RECENT RESULT OF THE CAVITY INSPECTION FOR THE SUPERCONDUCTING CAVITIES AT KEK-STF

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Abstract

The inspection of inner surface of the superconducting rf cavities is essential in achieving high accelerating gradient. The camera system developed by the Kyoto-KEK collaboration is a good tool to survey defect locations and to analyse a defect shapes in the inner surface of the cavities for boost accelerating gradient yield of 1.3 GHz superconducting 9-cell cavities. The inspection of the five STF baseline cavities in each process was carried out to study relations between a defect shape and a heating location of the cavities in the vertical test. The careful inspection of the EBW seams and neighboring region at equator and iris parts was carried out before the vertical test.

The vertical tests of these cavities using T-map with fixed thermometer allocation were carried out at STF in KEK from December 2008 to July 2009. Non-uniform EBW seams in the equator area and the strain inside of cavity were found at the heating locations detected by T-map at high field. The inspection result of these cavities will be presented in this paper.

KEK-STFにおける超伝導加速空洞の空洞内面検査

1. はじめに

KEK-STFでは、超伝導加速空洞における空洞性能 の歩留まり向上のために、高分解能カメラ(京都カ メラシステム[1])を用いた空洞内面検査を行ってい る。縦測定で観測される発熱位置およびそのときの 加速電界と空洞内面に見られる欠陥(幾何学的形状 変化やコンタミなど)との相関を調査するために、 STF Baseline空洞 (運転周波数1300MHz:空洞名 称: MHI-05からMHI-09) を用いて各処理工程にお ける空洞内面の状態を調べ、縦測定前に欠陥と思わ れる箇所を事前に調査して縦測定を行った。空洞内 面の主な検査箇所は、セル赤道部およびアイリス部 の電子ビーム溶接の溶接シームとその近傍の領域で ある。現在、空洞製作直後からの各表面処理工程に おける表面状態の変化を追跡しており、工業化にお ける加速空洞の品質基準の明確化を試みている。ま た、これらの欠陥と空洞性能との相関を詳細に調べ ることで、空洞内面検査工程の自動化[2]に必要な情 報が得られる。

2. 縦測定前の内面検査工程について

空洞内面検査の工程を以下に示す。

- A) 空洞受取後
- B) Pre-EP (5µm) 、EP-1 (100µm) 、アニール後

C) EP-2 (20~50 µ m) 、縦測定後

A)の検査は空洞性能の歩留まり向上における電子 ビーム溶接の品質管理および溶接のオペレーターへ のフィードバックのため重要なものである。 また、B)およびC)は表面処理時における作業の工程 管理や電解研磨処理および洗浄・組み立てなどにお ける工程管理に対する知見を得ることに繋がる。



図2:空洞受取後(左)、EP-1後(右)における赤 道部の表面状態(MHI-05)

図1にSTF Baseline空洞と内面検査における主な

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検査箇所を示す。図2にMHI-05の空洞受取後とEP-1後の赤道部における溶接シームの様子を示す。通 常行っている観察位置は、赤道部およびアイリス部 の電子ビーム溶接部すべてと赤道部の開先から± 15mmの領域である。

3. 各空洞における赤道部の電子ビーム溶 接の状態

図3にMHI-05およびMHI-06、図4にMHI-07から MHI-09のエンドセルおよびセンターセルの赤道部 における電子ビーム溶接シームの代表例を示す(空 洞受取直後の状態)。ここで、MHI-05およびMHI-06は2007年度に製作され、一方、MHI-07、MHI-08 およびMHI-09は2008年度に製作されたものであり、 各ロッドの品質に差は見られなかった。

