Influence of Depth of Cathode Arc-remelted Layer on Vacuum Insulation

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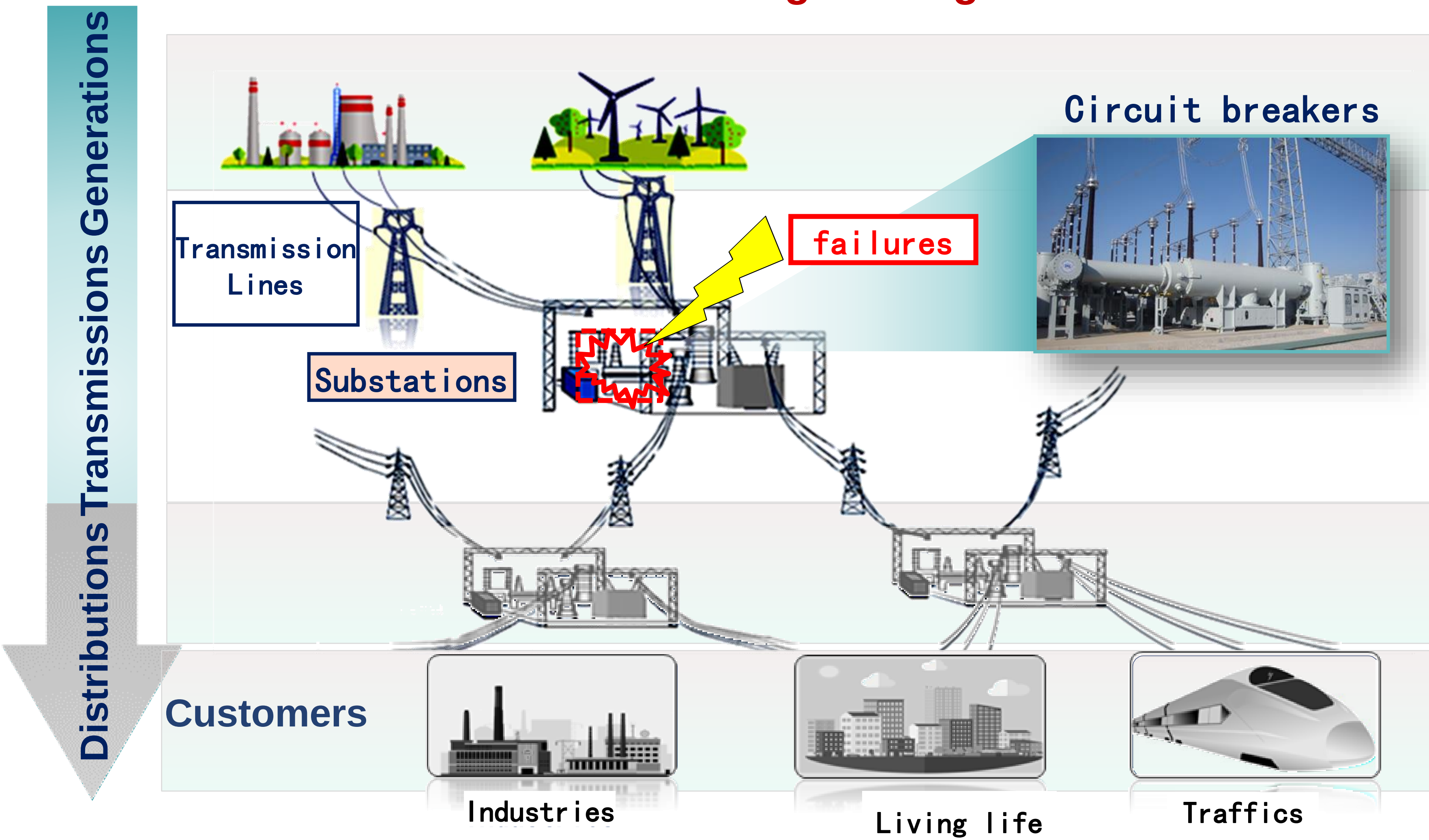
1. Introduction

