CHARACTERIZATION OF SURFACE DEFECTS ON EXFEL SERIES AND ILC-HIGRADE CAVITIES*

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Abstract

A detailed analysis of surface quality of around 100 EXFEL series and ILC-HiGrade SRF cavities has been performed applying high-resolution optical system OBACHT and replica. Typical surface features and defects as well as their influence on the cavity performance and possible repair methods are presented and discussed.

INTRODUCTION

Superconducting radio-frequency (SRF) niobium cavities are a key component of current and future efficient particle accelerators producing high-energy and high-intensity beams. The technology is a key to next-generation light sources, accelerator-driven sub-critical nuclear reactors and nuclear-fuel treatment, and new accelerators for material science and medical applications. The SRF cavities are made from high-purity niobium and undergo a complex multi-step production process to achieve high accelerating gradient, E_{acc}, and unloaded quality factor, Q_0 [1]. These quantities, together with the manufacturing yield, drive cost and performance factors such as cryogenics, beam energy, and machine length. The European X-ray Free Electron Laser (EXFEL) [2], currently under construction in Hamburg, requires for example 800 Tesla-shape nine-cell 1.3 GHz SRF niobium cavities operating at nominal average E_{acc} of 23.6 MV/m with Q_0 of at least 10^{10}. The future International Linear Collider (ILC) [3] would require the production of 16,000 such cavities operating at nominal average gradient of 31.5 MV/m with almost the same Q_0 factor. With such a quantity of cavities to be fabricated, an appropriate quality control (QC), failure reason clarification, possibilities for retreatment and repair of the SRF cavities, and the resulting manufacturing yield become very important issues.

The ability to detect performance-limiting defects, especially in early production steps, would significantly reduce repetition of expensive cold RF tests and retreatments of the cavities.

Inspection of the inner cavity surface by an optical system is an inexpensive and useful means for surface control and identification of critical or suspicious features.

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MEASUREMENT TECHNIQUE

OBACHT

Optical inspections of the cavities have been performed applying the high-resolution OBACHT system. OBACHT is a semi-automated inspection tool of the inner cavity surface and is based on the Kyoto camera system. It allows inspection of a large number of cavities with and without a He-tank as well as of the components that make up a complete cavity such as "dumbbells" and end groups. A "standard" cavity inspection concentrates on the welding seams at the equator and irises plus the area to the left and right of the equator welding seams and yields approximately 3000 images in 8 hours. One OBACHT image covers a cavity area of 12x9 mm^2 at the equator with at least 10 µm resolution. The positioning accuracy of a cavity mounted on a movable sled is about 10 µm, whereas the angular accuracy of the camera positioning is about 0.01°.

Replica

To gain information about the 3D topography of surface features or defects, a replica technique has been applied additionally on some defects, especially if an unambiguous interpretation of defects could not be performed based on the OBACHT images. Replica is a non-destructive surface-study method reaching resolution down to 1 µm by imprinting the details of the surface onto a hardened rubber. The footprint is subsequently investigated with a microscope or profilometer. 3D laser scanning microscope (Keyence VK-X100K) has been applied for topographic investigations of the replica-samples and provides up to 0.2 µm lateral and 10 nm height resolution.

SURFACE DEFECTS

Based on the optical inspections of the EXFEL series and ILC-HiGrade cavities, the following seven types of surface "defects" could be identified. These are scratches, foreign inclusions, welding errors, rough polishing, defects called "cat eyes", etching pits, and dust.

Scratches

The scratches (Fig. 1) are usually localized in the iris region of the cavities and are indications of some mishandling or errors during the production steps leading to contacts or collisions between production tools and cavities thus resulting in mechanical damages of the niobium surface. The main impact of such defects on the cavity performance is an excessive x-ray radiation in the

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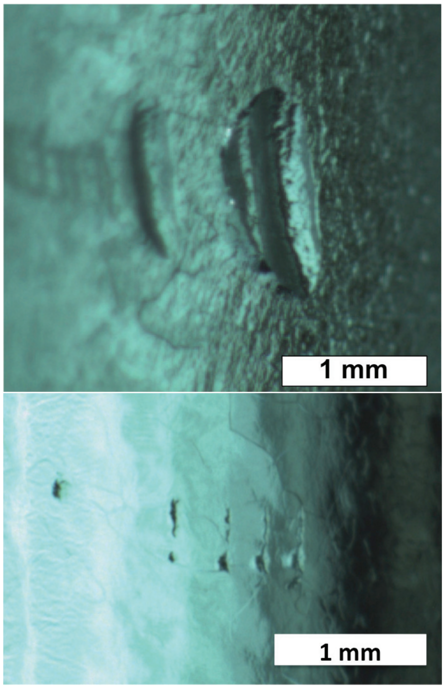