MHI-05およびMHI-06では、エンドセル(1-cellと 9-cell)の溶接シームは赤道部全周を通して安定で あった(幅、高さなど)。一方、センターセル(2cell~8-cell)では、赤道部一周の間に安定と不安定 な領域が混在していた(溶接シームの幅が2~5mmと ばらつきが大きい)。この不安定な溶接シームがで きる原因として、トリム加工における開先部の厚み に対する工作精度(0.1mm程度)が考えられ、MHI-07からMHI-09では、電子ビーム溶接の条件を最適 化し、赤道部全周を通して安定な溶接シームを得る ことができた[3]。これら溶接シームの違いが空洞性 能に与える影響についても調査の対象となる。



4. 縦測定時に観測された発熱箇所と空洞 内面の関係

2008年11月から2009年7月にかけて、MHI-

05~MHI-08の4空洞についてSTFに建設された電解研 磨施設で処理を行った後、縦測定を行った。縦測定 時には空洞外面に固定式の温度マッピングを取り付 け、常時クエンチ位置をモニターしている[4]。表1 にMHI-05、MHI-06、MHI-07およびMHI-08の各縦測 定で観測された発熱位置とそのときの電界強度およ び縦測定後に行った空洞内面検査の結果をまとめる。

MHI-05 (1st、2nd) およびMHI-06 (1st、4th) では、 パスバンドモードの測定において、High fieldで発熱 が観測された位置近傍に電子ビーム溶接シームが不 安定な箇所が観測された(他にも不安定な箇所が存 在するが、発熱が観測されない箇所もあった)。図 5はMHI-05で観測された溶接シームが不安定な箇所 の代表例である。図中のオレンジの円は温度セン サーの位置を示している。図6に図5で示した箇所の 空洞受取後の様子を示す。MHI-05 (2nd)、および MHI-06 (4th) のπモードでは、約20MV/mでクエン チが起こっているが、この発熱箇所周辺に対して異 常は観測されなかった。

 一方、STF電解研磨処理施設ではEP液中のニオブの溶け込み量が増加したため、2009年5月にEP液を 新液に交換した。EP液交換後、初めに処理を行った
2空洞(1回目: EP-2 MHI-06 5th、2回目: EP-2 MHI-07 1st)はField emissionで空洞性能が制限された。