Where do we come from? **Answer: Xi'an, China**

Terracotta Army

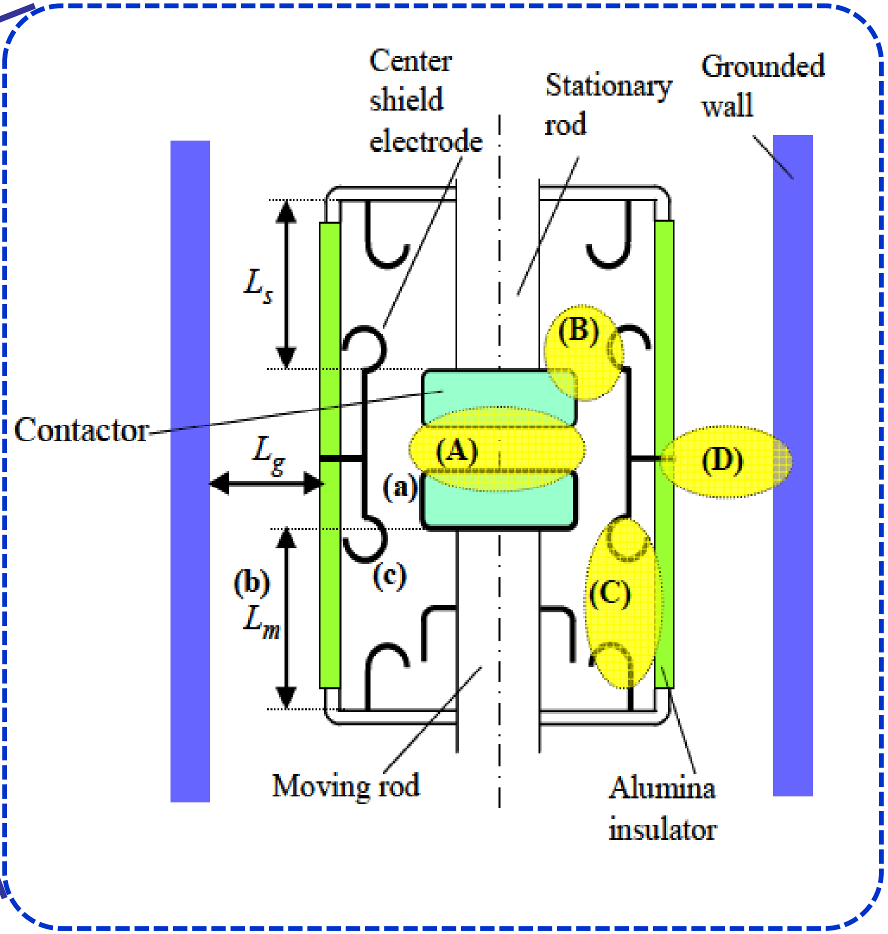
1. Introduction

What is our field? Power Engineering



1. Introduction

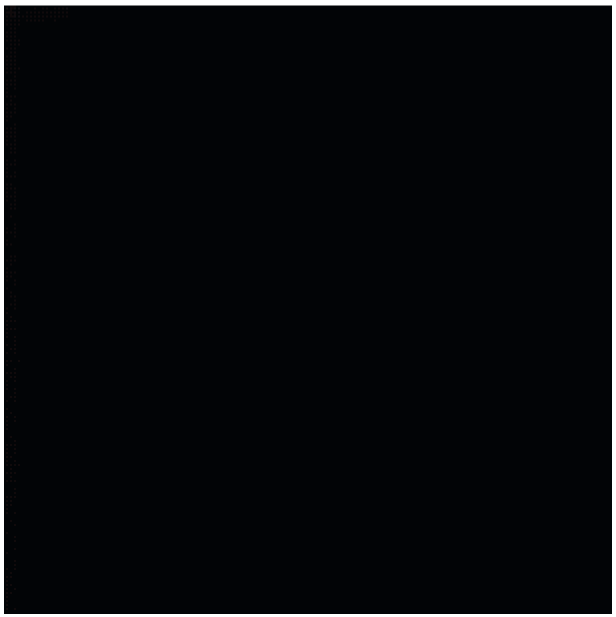
A 126kV single break vacuum circuit breaker
Xi'an Jiaotong Univeristy, Xi'an, China

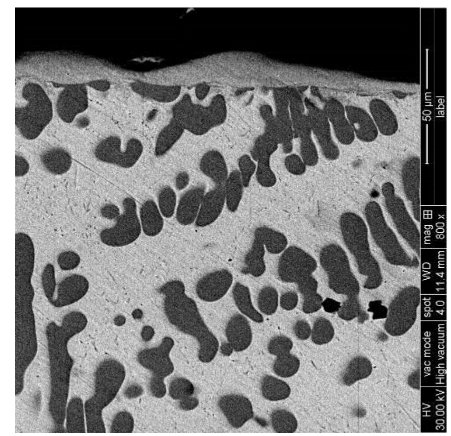


Vacuum gaps for possible breakdowns in vacuum interrupters

1. Introduction

- **Current conditioning is an effective way using vacuum arcs to improve vacuum interrupter's insulation, by producing a remelted layer on the electrode's surface.**



