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OPTICAL MEASUREMENT OF THE VELOCITY OF DIELECTRIC SURFACE ARCS*

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Abstract

Surface flashover arc discharge velocities on electron-beam-charged polymer sheets have been measured directly by detecting the light emitted at two points along a straight arc and measuring the time interval between light pulses. For Mylar, the average velocity is 1.2×10^6 m/s, and for Teflon the average velocity is approximately 7.3×10^5 m/s independent of sheet thickness. These velocities are about two to four times higher than previous measurements. The techniques employed to produce single, straight surface arcs are described.

Introduction

Electron-beam-charged, thin dielectric sheets experience electrical breakdown of two distinct types, punchthrough (bulk) arcs and flashover (surface) arcs, which have been the subjects of extensive study[1,2] in the context of their probable occurrence on spacecraft in synchronous orbit. The surface arc discharges exhibit both peak currents and pulse durations which are proportional to the square root of the specimen area[3,4,5,6,7]. This suggests that the arc duration is controlled by a well-defined arc propagation velocity which for a circular specimen can be estimated by dividing the specimen radius by the arc duration, a procedure which has led to velocity estimates usually in the range of 1.5×10^5 m/s to 3.0×10^5 m/s. One report of experiments on Kapton[8] gives the velocity range as 1 to 7×10^5 m/s, as deduced by the above procedure. Such a calculation presupposes the existence of a well-defined, unique velocity at which the arc propagates in straight radial lines from the specimen edge to its center: arc photographs[3,4,5] indicate that this presupposition is only partly valid, because the arc paths are very irregular and some are appreciably longer than the specimen radius, so that these velocity estimates are expected to be low.

Discharge arc propagation mechanisms have been postulated in various forms, as a transmission-line model[9], a "brushfire" model[10,11,12], and a plasma-tunnel model[4,13]. The early stages of a dielectric arc in the bulk of the material have been viewed as negative-streamer development[14] with a velocity computed at 1.65 $\times 10^5$ m/s in Teflon. It has been noted[11,12] that a typical ion accelerated by the breakdown potential achieves a velocity of 2.45×10^5 m/s and its motion across the charged surface could trigger a series of small discharges.

Direct measurements of arc velocity on Kapton have been made using two techniques[12]. A series of top-surface metal pads with wire leads gave a velocity of 2.5×10^5 m/s, and a series of segmented-substrate pads gave a velocity of 2.1×10^5 m/s. These techniques have been proved useful but they are also "invasive" in the sense that a top-surface pad or substrate segmentation could influence the progress of an arc. Optical techniques which involve a remote measurement of arc light emission are by their nature potentially much less invasive and are the subject of this work.

Experimental Techniques

The most straightforward non-invasive method of measuring arc propagation velocity is to measure the time interval as the arc traverses a known path between two points, by means of measuring the light emission from the arc at each point. However, the arc must travel in a straight line, and only one arc must occur. Furthermore, it must be ensured that the arc always starts outside the measurement region so that it propagates unidirectionally between the two measurement points: a start inside the measurement region followed by propagation in both directions would give a falsely high indication of velocity.

It is known from experiments in our laboratory that very light brushing of a Teflon specimen before exposure to an electron beam will result in surface arc discharges which follow the direction of the brush strokes: the single discharge shown in Fig.1 was produced by such very light, straight stroking with a camel's-hair brush. At NASA similar results have been obtained by rubbing with a soft tissue (N.J. Stevens and J.V. Staskus, personal communication). The procedure used for the experiments to be described here was to wipe the specimen lightly in one direction with a lens tissue dampened with acetone. Inspection under a microscope showed that this procedure produced faintly visible sub-micron-width scratches on the polymer surface. In addition we have found that, as an oblong mask aperture covering the specimen is narrowed, the number of parallel arcs diminishes. Thus we have been able to select experimental conditions such that the vast majority of arcs are single straight ones.

Numerical computations of electron orbits showed that charge accumulates preferentially in the corner regions of a rectangular-masked specimen. Thereafter experimentally it was shown that an oblong mask with a sharp "corner" at one end produced discharges which started preferentially from that end. However an even better technique to ensure discharge initiation near one end of the specimen proved to be the making of a very small pinhole there.