表1:		縦測定後に行っ	た空洞内面	検査の)結:	果
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Cavity # of Cause of limitation Heating location Result of inspection (after V.T. with T-map Cause of limitation MH-05 1** 27.3 @ PLmode Pield emission #5 cell equator, 1=60-150deg. Unstable: With of the EBW seam is narro No defect in outside weld area. 2*4 19.7 @ PL 89, 49, 39 Defect 7 Quench #6 cell equator, 1=50-150deg. No defect in outside weld area. 2.5 (mm x2 39) @ 59 Quench #3 cell equator, 1=10-150deg. Instable: Within of the EBW seam is narro No defect in outside weld area. 32.9 @ 69 Quench #6 cell equator, 1=120-180deg. Unstable: Within of the EBW seam is narro No defect in outside weld area. 32.9 @ 69 Quench #6 cell equator, 1=270-360deg. Unstable: Within of the EBW seam is narro No defect in outside weld area. MH-06 1* 25.7 @ PI-mode #7 cell equator, 1=200-300deg. Unstable: Within of the EBW seam is narro No defect in outside weld area. Quench #5 cell equator, 1=300-350deg. Unstable: Within of the EBW seam is narro No defect in outside weld area. 4* 19.6 @ PI, 89, 79, 69, 59, 49 #6 cell equator, 1=300-350deg. No defect in outside weld area. 5* 21.1 @ Pi-mode K6 cell equator, 1=200-300deg. Unstable: Within of the EBW seam is narro. No defect in outside weld area.
NH-05 1# 27.3 @ Pi-mode Pield emission #5 cel equator, 1=60-150deg. Unstable : Width of the EBW seam is name No defect in outside weld area. 2*4 19.7 @ Pi, R9, R9, R9, R9, R9, R9, R9, R9, R9, R9
2*4 157 @ Pi, 803, 49, 39 #6 cell equator, 1=50-150deg. No defect in outside weld area. 2:6 (max 32.9) @ 59 #3 cell equator, 1=50-150deg. Unstable: Width of the EBW seam is nare. 2:9 @ 0.6 #6 cell equator, 1=10-180deg. Unstable: Width of the EBW seam is nare. 2:9 @ 0.6 #6 cell equator, 1=120-180deg. Unstable: Width of the EBW seam is nare. 2:9 @ 0.6 #6 cell equator, 1=270-360deg. Unstable: Width of the EBW seam is nare. 3:2.9 @ 0.6 #6 cell equator, 1=270-360deg. Unstable: Width of the EBW seam is nare. 0uench #7 cell equator, 1=150-180deg. Unstable: Width of the EBW seam is nare. 0uench #7 cell equator, 1=150-180deg. Unstable: Width of the EBW seam is nare. 0uench #6 cell equator, 1=150-180deg. Unstable: Width of the EBW seam is nare. 0uench #6 cell equator, 1=200-300deg. Unstable: Width of the EBW seam is nare. 0uench #6 cell equator, 1=200-300deg. Unstable: Width of the EBW seam is nare. 0uench #6 cell equator, 1=200-300deg. Unstable: Width of the EBW seam is nare. 0uench #6 cell equator, 1=200-300deg. Unstable: Width of the EBW seam is nare. 0uench #6 cell equ
4* 25.6 (max 32.9) @ 59 #3 cell equator, 1=180-2406eg Unstable : Width of the EBW seam is name No defect in outside weld area. 29.2 @ 0.9 #5 cell equator, 1=120-180deg Unstable : Width of the EBW seam is name No defect in outside weld area. 32.2 @ 0.69 #6 cell equator, 1=270-360deg Unstable : Width of the EBW seam is name No defect in outside weld area. MHI-06 1* 25.7 @ Pi-mode #7 cell equator, 1=150-180deg Unstable : Width of the EBW seam is name No defect in outside weld area. MHI-06 1* 25.7 @ Pi-mode #7 cell equator, 1=100-180deg Unstable : Width of the EBW seam is name No defect in outside weld area. 0uench #7 cell equator, 1=200-300deg Unstable : Width of the EBW seam is name No defect in outside weld area. 19.6 @ Pi.8 @ 79, 69, 59 #9 cell equator, 1=200-300deg Unstable : Width of the EBW seam is name No defect in outside weld area. 20.9 19.6 @ Pi.8 @ 79, 69, 59 #9 cell equator, 1=300-350deg No defect in outside weld area. 39.9 @ 3/9 #9 cell equator, 1=200-300deg Unstable : Width of the EBW seam is name No defect in outside weld area. 5* 21.0 @ Pi.mode No defection due to RF cable Field emission No defect in outside weld area. 5* 21.0 @ Pi.mode No