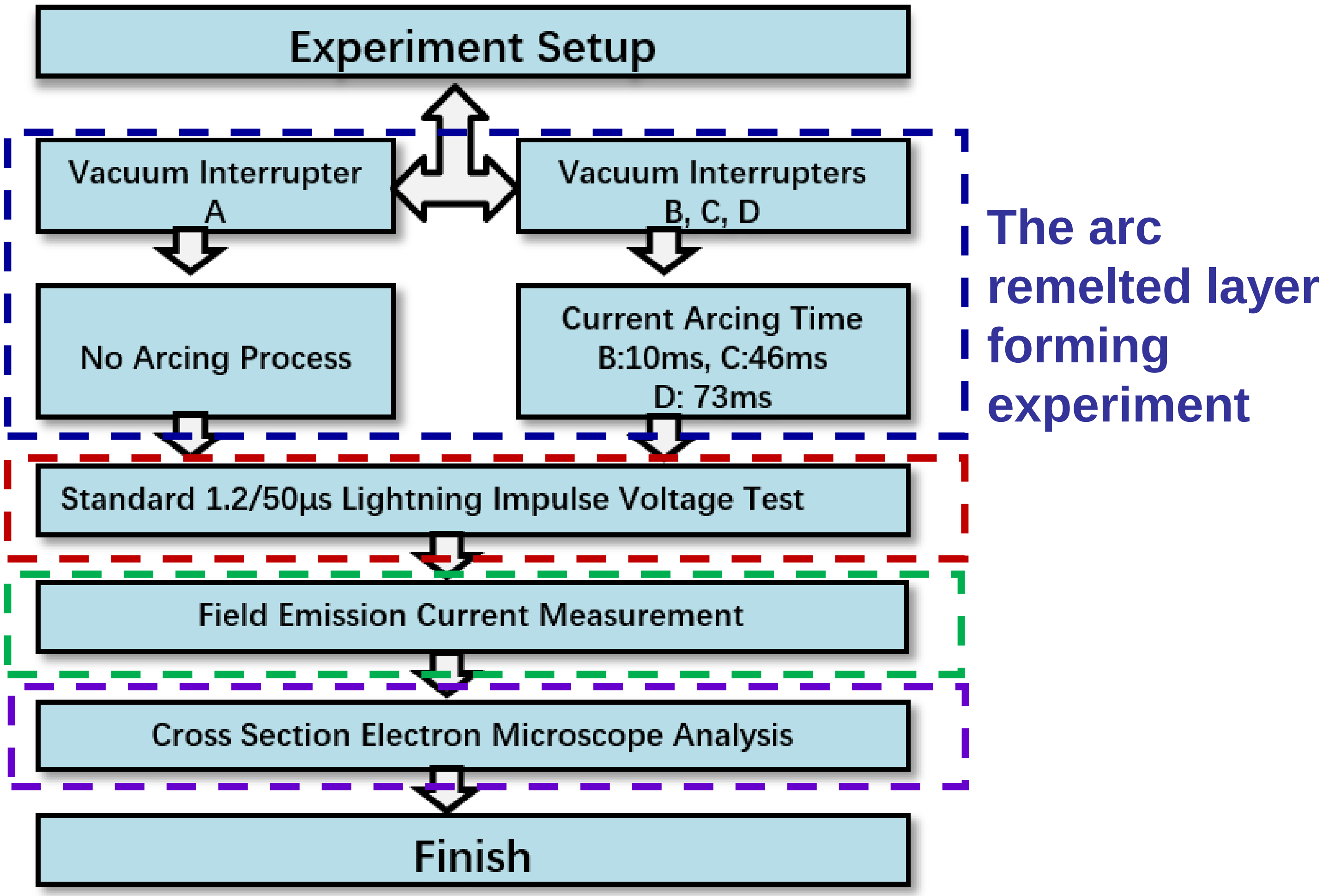


Melted layer produced by current conditioning

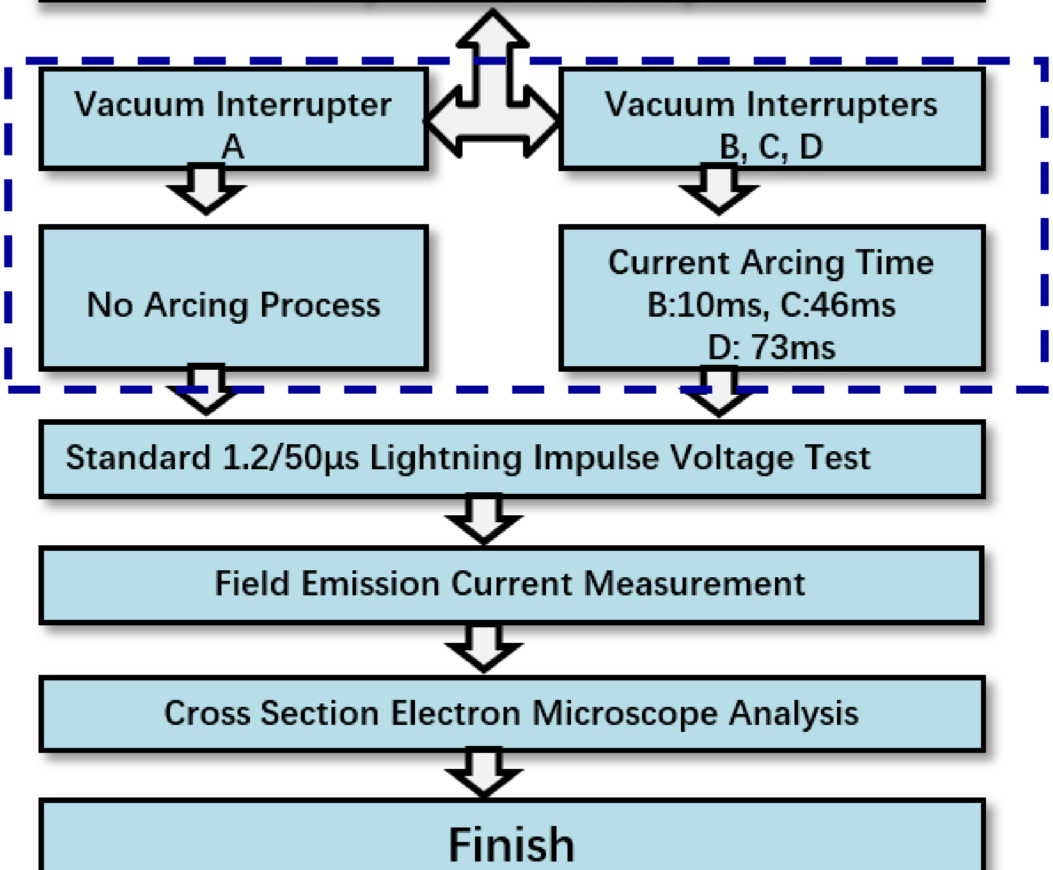
- **The objective of this paper is to determine the influence of the depth of cathode arc-remelted layer on vacuum gap's insulation.**

2. Experimental Setup

◆ System Setup :



3. Experimental Results

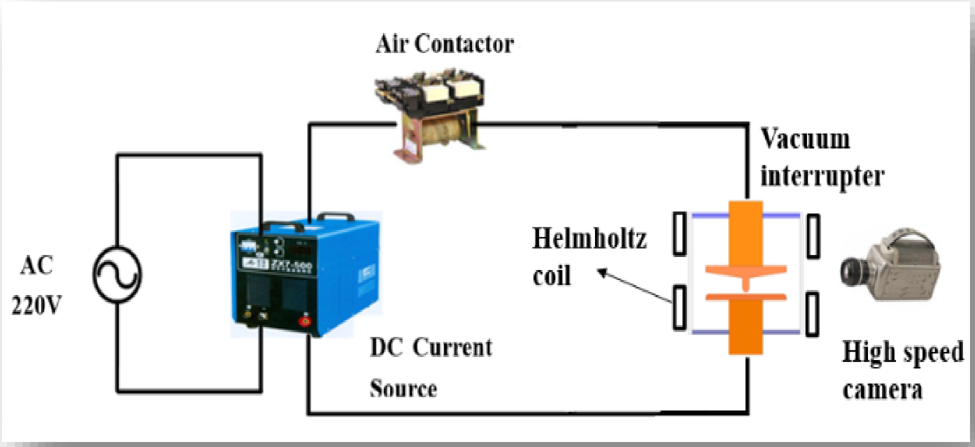


The arc remelted layer forming experiment

3. Experimental Results

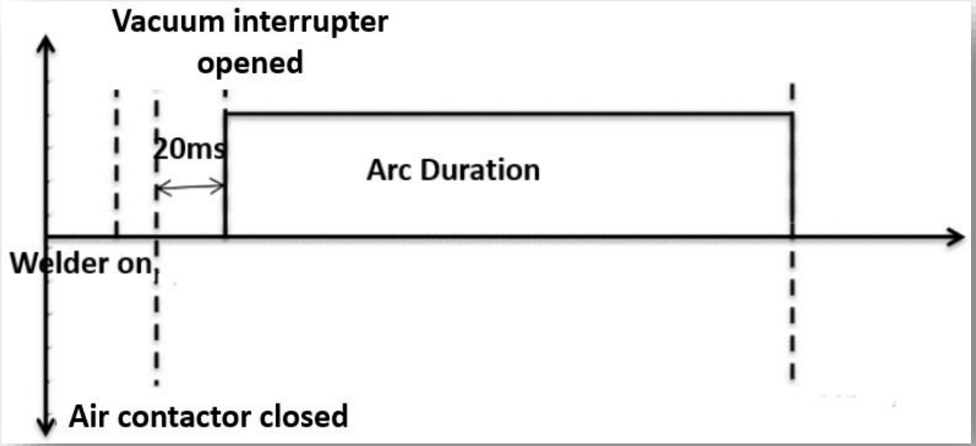
◆ A: The melted layer forming experiment

the experiment circuit



I_{DC} = 250 A
B_{AMF} = 60 mT

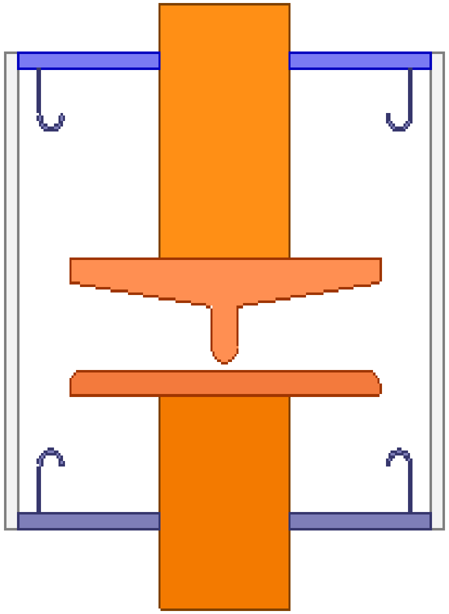
the time sequence of the experiment



Plane electrode-cathode ; Rod electrode-anode

3. Experimental Results

◆ A: The melted layer forming experiment



- Electrode material:

  plane: CuCr25

  rod: CuCr25

- Parameters:

  Φplane = 48 mm,

  Φrod = 4 mm,

  d = 1 mm.