The final experimental arrangement is shown in Fig. 2. The optical fibres were located in slots on the underside of the mask, with the fibre ends 1 cm in from the slot ends so that the slots served as collimators for the incident light. The fibres carried the discharge light to two avalanche photo-diodes which were connected to a dual-beam 400 MHz oscilloscope. The measured light pulses had risetimes of the order of 20 ns (the pulse rise was used for the velocity calculations) and decay times of the order of 120 ns. Calibration was achieved by inserting both fibres in the

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same slot and adjusting the oscilloscope for coincident traces from actual arcs. The optical fibre separation was 3 cm, but separations of 2 cm and 1 cm were also tried with proportional decreases in pulse separation intervals. Typical detected light pulses for a 3 cm spacing are shown in Fig.3. The beam accelerating voltage was 20 kV and the beam current density was 100 nA/cm^2. Various specimens were used but all were cut with the same orientation from the same sheet.

Results

The results for Mylar (spacecraft grade, back-aluminized, 75 μm thick) are shown in Fig.4. The points shown in the figure give a mean velocity of 11.6×10^5 m/s. For comparison, consider previously reported results[15] for the same material in which a mean substrate pulse duration of 25 ns and a circular mask area of 11.7 cm^2 give a velocity estimate of 7.7×10^5 m/s. Earlier measurements of pulse duration[3,4] suggested a velocity of about 3×10^5 m/s but those specimens were commercial-grade Mylar, so it may be that a direct comparison with the present results is not valid. Not shown in Fig.4 and not included in the statistics is one measurement at 70×10^5 m/s which may have been initiated between the optical fibres rather than at the pinhole.

The results for two thicknesses of Teflon are shown in Figs.5 and 6. The mean velocities of 7.5×10^5 m/s for 60 μm unmetallized Teflon and 7.2×10^5 m/s for 125 μm back-silvered Teflon suggest that the arc velocity is independent of material thickness. For comparison, consider previously reported results[15] in which a mean substrate pulse duration of 58 ns and a mask aperture area of 11.7 cm^2 give a velocity estimate of 3.3×10^5 m/s; earlier measurements of pulse duration are similar[3,4].

Discussion

The only "invasive" aspect of the experimental technique used is the wiping procedure which scratched the polymer surface slightly. These scratches are appreciably less than a micron in width and presumably no deeper than that. For comparison, discharge damage tunnels[4] are somewhat wider and up to a few microns below the surface, so it would appear plausible that the wiping procedure could exert an arc-guiding influence without affecting greatly the basic mechanism (hence velocity) of discharge propagation. It is worth noting that without wiping, the surface would have been contaminated with dust and other foreign matter.

The measured difference in velocity between Teflon and Mylar confirms the earlier and less direct evidence of such a velocity difference (Balmain and Hirt[15]). However it is not clear what physical property of the two materials is primarily responsible for this difference.

In summary, the first direct optical measurement of surface arc velocity on spacecraft dielectric materials is reported. The mean velocities are greater than previous estimates by factors ranging from 2 to 4, factors which are too large to be explained entirely by the straightness of the present arc paths in comparison with previous ones. The velocity appears to be independent of material thickness but dependent on material composition.

References

1. Spacecraft Charging Technology 1978. NASA Conference Publication 2071/AFGL-TR-79-0082.

2. Spacecraft Charging Technology 1980. NASA Conference Publication 2182/AFGL-TR-81-0270.

3. K.G. Balmain, "Scaling laws and edge effects for polymer surface discharges", in Ref.1, pp.646-656.

4. K.G. Balmain and G.R. Dubois, "Surface Discharges on Teflon, Mylar and Kapton", IEEE Trans. Nucl. Sci., Vol. NS-26, No.6, pp.5146-5151, Dec. 1979.

5. K.G. Balmain, "Surface discharge effects", Progress in Astronautics and Aeronautics, Vol.71, pp.276-298, 1979.

6. P.R. Aron and J.V. Staskus, "Area Scaling investigations of charging phenomena", in Ref.1, pp.485-506.

7. T.M. Flanagan, R. Denson, C.E. Mallon, M.J. Treadaway, and E.P. Wenaas, "Effect of laboratory simulation parameters on spacecraft dielectric discharges", IEEE Trans. Nucl. Sci., Vol. NS-26, No. 6, pp.5134-5140, Dec. 1979.

8. M.J. Treadaway, C.E. Mallon, T.M. Flanagan, E.P. Wenaas, R. Denson, "The effects of laboratory simulation parameters on spacecraft dielectric discharges", ECEMP Phenomenology Memo #30, prepared for Computer Sciences Corp. on AFWL Contract No.F29601-78-C-0012, Subtask 733-05/00, 13 July 1979.

