Study on optimum electron beam welding conditions

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1. Accelerating field of modern superconducting radiofrequency (SRF) cavities are often limited by quenches.

2. Quench locations can be identified by the temperature mapping and optical inspection system. According to these observations, poor weld is one of causes of quenches.

3. The above suggest that optimizing Electron beam welding (EBW) conditions might solve the quench problems.
Introduction

1. Accelerating field of modern superconducting radiofrequency (SRF) cavities are often limited by quenches.

2. Temperature mapping (T-mapping) and optical inspection system can identify quench locations. According to these observations, poor weld is one of the causes of quenches.

3. The above suggest that optimizing Electron beam welding (EBW) conditions might solve the quench problems.

\[ Q_0 \text{ vs. } E_{acc} \text{ Curve @ } \pi \text{ mode for TOS#2 1st V.T. (2012/2/2)} \]

- 4.2K
- 1.7-2.0K (1st)
- 1.7K (2nd)

Quench@31MV/m

Yasuchika Yamamoto
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2. Quench locations can be identified by the temperature mapping and optical inspection system. According to these observations, poor weld is one of causes of quenches.

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Outline

• Experiment and EBW parameters
• Typical geometries of weld beads
• Search for good parameter-regions
• Magnetic field enhancement at pits
• Summary and outlook
Experiments and parameters
1. Cut out Nb test-pieces (150mm × 150mm)
2. Pre-weld etchings (10–30μm) by 1:1:1 BCP solution.
3. EBW at the next room
Examples of test pieces (heads↑ and tails↓). Various combinations of parameters were tried.
EBW parameters

1. Combinations of generator position and welding direction

2. Accelerating voltage, $V_a$ (kV)

3. Beam current, $I_b$ (mA)

4. Welding speed, $v$ (mm/s)

5. $a_b$-factor
EBW parameters

1. Combinations of generator position and welding direction

2. Accelerating voltage, $V_a$ (kV)

3. Beam current, $I_b$ (mA)

4. Welding speed, $v$ (mm/s)

5. $a_b$-factor
EBW parameters

1. Combinations of beam generator position and welding direction

(a) V-H

2. Accelerating voltage, $V_a$ (kV),

3. Beam current, $I_b$ (mA),

4. Welding speed, $v$ (mm/s),

5. $a_b$-factor
EBW parameters

1. Combinations of beam generator position and welding direction

(a) V-H

(b) H-H

2. Accelerating voltage, $V_a$ (kV),

3. Beam current, $I_b$ (mA),

4. Welding speed, $v$ (mm/s),

5. $a_b$-factor
EBW parameters

1. Combinations of beam generator position and welding direction

(a) V-H

(b) H-H

(c) H-D
EBW parameters

1. Combinations of beam generator position and welding direction

(a) V-H

(b) H-H

(c) H-D

(d) H-U
EBW parameters

1. Combinations of beam generator position and welding direction,

2. Accelerating voltage, $V_a$ (kV)

3. Beam current, $I_b$ (mA)

4. Welding speed, $v$ (mm/s)

5. $a_b$-factor
EBW parameters

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2. Accelerating voltage, $V_a$ (kV)

3. Beam current, $I_b$ (mA)

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5. $a_b$-factor

$P = V_a \times I_b$
EBW parameters

1. Combinations of beam generator position and welding direction

2. Accelerating voltage, $V_a$ (kV)

3. Beam current, $I_b$ (mA)

4. Welding speed, $v$ (mm/s)

5. $a_b$-factor

Energy deposition per length $\frac{V_a I_b}{v}$
EBW parameters

1. Combinations of beam generator position and welding direction

2. Accelerating voltage, $V_a$ (kV)

3. Beam current, $I_b$ (mA)

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EBW parameters

1. Combinations of generator position and welding direction
2. Accelerating voltage, $V_a$ (kV)
3. Beam current, $I_b$ (mA)
4. Welding speed, $v$ (mm/s)
5. $a_b$-factor