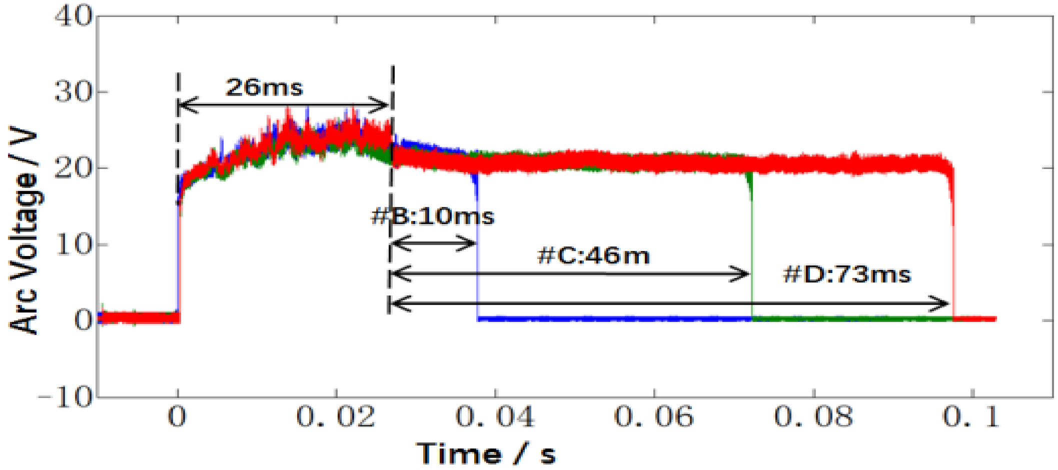
- When forming the arc-remelted layer, the rod was the anode.

- During the lightning impulse voltage test, the rod was the cathode.

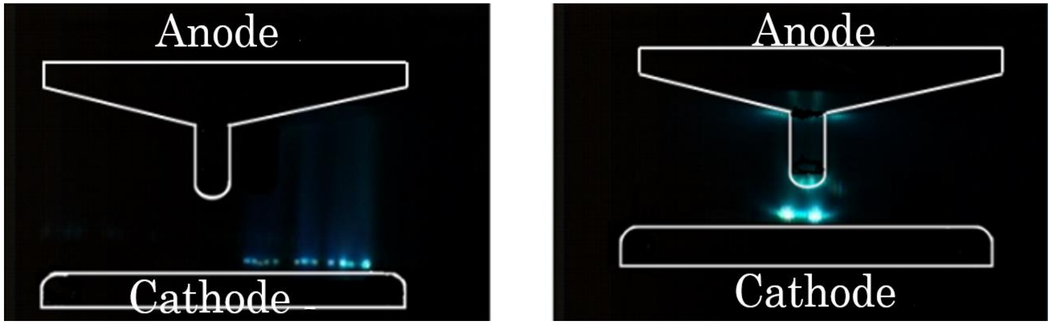
Note: the arc-remelted layer, with different depths, was formed on the rod electrode.

3. Experimental Results

◆ A: The melted layer forming experiment



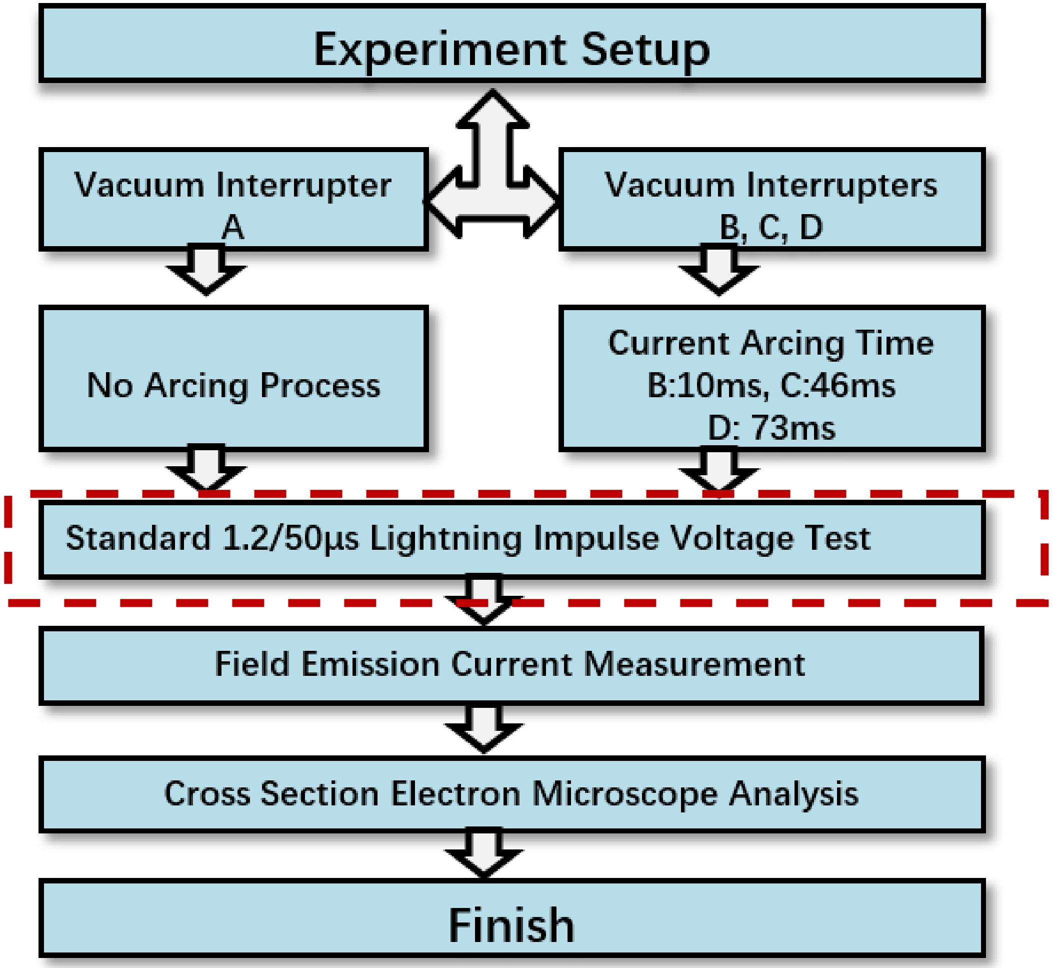
Arc voltage of vacuum interrupter B, C, D