Figure 1: Typical OBACHT images of scratches found on irises of EXFEL series and ILC-HiGrade cavities.

operational range of E_{acc} of the cavities due to the electron field emission, enhanced on sharp edges and spikes in the scratched regions. The high-pressure ultra-pure water rinsing (HPR) and in some cases even a light buffered chemical polishing (BCP) of around 10 µm (maximum possible due to constrains of the helium tank) followed by the high-pressure ultra-pure water rinsing (HPR) could not cure the field emission load of the cavities with such defects. Local grinding and more heavy etching were needed. This requires, however, additionally a complete tank removal, retuning of the cavities, and a second whole surface preparation pass. This operation upsets the mass production flow. Few reasons for the scratches have been identified in the EXFEL production flow and were mostly some occasional accidents.

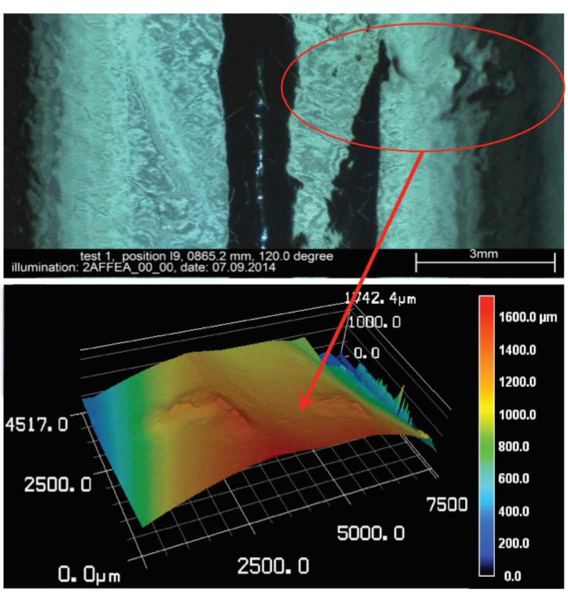

Figure 2: OBACHT (top) and laser microscope on replica-sample (bottom) images of scratches on a cavity limited at 23 MV/m by quench with strong radiation, usable gradient 16 MV/m.

In one case, however, almost **10** cavities were affected by the same error before it was localized. Such an example is presented in Fig. 2. Here the irises 2 to 8 of the cavity were scratched at almost the same angle. During the cryogenic cold RF test the cavity reached 23 MV/m of maximum gradient, limited by thermal breakdown (quench) with strong radiation. The usable gradient of the cavity was just 16 MV/m. Additional HPR and 10 µm BCP polishing could not cure the cavity. Additional local grinding will be applied for this cavity to remove the defect as qualified and already applied for several other cavities [4].

Foreign Inclusions

Foreign material inclusions seem to be the most critical defects. Of more than 785 cavities fabricated for the EXFEL up to now, around **20** cavities have been discovered with strong indications of presence of foreign material inclusions on the inner surface. Such cavities are

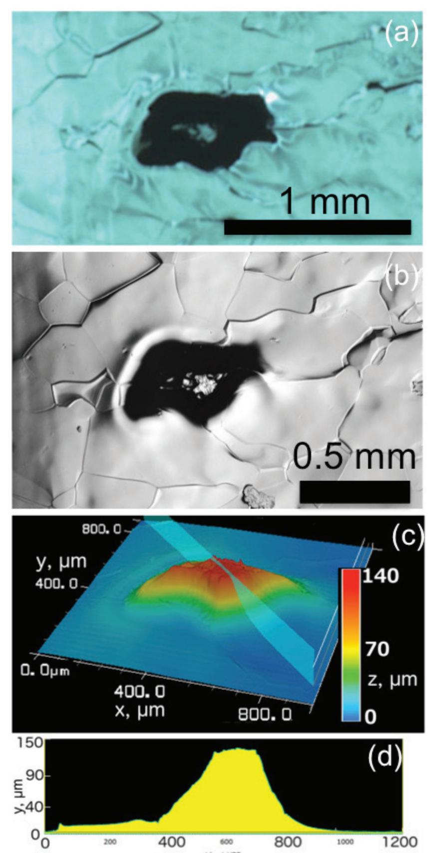

Figure 3: Foreign inclusion observed by OBACHT (a) and visualized by laser scanning microscopy on replica sample (c-e). The height of the protrusion is about 130 µm.