$\quad a_b \equiv \frac{l}{f}$

Defocused

Focused: $a_b = 1$

Defocused: $a_b < 1, a_b > 1$
EBW parameters

1. Combinations of generator and welding direction,
2. Accelerating voltage, $V_a$ (kV),
3. Beam current, $I_b$ (mA),
4. Welding speed, $v$ (mm/s),
5. $a_b$-factor
Typical geometries of weld beads
Underbead geometry (case (a): V-H)

Case (a) Vertical gun direction and Horizontal welding direction.
Underbead geometry (case (a): V-H)

Case (a) Vertical gun direction and Horizontal welding direction.
Underbead geometry (case (a): V-H)

Case (a)
Vertical gun direction and Horizontal welding direction.

Case (a)

Vertical gun direction and Horizontal welding direction.
Underbead geometry (case (a): V-H)

Cross section of an underbead

Welding direction

Gravity

Inside a test piece

Case (a) Vertical gun direction and Horizontal welding direction.
Underbead geometry (case (b): H-H)

**Case (b)**
**Horizontal** gun direction and **Horizontal** welding direction.
Underbead geometry (case (b): H-H)

Case (b) **Horizontal** gun direction and **Horizontal** welding direction.
Underbead geometry (case (b): H-H)

Inside a test piece

Gravity

Welding direction

Case (b) Horizontal gun direction and Horizontal welding direction.
Underbead geometry (case (c): H-D)

Case (c) **Horizontal** gun direction and **Downward** welding direction.
Underbead geometry (case (c): H-D)

Underbead

Welding direction

Gravity

Case (c) **Horizontal** gun direction and **Downward** welding direction.
Underbead geometry (case (c): H-D)

Underbead

Welding direction

Gravity

Cross section of an underbead

Inside a test piece

Case (c) Horizontal gun direction and Downward welding direction.
Underbead geometry (case (d): H-U)

Case (d) **Horizontal** gun direction and **Upward** welding direction.
Underbead geometry (case (d): H-U)

Welding direction and Upward welding direction.
Underbead geometry (case (d): H-U)

Case (d) horizontal gun direction and upward welding direction.
Underbead geometry

Case (a): V-H

Case (b): H-H

Case (c): H-D

Case (d): H-U
Underbead geometry

Case (a): V-H

Case (b): H-H
Search for good parameter-regions
Examples of underbeads

Good weld

Poor weld

Holes

Weld spatters

Narrow underbeads
Good parameter-regions

60 kV

Defocused $a_b < 1$

Focused $a_b = 1$

Defocused $a_b > 1$

Beam current $I_b$ (mA)
Good weld parameter regions:

- **Defocused** $a_b < 1$
- **Focused** $a_b = 1$
- **Defocused** $a_b > 1$

- Beam current $I_b$ (mA)
- Voltage $V$ (kV)

Diagram showing weld quality under different beam current and voltage conditions.
Good parameter-regions

60 kV

Weld spatters

Good weld

Defocused $a_b < 1$

Focused $a_b = 1$

Defocused $a_b > 1$

Beam current $I_b$ (mA)

$60 \text{kV}$

Test piece
60 kV holes

Defocused $a_b < 1$
Focused $a_b = 1$
Defocused $a_b > 1$

Weld spatters

Good weld Good weld

Good parameter-regions

Beam current $I_b$ (mA)

$60 \text{kV}$ holes

Focused $a_b = 1$
Good parameter-regions

- 60 kV
- Defocused $a_b < 1$
- Focused $a_b = 1$
- Defocused $a_b > 1$
- Good weld
- Weld spatters
- Narrow underbeads

Beam current $I_b$ (mA)

$\text{holes}$

Test piece
Good parameter-regions

- **60 kV**

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**Beam current**

- **Defocused**: $a_b < 1$
- **Focused**: $a_b = 1$
- **Defocused**: $a_b > 1$
Good parameter-regions

- **60 kV**
- **90 kV**

**Beam current**

- Defocused: $a_b < 1$
- Focused: $a_b = 1$
- Defocused: $a_b > 1$
Good parameter-regions