9. R. Leadon and J. Wilkenfeld, "Model for breakdown process in dielectric discharges", in Ref.1, pp. 704-710.

10. G.T. Inouye and J.M. Sellen, "A proposed mechanism for the initiation and propagation of dielectric discharges", Proc. 1978 Symposium on Effects of the Ionosphere on Space and Terrestrial Systems (NRL/ONR), pp.309-312.

11. G.T. Inouye, "Brushfire arc discharge model", in Ref.2, pp.133-162.

12. G.T. Inouye, "Implications of arcing due to spacecraft charging on spacecraft EMI margins of immunity", TRW Report No.36186-6016-UE-00/NASA CR 165442, March 10, 1981.

13. K.G. Balmain, "Surface discharge arc propagation and damage on spacecraft dielectrics", ESA Document SP-145, pp.209-214, Proceedings of the ESA Symposium on Spacecraft Materials, Noordwijk, The Netherlands, 2-5 Oct. 1979.

14. B.L. Beers, V.W. Pine, H.C. Hwang, and H.W. Bloomberg, "Negative streamer development in Teflon", IEEE Trans. Nucl. Sci., Vol. NS-26, No. 6, pp.5127-5133, Dec. 1979.

15. K.G. Balmain and W. Hirt, "Dielectric surface discharges: effects of combined low-energy and high-energy incident electrons", in Ref.2, pp.115-128.

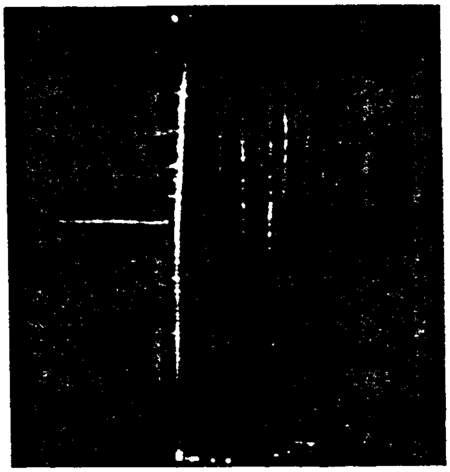

Fig.1
A single spontaneous multi-arc discharge event on 50 μm thick Teflon, following light brushing in a direction parallel to the arc paths. Incident beam: 20 keV electrons.

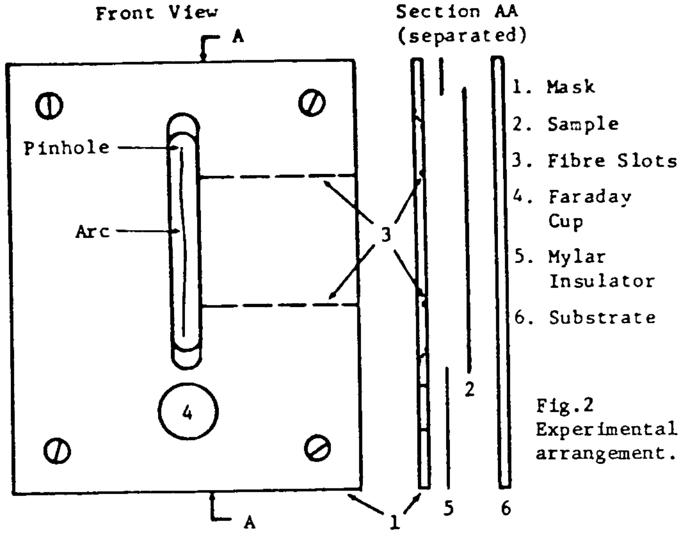

Fig.2
Experimental arrangement.

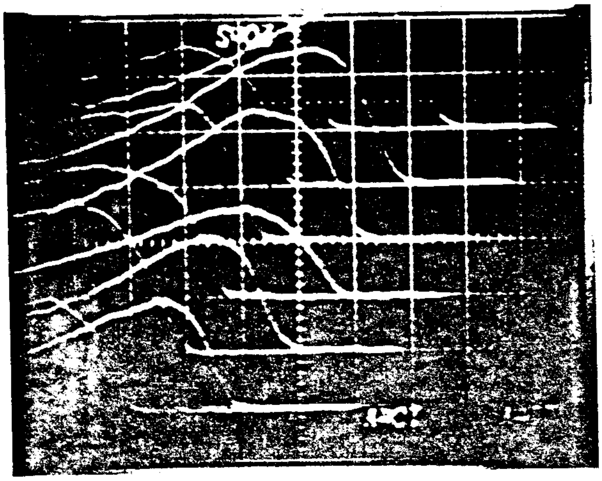

Fig.3 Typical measured light pulses from six arc discharges on Teflon. The two optical fibres are spaced 3 cm apart. The time differences are established by straight-line extrapolation from the steepest parts of the curves to the common baseline.