vacuum arc appearances in the arcing duration

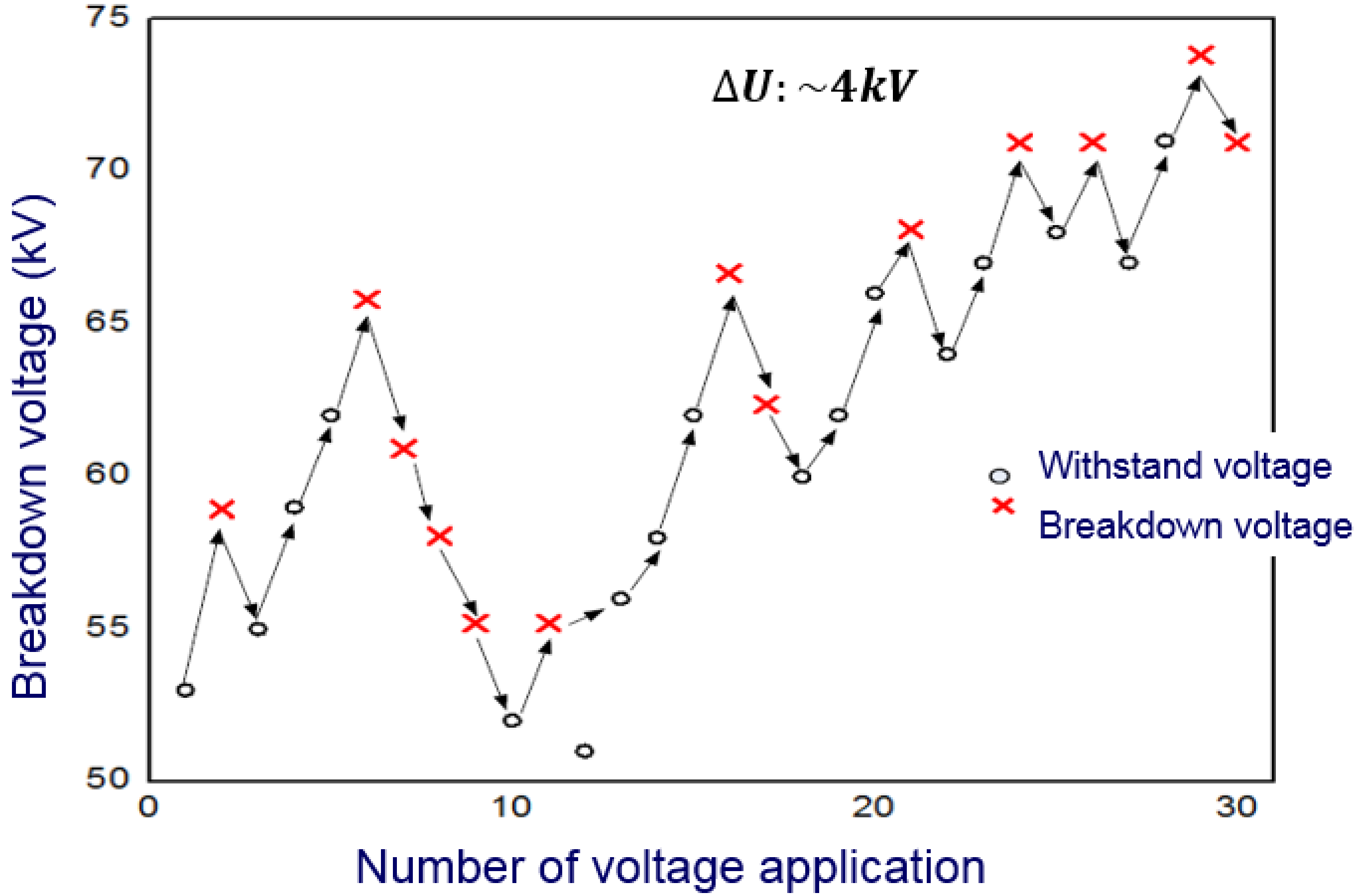
- In the first 26 ms, the arc voltage fluctuated and it corresponded that the vacuum arc rotated randomly on the cathode.
- After that, the arc voltage kept stable, around 20 V. The vacuum arc was opposite to the rod anode.
- So, the arcing time of vacuum interrupters B, C, D were 10 ms, 46 ms, 73ms, respectively.

3. Experimental Results



3. Experimental Results

◆ B: Lightning impulse breakdown voltage test



Plane electrode-anode ; Rod electrode-cathode

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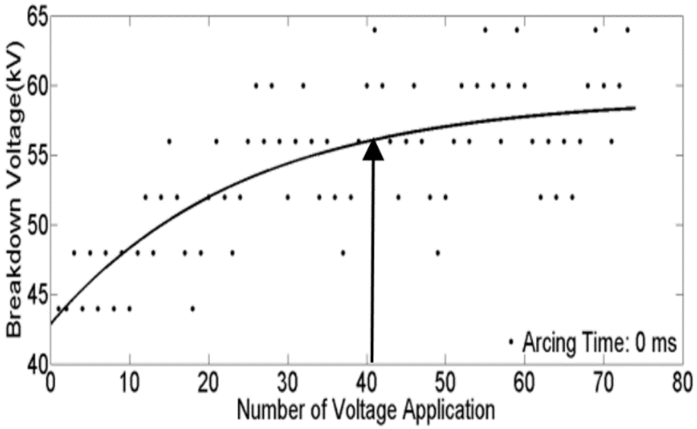
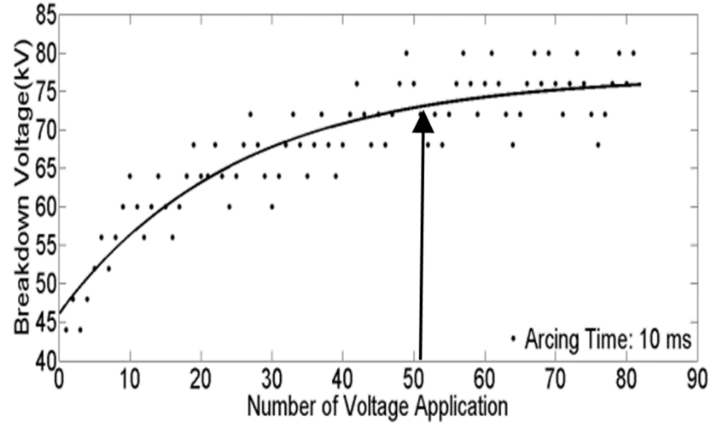
3. Experimental Results

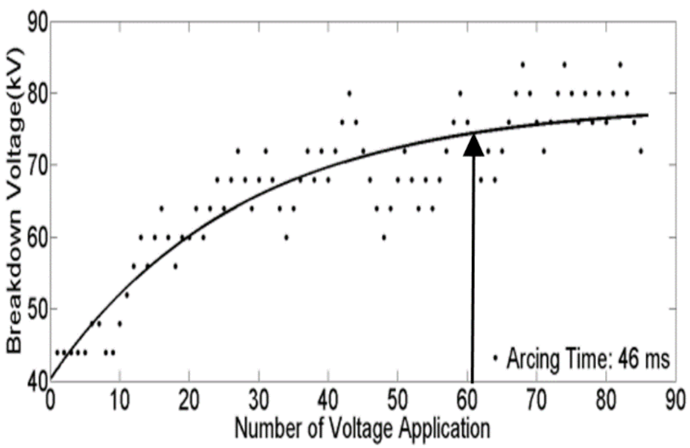
◆ B: Lightning impulse breakdown voltage test