Beam current

Defocused $a_b < 1$
Focused $a_b = 1$
Defocused $a_b > 1$
Good parameter-regions

THIOA03
Cavity Fabrication Study in CFF at KEK,
Masashi Yamanaka (KEK)
Discussions on pit
Magnetic field enhancement at pits

Direction of magnetic field

Height (μm)

Position (μm)

magnetic field

atmosphere

niobium
Magnetic field enhancement at pits

Magnetic field is enhanced at edges

- Direction of magnetic field
- Magnetic field is enhanced at edges
Magnetic field enhancement at pits

Magnetic field is enhanced at edges

Shape of the bottom is not important
Magnetic field enhancement at pits

The simplest model is a two-dimensional pit with a triangular section.
Magnetic field enhancement at pits

The simplest model is a two-dimensional pit with a triangular section.

- A slope angle $\alpha$,
- Pit size $R$,
- Round edge radius $r_e$.
Magnetic field enhancement at pits

The simplest model is a two-dimensional pit with a triangular section

The magnetic field enhancement factor at the edges are given as a function of a slope angle $\alpha$, pit size $R$, and round edge radius $r_e$:

$$\beta^* = P(\alpha) \left( \frac{R}{r_e} \right)^{\frac{\alpha}{1+\alpha}}$$

$P(\alpha)$ is given in Poster TUP008
\[ \beta^* = P(\alpha) \left( \frac{R}{r_e} \right)^{\frac{\alpha}{1+\alpha}} \]

\[ B_{\text{break down}}^{\text{peak}} \sim \frac{200 \text{ mT}}{\beta^*} = \frac{200 \text{ mT}}{P(\alpha)} \left( \frac{r_e}{R} \right)^{\frac{\alpha}{1+\alpha}} \]

\[ E_{\text{acc}}^{\text{break down}} = g^{-1} B_{\text{break down}} = g^{-1} \frac{200 \text{ mT}}{P(\alpha)} \left( \frac{r_e}{R} \right)^{\frac{\alpha}{1+\alpha}} \]

where \( g = B_{\text{peak}}/E_{\text{acc}} \) for a given cavity shape
Comparisons with vertical test results

\( \alpha, R, \) and \( r_e \) are measured from pit profiles

**Pit (1)**

TOS-02 cavity, cell#7-173°

\[ \alpha = 0.19 - 0.23 \]
\[ R = 90 - 110 \, \mu m \]
\[ r_e = 27 - 33 \, \mu m \]

**Pit (2)**

MHI-05 cavity, cell#6-320°

\[ \alpha = 0.24 - 0.30 \]
\[ R = 52 - 64 \, \mu m \]
\[ r_e = 20 - 24 \, \mu m \]
Comparisons with vertical test results

\[ \alpha = 0.19 - 0.23 \]
\[ R = 90 - 110 \ \mu m \]
\[ r_e = 27 - 33 \ \mu m \]

\[ \alpha = 0.24 - 0.30 \]
\[ R = 52 - 64 \ \mu m \]
\[ r_e = 20 - 24 \ \mu m \]
Comparisons with vertical test results

TUP008
Model of the magnetic field enhancement at pits,
Takayuki Kubo (KEK)

\[ R = 90 - 110 \, \mu m \]
\[ r_e = 27 - 33 \, \mu m \]

\[ R = 52 - 64 \, \mu m \]
\[ r_e = 20 - 24 \, \mu m \]
Summary

• We started a study on optimum EBW parameters.
• Beam generator position and welding direction dramatically affect a geometry of weld bead.
• Parameter regions for good welds were surveyed.
• Formula for a magnetic enhancement factor at pits was derived, which agree with experiments.

To accumulate statistics is a future work.
Backup
Figure 4: Examples of contaminants found after the BCP [3]. The contaminants include carbon and oxygen, or carbon, nitrogen and oxygen.

Figure 5: Schematic layouts of the speculated pit formation mechanism [3]. Contaminants involved in molten Nb cause a pit formation.