usually limited by thermal breakdown at fields well below 20 MV/m. Figure 3 represents a defect found on the inner surface of a cavity limited by thermal breakdown at 16 MV/m. Replica studies helps to better visualize the defect-areas and analyse its microstructure without cavity-destruction. The defects look very similar to the inclusions observed on niobium sheets and extracted samples. Such defects illustrate clearly pronounced protrusion of 120 to 140 µm and are usually not affected by the main EP treatment as revealed by laser scanning microscopy on replica samples. Similar etching behaviour has been observed e.g. in the past by presence of aluminium flakes on the surface [5]. This indicates different chemical properties of the defects than of the niobium. Additionally, the surface microstructure of the inclusions is completely different from the niobium surface. These facts are considered as strong hints for foreign material inclusions. A similar morphology difference has been observed on foreign inclusions confirmed by SEM and EDX material analysis. Such analysis in the cavities is unfortunately not yet possible without cavity destruction.

It can be surmised that the inclusions were embedded during one of the production steps like deep drawing, clamping for machining, or assembly for EBW. Such big defects of more than 500 µm size would be definitely

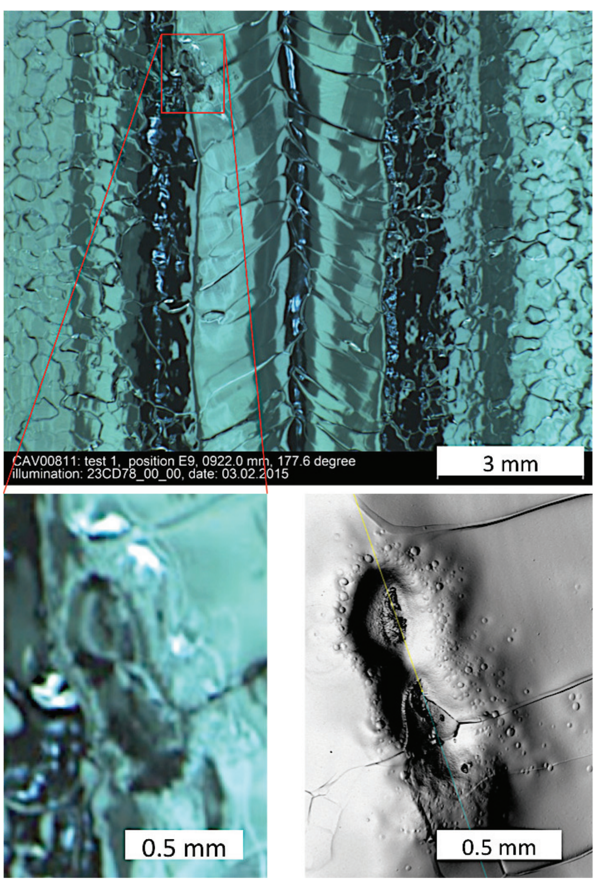

Figure 4: Surface erosion with a foreign inclusion (marked by red square on top and magnified on lower left image) observed by OBACHT and additionally visualized by laser microscopy on surface-replica (lower right).

detected by the eddy-current scanning of the niobium sheets.

The defects have to be locally grinded away and followed by the second full surface preparation step.

Another kind of defects associated with foreign material inclusions is shown in Fig. 4. The local surface erosions have been observed on the equator-welding seams of several cavities. In the presented case, the cavity reached only 16 MV/m limited by thermal breakdown without any radiation. X-ray fluorescence spectroscopy confirmed the presence of iron as a foreign inclusion in the defect area [6].

The repair of such cavities is not really feasible since the pollution seems to go deep into the material and remain after almost 150 µm material removal.

Welding Errors

An incomplete penetration of the welding seams (Fig. 5, top), strong variation of the seam-width, and rough welding are some difficulties that occurred during the ramp-up phase of the EXFEL cavity production. Optical inspections with conventional endoscopes at companies gave some indications of the problem. Detailed analysis of the defects was done using OBACHT system. Meanwhile, settling the welding parameters solved the problem with the incomplete welding and only some variation of the seam-width could be observed. The cavities with the incomplete welding have never been cold RF tested since problems with low field quenches and leak tightness were expected.