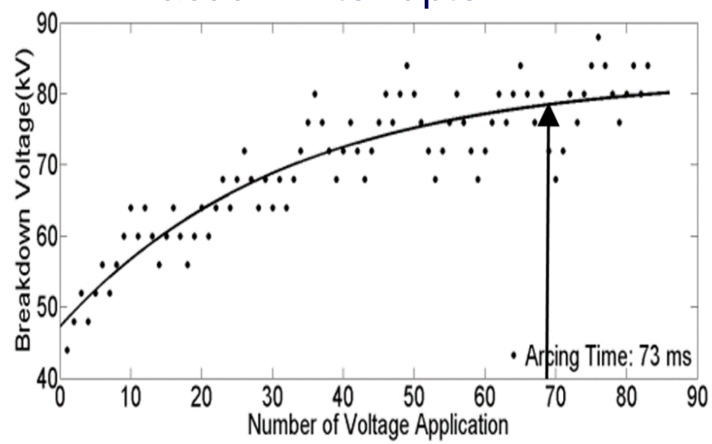
Vacuum Interrupter A



Vacuum Interrupter B



Vacuum Interrupter C

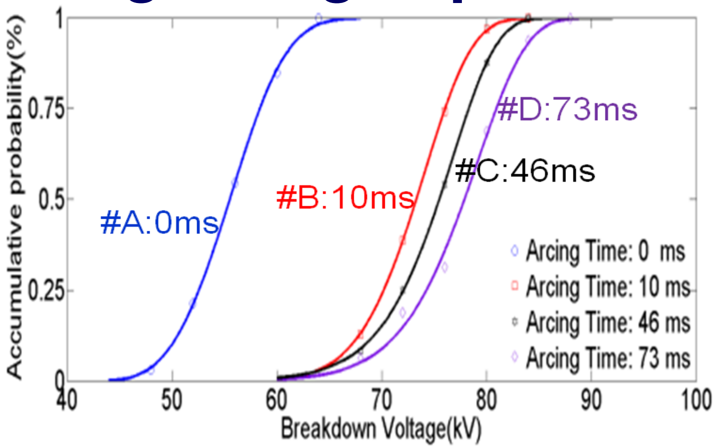


Vacuum Interrupter D

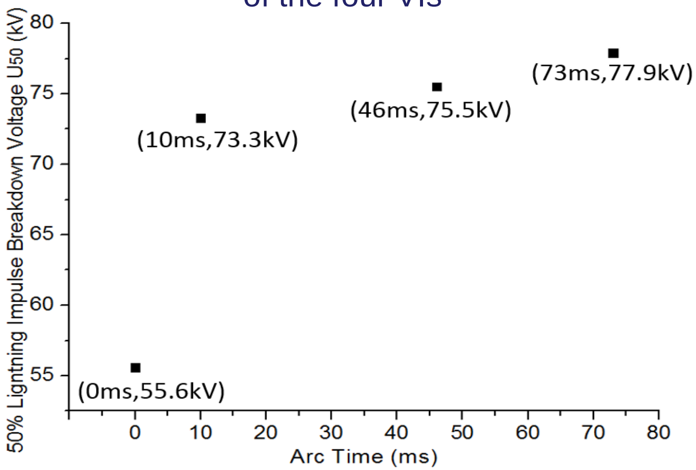
The scattering of breakdown voltage and the fitting conditioning curve of vacuum interrupter

3. Experimental Results

◆ B: Lightning impulse breakdown voltage test



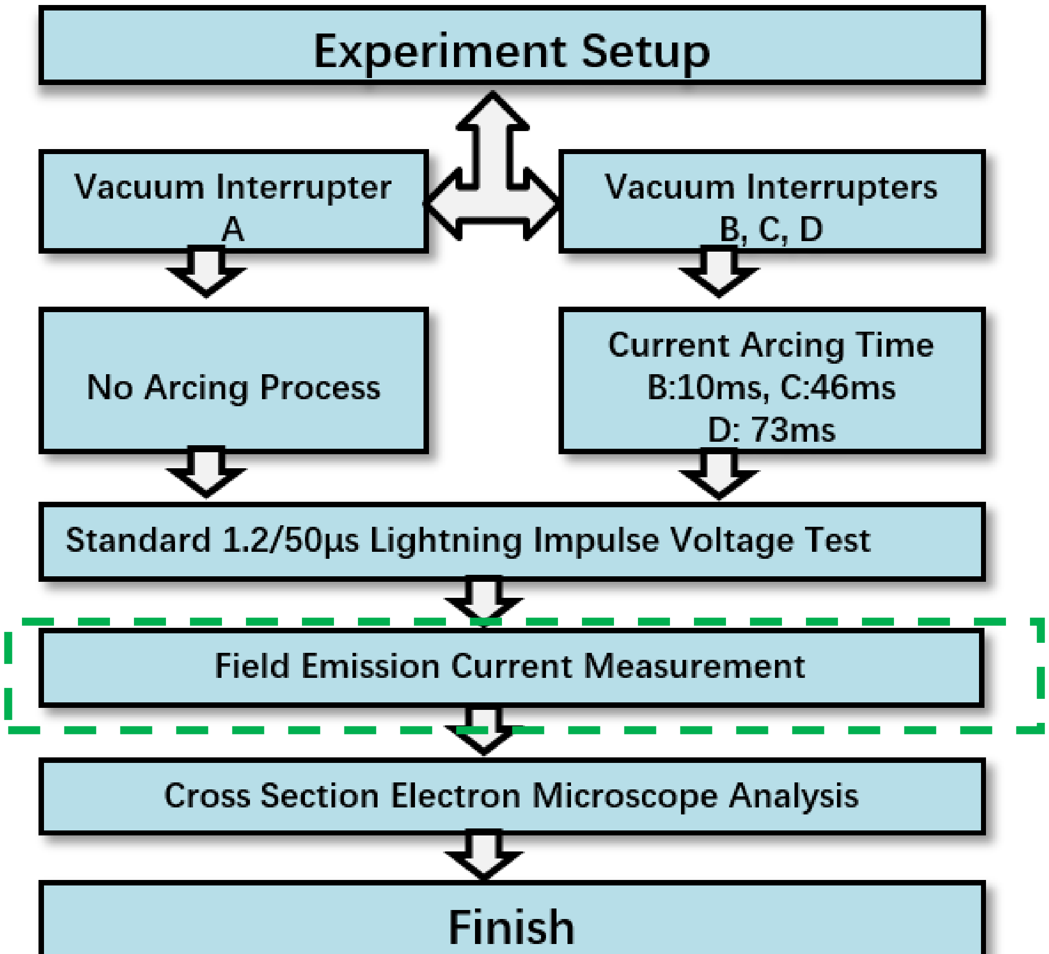
The accumulative probability of breakdown voltage of the four VIs



