhered at electrode surfaces. Lint-free solvent wiping is an obligatory procedure for everyone who is going to keep high hold-off in vacuum, which removes most of particles. The rest of particles are distributed with wiping among surface irregularities. That is why surface roughness affect strongly hold-off.

The second-largest cause of vacuum breakdown is chemical cleanness of electrode surfaces. This is proved unambiguously by positive influence of electron-beam surface irradiation in the mode of surface melting on hold-off.

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