Image: Second
32.9 @ 69 #6 cell equator, 1=270-360deg, Quench Unstable: Width of the EBW seam is name. No defect in outside weld area. MH-06 1* 25.7 @ Phmode #7 cell equator, 1=150-180deg. Unstable: Width of the EBW seam is name. No defect in outside weld area. 35.4 @ 90 #5 cell equator, 1=200-300deg. Unstable: Width of the EBW seam is name. No defect in outside weld area. 4* 19.6 @ PI, 80, 70, 89, 59, 49; #9 cell equator, 1=200-300deg. Unstable: Width of the EBW seam is name. No defect in outside weld area. 5* 21.0 @ PI mode Field emission *6 cell equator, 1=200-300deg. Unstable: Width of the EBW seam is name. No defect in outside weld area. 5* 21.0 @ PI mode Field emission No defection due to RF cable field emission Modelection the stams were observed all over of inside of cavity. Noke: EP acid charge before EP2 process. track process track first time after changing EP acid (New one)
MH-06 1 ^M 25.7 @ PI-mode Field emission ? #7 cell equator, 1=150-180deg. Unstable: Width of the EBW seam is narc. No defect in outside weld area. 35.4 @ 3.9 #5 cell equator, 1=200-300deg. Unstable: Width of the EBW seam is narc. No defect in outside weld area. 4 th 19.6 @ PL 80, 77, 80 f; 59, 91, 20 ench #9 cell equator, 1=200-300deg. Unstable: Width of the EBW seam is narc. No defect in outside weld area. 5 th 21.9 @ Ptmode Field emission #0 defection due to RF cable trouble Unstable: Width of the EBW seam is narc. No defect in outside weld area. 5 th 22.1 @ Ptmode Field emission No defection. The stains were observed all over of inside of cavly. Akt of stains found after V. T. by cavity inspection. The stains were observed all over of inside of cavly. No ker Pa aid (harge before EP2 process. IN2 Process. Na2 First time after changing EP aid (Navo one
35.4 @ 3/9 Ouench #5 cell equator, 1=200-300deg Aug. Unstable: Width of the EBW seam is narro No detect in outside weld area. 4* 19.6 @ Pi, 86, 79, 69, 59, #9 cell equator, 1=300-350deg Arg. No detect in outside weld area. 9 Defect 7 Quench Unstable: Width of the EBW seam is narro No detect in outside weld area. 5* 22.1 @ Primode Field emission No detect in outside weld area. Field emission No detect in outside weld area. Ariotte You detect in outside weld area. 5* 22.1 @ Primode Field emission No detection due to RF cable trouble Note: EP acid changed before EP process. Ize 2 process. Ize 2 process. Ize 2 process. Ize 3 process was First time after changing EP acid (New one
4 th 19.6 @ Pi, 80, 79, 69, 59, 49 cell equator, 1=300-350deg. No detect in outside weld area. 9 Defect ? Quench Unstable :: Width of the EBW seam is name 39.9 @ 39 #5 cell equator, 1=200-300deg. Unstable :: Width of the EBW seam is name 5 th 22.1 @ Primode No detection due to RF cable No detect in outside weld area. Field emission Alot of stains found after V. T. by cavity inspection. The stains were observed all over of inside of cavity. Note: EP acid changed before EP2 process. RP2 process was First time after changing EP acid (New one)
Defect 7 Quench #5 cell equator, t=200-3004eg Unstable : Width of the EBW seam is narro Quench Work No defect in outside weld area. 5 th 22.1@ PI-mode No detection due to RF cable