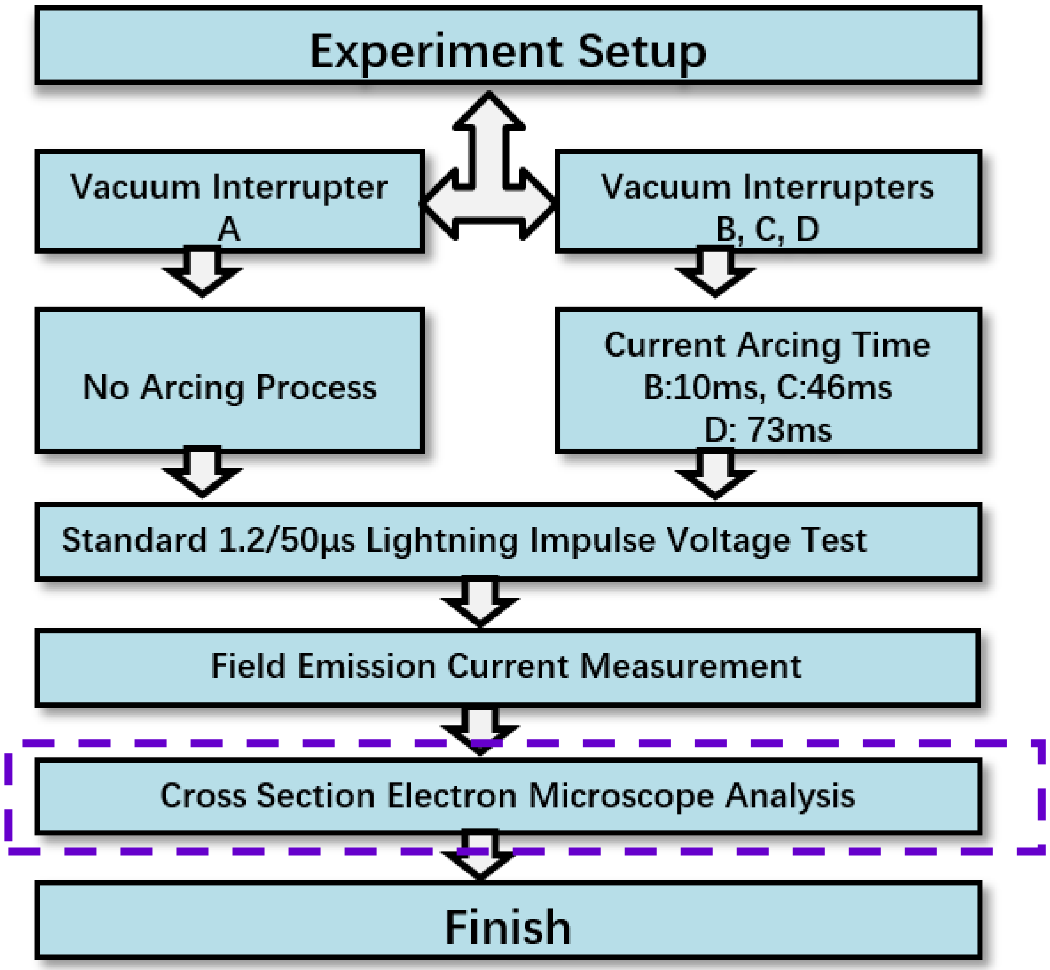
The relationship between the 50% lightning impulse breakdown voltage, U50, and the arcing time of the four VIs.

- The breakdown voltage probability distribution of vacuum interrupters A, B, C, D fitted Weibull distribution.
- With arcing times of 10, 46, and 73 ms, U_{50} was higher than that of the no arcing case. The arcing improved the breakdown voltage.
- The U_{50} of the arcing times of 10, 46, and 73 ms were 73.3, 75.5, and 77.9 kV, respectively. They were quite close to each other, so the different arcing times had little influence on the breakdown voltage.

3. Experimental Results

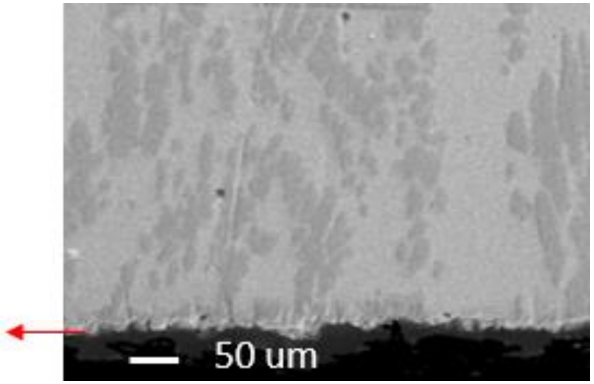


3. Experimental Results



3. Experimental Results

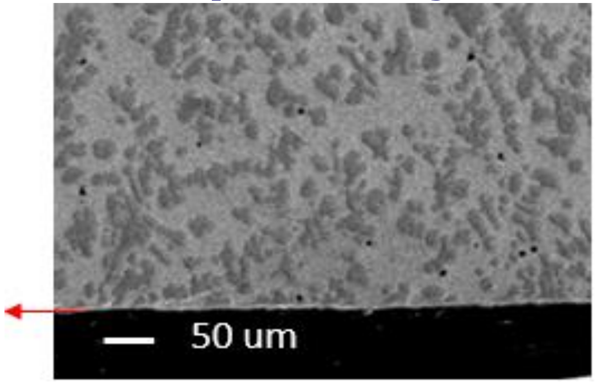
◆ D: Cross section electron microscope analysis