A complicated repair of such cavities is required, which was usually done by the immediate second pass welding if discovered during the welding. Re-welding after some surface processing steps is accomplished with some pollution of the welding joint. Some problems with

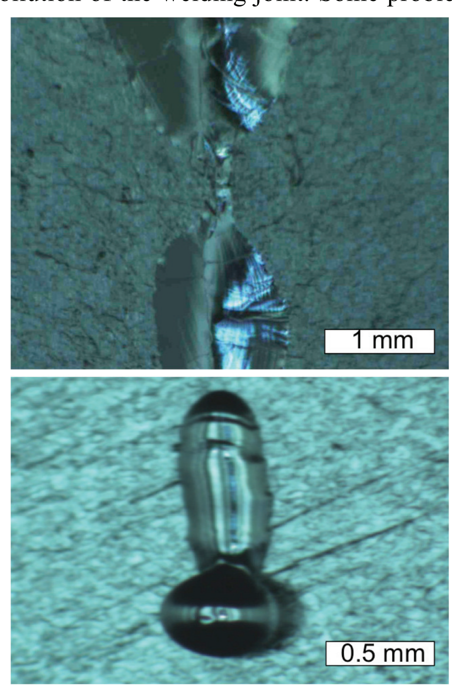

Figure 5: Incomplete welding seam (top) and welding spatter on the inner cavity surface.

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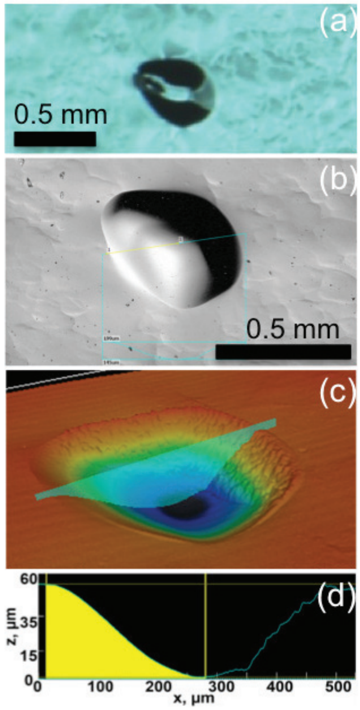

Figure 6: OBACHT and replica investigation of a “cat eye” on the surface of cavity: (a) OBACHT image and (b) 3D view, (c) topography view, and (d) a profile of the “cat eye” as measured by means of a 3D laser scanning microscope on a replica sample.

the final length and high order mode (HOM) spectrum of the cavity can occur due to higher material shrinkage of double welding.

The ~mm-sized “spatters” (Fig. 5, bottom) are occasionally occurring on the surface during the electron beam welding as observed during the endoscope and OBACHT inspections. This might happen due to sparks in the high voltage circuit of the welding machine or due to the presence of some dust in the contact of two Nb half-cells. Dust flakes have often been observed around the “spatters” area, those supporting the second idea. The reason for this is as yet unclear and is the subject of further investigation as well. As a consequence, additional local repair of the cavities is required to remove these defects, which are essentially unaffected by the standard EP/BCP polishing procedure. The local grinding of such defects has been successfully applied on several cavities as reported elsewhere [4].

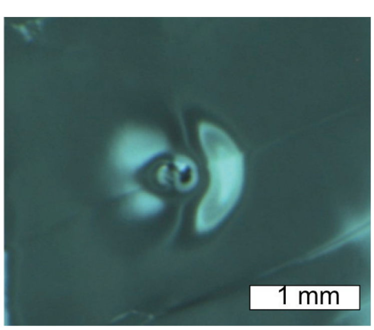

Figure 7: Typical OBACHT image of etching pit on the cavity surface.

“Cat eyes” and Etching Pits

The defects called “cat eyes” are probably the most often appearing defects on the surface. The reason for this is as yet not fully clear and is the subject of further investigations. Replica studies indicate that these are rounded etching holes as shown in Fig. 6. The “cat eyes” and etching pits (Fig. 7) both are etching artefacts. The nature of these artefacts seems to be different because of their different geometry and optical appearance. Whereas the etching pits are most probably created due to a sticking of hydrogen bubbles on the surface during the etching process, the “cat eyes” are most probably originating from local material properties such as defects or even inclusions. The “etching pits” and “cat eyes” seem to be harmless in terms of SRF properties since several cavities showed excellent results exceeding even ILC specifications despite of the observation of many such defects on the surface.

Rough Surface

Rough surface is a polishing artefact appearing mostly due to a switch of the EP polishing process from the