39 9 @ 39 #5 cell equator, t=200-300deg. Unstable: Widin of the EBW seam is narrown of the end of
5 th 22.1@ Pi-mode No detection due to RF cable trouble
A lot of stains found after V/T. by cavity inspection. The stains were observed all over of inside of cavity. Note: EP acid changed before EP-2 process. EP-2 process was First time after changing EP acid (New one)
Note: EP acid changed before EP-2 process. EP-2 process was First time after changing EP acid (New one)
KEK-STF.
Cavity # of Eacc [MV/m] @ Mode Heating location Besult of inspection
V.T. Cause of limitation (after V.T. with T-map)
MHI-07 1 ^{ss} 16.5@Pi-mode #1 cell equator, t=60~150deg. Stain
16.7~19.1 @ 8/9, 7/9, 6/9 #1 cell equator, t=60~100deg. Stain
24.8@ 5/9 #1 cell equator, t=230-340deg. Stain Quench
30.6@ 3/9 #2 cell equator, t=120~210deg. Stain Quench
26.7@ 4/9 #4 cell equator, t=30~120deg. Stain Quench
A lot of stains found after V.T. by cavity inspection. The stains were observed all over of inside of cavity.
Note: EP-2 process was Second time after changing EP acid (New one) at KEK-STF.
Note: EP-2 process was Second time after changing EP acid (New one) at KEK-STF. MHI-08 1 st 16.0 @ Pi-mode #2 cell equator, t=140-200deg. Heavy Stain: Contamination ? Quench #2 cell equator, t=140-200deg. #2 cell equator rea, t=172 deg. Stra = 450'800 µm
Note: EP-2 process was Second time after changing EP acid (New one) at KEK-STF. MHI-08 1 st 16.0 @ Pi-mode Quench #2 cell equator, t=140-200deg. Heavy Stain: Contamination ? #2 cell equator area, t=172 deg. Size = 450°800µm 16.0 - 17.0 @ Pi, 09, 4/9, 3/9, Quench #2 cell equator, t=140-200deg. Heavy Stain: Contamination ? Size = 450°800µm
Note: EP-2 process was Second time after changing EP acid (New one) at KEK-STF. MH-08 1 st 10.0 @ Pi-mode Quench #2 cell equator, t=140-200deg. Size = 450'800µm Heavy Stain: Contamination ? #2 cell equator area, t=172 deg. Size = 450'800µm 16.0 ~ 17.0 @ Pi, 8/9, 4/9, Quench #2 cell equator, t=140-200deg. Size = 450'800µm Heavy Stain: Contamination ? #2 cell equator area, t=172 deg. Size = 450'800µm 28.4 @ 7/9 Quench #1 cell equator, t=160-240deg. Stain
Note: EP-2 process was Second time after changing EP acid (New one) at KEK-STF. MH-08 1 st 10.0 @ Pi-mode Quench #2 cell equator, t=140-200deg. Size = 450'E00gm Heavy Stain: Contamination ? #2 cell equator res, t=172 deg. Size = 450'E00gm 16.0 - 17.0 @ Pi, 8/9, 4/9, 3/9, Quench #2 cell equator, t=140-200deg. Size = 450'E00gm Heavy Stain: Contamination ? #2 cell equator res, t=172 deg. Size = 450'E00gm 28.4 @ 7/9 Quench #1 cell equator, t=180-240deg. Quench Stain 25.3 - 26.5@ 6/9, 59 #3 cell equator, t=200-270deg. Little bit stain in outside weld area.
Note: EP-2 process was Second time after changing EP acid (New one) at KEK-STF. MH-08 1* 10.0 @ P-imode Quench #2 cell equator, t=140-200deg. Heary Stain: Contamination ? Bio: e = 450'800µm 16.0 - 17.0 @ Pi, M9, 4/9, Quench #2 cell equator, t=140-200deg. Heary Stain: Contamination ? Bio: e = 450'800µm 28.4 @ 7/9 #1 cell equator, t=180-240deg. Heary Stain: Contamination ? Bio: e = 450'800µm 25.3 - 26.5 @ 69, 50 #3 cell equator, t=200-270deg. It leb bit stain in outside weld area. Quench A lod of stains found affer VT. by cavity inspection. The stains were observed at both side beam pipe, #1 = A A lod of stains found affer VT. by cavity inspection. The stains were observed at both side beam pipe, #1 = A