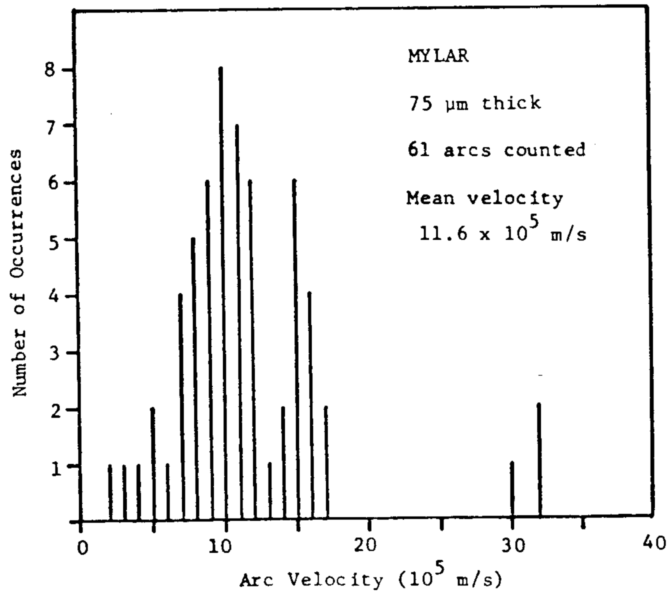

Fig.4 Distribution of measured velocities on Mylar sheet.

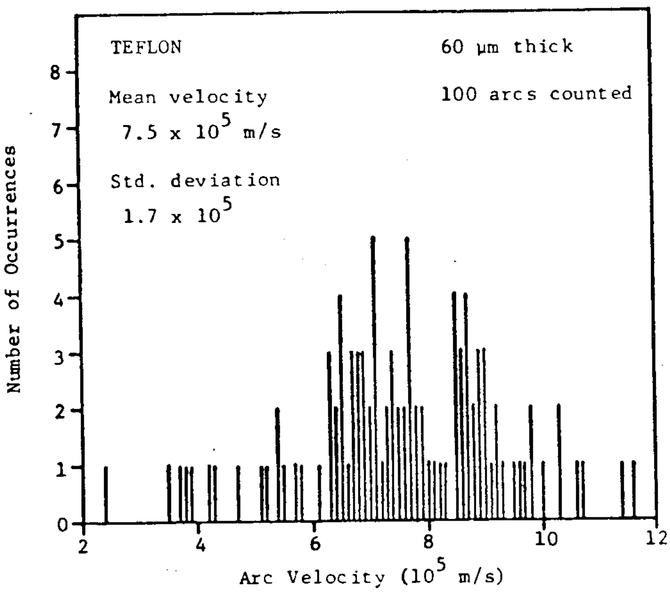

Fig.5 Distribution of measured velocities on 60 μm thick Teflon.

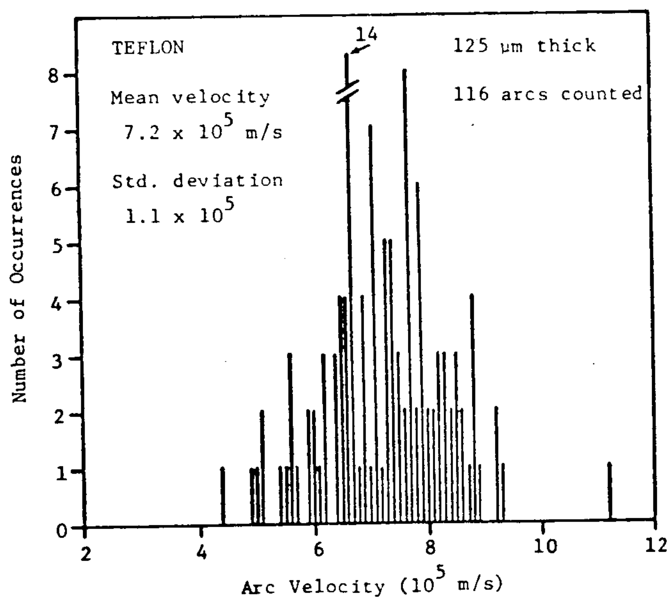

Fig.6 Distribution of measured velocities on 125 μm thick Teflon.