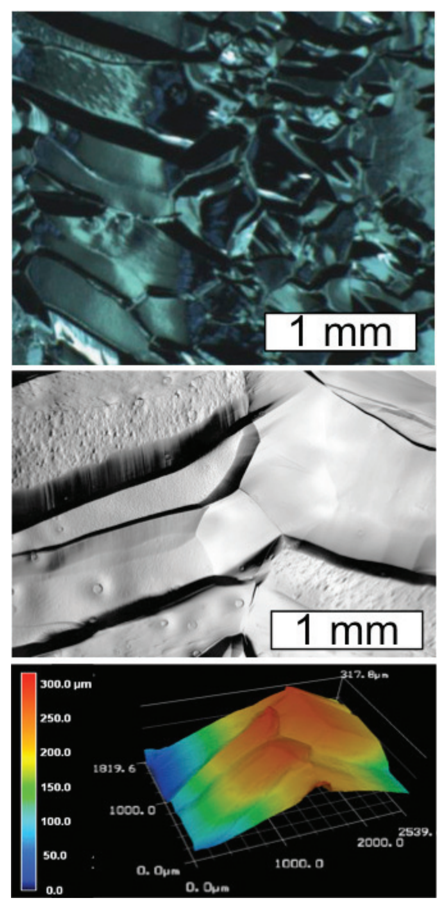

Figure 8: Typical OBACHT image of etching pit on the cavity surface.

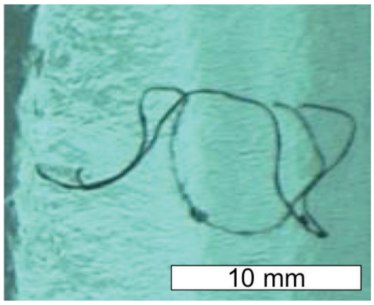

Figure 9: Typical OBACHT image of dust (fibre) contamination on the cavity surface.

polishing to etching regime. It happens when improper polishing parameters like acid temperature, current density etc. have been applied. Only very few cavities were affected by this. In the polishing regime sharp edges and burrs are smoothed out and a very glossy surface is obtained, whereas the etching regime leads to different polishing rate at grains of different orientation and grain boundaries and leads to sharp edges and steps between the grains. An example of a very rough surface is presented in Fig. 8. Here some tests have been performed with the EP system leading to the very rough surface. The cavities with such defects show usually a very low quality factor Q_0 and achievable accelerating gradient E_{acc}. The cavity in the presented case reached only 16 MV/m maximum E_{acc} and had a strong Q_0 slope at E_{acc} above 10 MV/m.

Dust is probably the second most frequently observed defect on the surface (Fig. 9). Contamination of the cavity surface with dust particles leads to an enhanced x-ray radiation due to field emission from irises, i.e. high electric field regions. Low Q_0 or early quenches are possible if some dust is located on the equators, i.e. in the high magnetic field regions.

The main reason for such contamination is cleanliness of the assembly process as well as the reliability of the cleaning procedure. It must be pointed out, however, that it is difficult to use OBACHT results to judge about the cleanliness since OBACHT tests are performed not in a cleanroom environment. Some pollution may happen during or before the OBACHT tests.

The cavities polluted with dust particles require usually only one additional HPR cycle to recover their performance. Second assembly and cryogenic RF test is still required to confirm the success of cleaning.

The distribution of detected surface defects over almost 100 inspected EXFEL series and ILC-HiGrade cavities is presented in Fig. 10. These are preliminary results because of the still running cavity production. One can see, that scratches, welding errors, and foreign inclusions are the most critical surface defects. The scratches and welding spatters can be successfully removed by local grinding technique, whereas the incomplete weld penetration and contaminations by foreign material, especially of the welding seam, is still to be understood and repair procedure to be defined or even not possible.

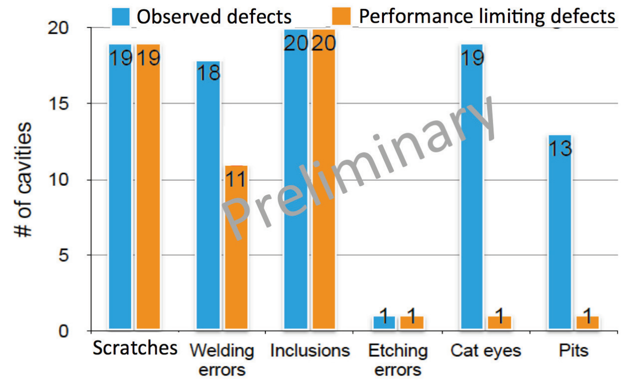

Figure 10: Distribution of defects observed during optical inspections of about 100 EXFEL and ILC-HiGrade cavities.

CONCLUSIONS

Handling (scratches), cleanliness (contamination), and reliability of EBW welding seem to be most critical cavity production steps. Almost all defects leading to accelerating gradient below 20 MV/m have been identified by a “simple” optical inspection tool. It would reduce significantly the repetition of treatment and cryogenic tests of cavities by earlier detection of failures. Such systems as OBACHT and replica contribute greatly to understanding and improvement of the EXFEL fabrication.

Around 8% of cavities from the actual series production for the EXFEL are with “serious” defects, which could not be fixed by HPR and light BCP and require more comprehensive repair.

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