Heating area #6 cell equator :270° ~ 360° :Sensor 300° ⊿T=10 K, 330° ⊿T=10 K, 350° ⊿T=8 K



図5: MHI-05 (2nd) で観測された発熱箇所の内面 状態(縦測定後:#6-cell 赤道部、角度304~350°) #6 equator, 279~325 degree. Condition: As received.



図6:MHI-05で観測された発熱箇所の内面状態 (受け取り直後:#6-cell 赤道部、角度279~325°)

MH-06 1-cell equator, t = 306 deg. Downstream : Outside weld area
MH-06 #9-BP, t = 241 deg. -1
MH-06 #9-BP, t = 241 deg. -2

Image: MH-06 #9-BP, t = 241 deg. -1
Image: MH-06 #9-BP, t = 241 deg. -1
Image: MH-06 #9-BP, t = 241 deg. -2

Image: MH-06 #9-BP, t = 241 deg. -1
Image: MH-06 #9-BP, t = 241 deg. -1
Image: MH-06 #9-BP, t = 241 deg. -2

Image: MH-06 #9-BP, t = 241 deg. -1
Image: MH-06 #9-BP, t = 241 deg. -1
Image: MH-06 #9-BP, t = 241 deg. -2

Image: MH-06 #9-BP, t = 241 deg. -1
Image: MH-06 #9-BP, t = 241 deg. -1
Image: MH-06 #9-BP, t = 241 deg. -2

Image: MH-06 #9-BP, t = 053 deg.
Image: MH-06 #9-BP, t = 037 deg.
Image: MH-06 #9-BP, t = 184 deg. -1

Image: MH-06 #9-BP, t = 053 deg.
Image: MH-06 #9-BP, t = 037 deg.
Image: MH-06 #9-BP, t = 184 deg. -1

Image: MH-06 #9-BP, t = 053 deg.
Image: MH-06 #9-BP, t = 037 deg.
Image: MH-06 #9-BP, t = 041 deg. -1

Image: MH-06 #9-BP, t = 053 deg.
Image: MH-06 #9-BP, t = 037 deg.
Image: MH-06 #9-BP, t = 041 deg. -1

Image: MH-06 #9-BP, t = 053 deg.
Image: MH-06 #9-BP, t = 037 deg.
Image: MH-06 #9-BP, t = 041 deg. -1

Image: MH-06 #9-BP, t = 053 deg.
Image: MH-06 #9-BP, t = 041 deg. -1
Image: MH-06 #9-BP, t = 041 deg. -1

Image: MH-06 #9-BP, t = 053 deg.
Image: MH-06 #9-BP, t = 041 deg. -1
Image: MH-06 #9-BP, t = 041 deg. -1

Image: MH-06 #9-BP, t = 053 deg.
Image: MH-06 #9-BP, t = 041 deg. -1
Image: MH-

図7:新液でEP-2を行った際、空洞内部に発生した シミの様子(例:MHI-065thの縦測定後の様子)

図7はEP液交換後、初めて処理をしたMHI-06 (5th)の内面状態であり、空洞内面全域に亘ってシ ミ状の異常が多数観測された。また、2回目に処理 をしたMHI-07(1st)に関しても同様に空洞内面全 域に亘って同様の異常が多数観測された。また、縦 測定時に観測された発熱位置に対しては、近傍にシ ミ状の異常が観測されるケースが多かった。3回目 に処理を行ったMHI-08(1st)では、シミ状の異常 の総量は格段に減少し、程度の軽いものが両ビーム パイプ、1-cell~3-cellおよび7-cell~9-cellに観測された。 空洞性能は2-cell赤道部におけるクエンチで制限さ れ、電界強度は16MV/mであった。図8にMHI-08 (1st)の2-cellで観測された発熱箇所中心のEP-2処 理前後における内面状態を示す。縦測定後観測した 結果、2-cell赤道部のt=172[°]の位置に粒界に沿った 形で黒く変質している異常が見つかった(サイズ: 450 μ m×800 μ m)。EP-2前の様子では、このよう な異常は観測されていないため、EP-2以降の工程で 発生したものであると考えられる。また、今回観測 されたシミ状の異常などの詳細な成分分析は、現在、 KEKの加藤、西脇らの表面研究チームが調査中であ る。



図8: MHI-08(1st) で観測された発熱箇所の内面 状態(EP-2前後での比較: 2-cell、角度172°)

5. まとめ

今回、超伝導加速空洞における空洞性能の歩留ま り向上のために、京都カメラシステムを用いて、 STF baseline空洞(MHI-05~MHI-09)の各処理工程 における空洞内面検査を行った。MHI-05および MHI-06では、電子ビーム溶接シームの不安定な箇 所の一部でHigh fieldに達した際クエンチが観測され た。MHI-07およびMHI-08では、表面状態に対して シミ状の異常などが観測された。依然として空洞性 能はField emissionで制限される場合が多いため、電 子ビーム溶接シームなどの空洞の品質を評価するに あたっては、各処理工程に対するより深い理解が必 要である。

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