VI A arcing time: 0 ms

No arc-remelted layer, rough surface

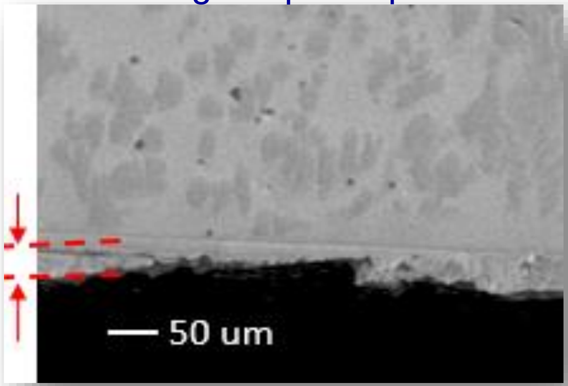
Average depth: 0 μm



VI B arcing time: 10 ms

A thin arc-remelted layer with smooth surface

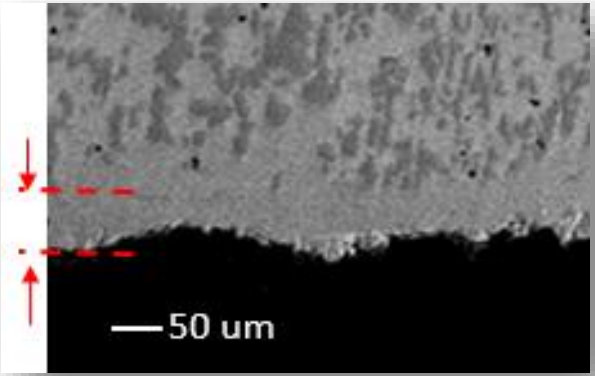
Average depth: 5 μm



VI C arcing time: 46 ms

Arc-remelted layer: 10-50 μm

Average depth: 35 μm



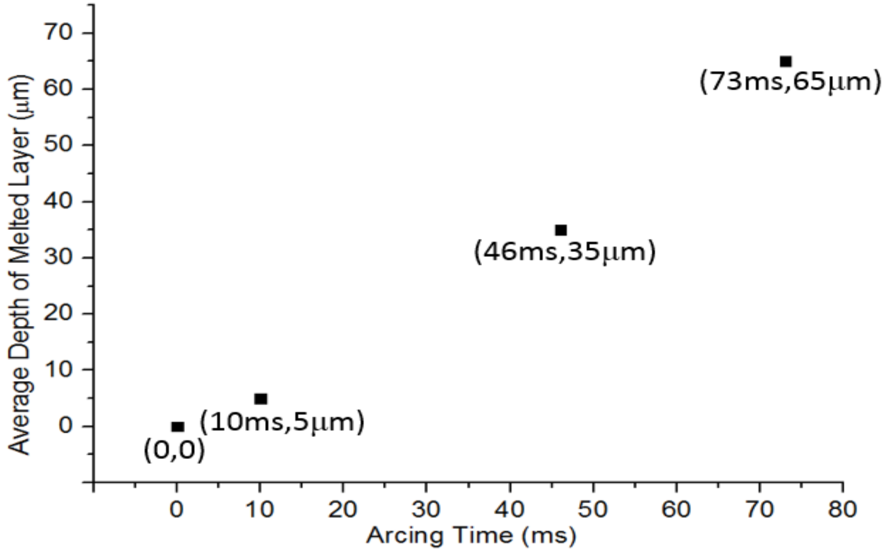
VI D arcing time: 73 ms

Arc-remelted layer: 50-80 μm

Average depth: 65 μm

3. Experimental Results

◆ D: Cross section electron microscope analysis

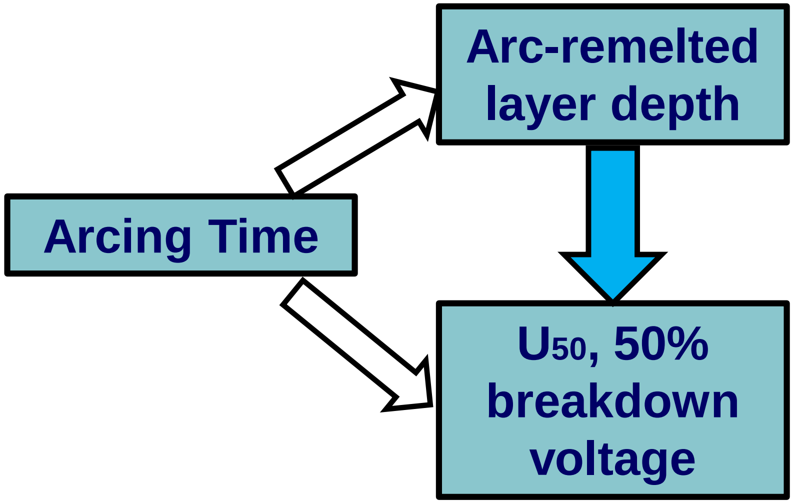


arcing time and average depth of arc-remelted layer.

- The average depths of the arc-remelted layers 0, 5, 35, and 65 μm corresponded to arcing times of 0, 10, 46, and 73 ms, respectively.
- The average depth of arc-remelted layer was proportional to the arcing time.

3. Experimental Results

◆ E: Relationship between arc-remelted layer depth and the breakdown voltage



- Having an arc-remelted layer apparently improved vacuum insulation significantly.
- The various depth of the arc-remelted layer seem have close vacuum insulation level.

Vacuum interrupter	Average depth of arc-remelted layer / μm	50% breakdown voltage / kV
A	0	55.6
B	5	73.3
C	35	75.5
D	65	77.9

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4. Discussion

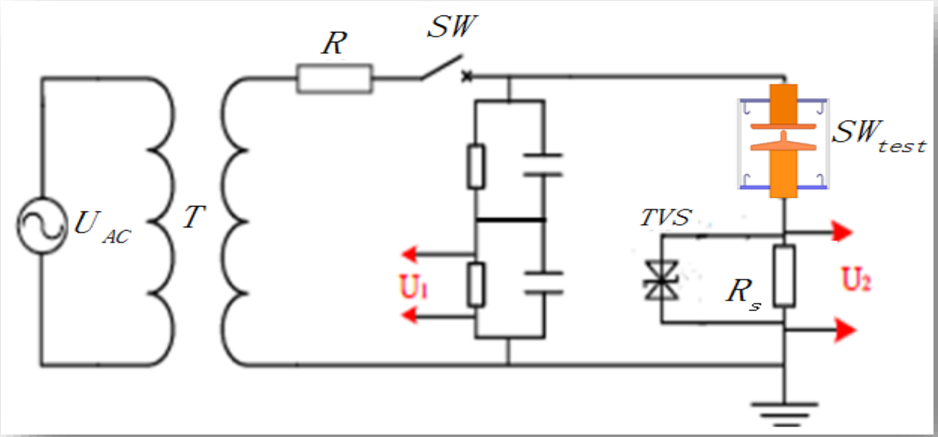
- Observation: Arcing times of 0, 10, 46 and 73 ms corresponded to

1) the average arc-remelted layer depths of 0, 5, 35 and 65 μm, respectively.
2) The 50% breakdown voltages of 55.6, 73.3, 75.5, and 77.9 kV

- It is not surprising that an arc-remelted layer significantly increase the breakdown voltage.
- However, the arc-remelted layers seem have virtually no influence on the vacuum insulation level, why?
- Is the vacuum insulation level decided by the electrode surface conditions, not the arc-remelted layer depth?

4. Discussion

◆ C: Field emission current measurement



The field emission current measurement circuit

Gap spacing : 1.0 mm
Rs : 2kΩ
BD voltage of TVS: 15 V
Maximum leakage current before BD of TVS: 1 μA

The field emission current I and the applied voltage V fit Fowler-Nordheim equation

$$\ln\frac{I}{V^2}=\ln\left[\frac{1.54\times10^{-6}A_e\beta^2 10^{4.52\Phi^{-0.5}}}{\Phi d^2}\right]-\frac{2.84\times10^9 d\Phi^{1.5}}{\beta}\bullet\frac{1}{V}$$

CuCr25, Φ: 4.6 eV

4. Discussion

◆ Electric field enhancement factor

Vacuum interrupter	Peak value of voltage /kV	Electric field enhancement factors β	Breakdown	
A	39.9	270	No.1	
B	42.7	340	--	No.2
C	39.9	273	No.1	
D	39.9	275	No.1	

The field emission current measurement were carried out before the first breakdown. Therefore, sample B is out of consideration.

- β values of sample A, C and D were nearly the same, around 273 at the same applied voltage.
- Remember: The 50% breakdown voltages of sample C and D with arcing (75.5 kV and 77.9 kV) were much higher that that of sample A (55.6 kV) without arcing.

4. Discussion

The similar β values suggest the similar contact surface conditions.

However, similar surface conditions lead to different breakdown voltage?

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4. Discussion

◆ Electric field enhancement factor?

Fowler-Nordheim equation

$$\ln\frac{I}{V^2} = \ln\left[\frac{1.54\times10^{-6}A_e\beta^2 10^{4.52\Phi^{-0.5}}}{\Phi d^2}\right] - \frac{2.84\times10^9 d\Phi^{1.5}}{\beta}\bullet\frac{1}{V}$$

CuCr25, work function: 4.6 eV

Same value for the cases with and
without the arc-remelted layers

- ➢ How to deal with the work function with and without the arc-remelted layers to reflect the difference on the arc-remelted layers?
- ➢ Different β values should distinguish the contact surface with and without the arc-remelted layers…

Thanks for your attention！