ANALYSIS OF THE COATING SUCCESS RATE IN THE SERIES PRODUCTION OF Nb/Cu SUPERCONDUCTING RF CAVITIES FOR LEP2

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Abstract

Correlating optical surface analysis to temperature mapping of low performance cavities provides information on the state of the inner surface. We evaluate statistically the defect appearance in different selected zones of the cavity and draw conclusions on deviating fabrication processes. Chemicals retention and structural defects left over after the wet chemical processing are identified as the major imperfections in the substrate surface preparation. They can cause a lack of coating adherence followed by excessive heat-up and melting of localized Nb zones under RF power. Inclusion of particles adsorbed on the surface by local heating can occur during cavity testing or machine operation. We propose specific recovery procedures for the different layer defects observed.

1. INTRODUCTION

For the energy upgrade of the LEP storage ring at CERN Nb sputter coating of OFHC-copper 4-cell structures has been chosen for the series production of 256 superconducting 350 MHz cavities. Compared to the Nb sheet material processing, this technology presents some interesting advantages like strongly reduced material costs, increased stability against thermal breakdown and some future potential by the ongoing research in material science and thin film technology. However, the various manufacturing and assembly steps like e-beam welding, Cu chemistry, ultra-high vacuum and plasma creation for deposing Nb uniformly on the 5.5 m^2 inner surface are highly delicate processes requiring clean room assembly, ultra-pure water treatment and many other precautions often adapted from the integrated circuit (IC) technology. Contractually fixed cavity acceptance criteria include a quality factor Q(E) of at least $3.4*10^9$ at 6 MV/m (4.5K) in the vertical RF test. Cavities failing in that respect got their Nb coating chemically removed (stripping) and were send back to industry for a second or even third coating causing extra costs and difficulties for a precise production planning. The initially available diagnostics tools like temperature mapping (hot-spots) and simple mirror based inspection tools were insufficient for a clear understanding of hysteretical Q(E) curves, increased losses and "quenches". Hence, we have undertaken a systematic performance analysis assisted by a dedicated video camera inspection bench for improving our knowledge on macroscopic surface and interface defects causing the undesirable Q-factor behavior. Cavity inspection was introduced as an additional step in the formal rejection procedure, the results are held available in an inspection data base and also send to the manufacturer. After the visual inspection of 62 cavities/assembled units, we are now able to classify the observed deviations from a uniform surface in correlation to performance drops and hot-spot locations. Furthermore, defect type and appearance statistics provide a means of production quality control by indicating deviating manufacturing processes.

2. THE INSTRUMENTS

2a. Optical Inspection

The entire 5.5 m^2 inner cavity surface can be inspected using a computer controlled video camera inspection [1] bench equipped with two lenses of different focal length. The camera mounted on a robot arm is guided in automatic mode along circular paths in fix focus geometry. Four necessary coordinates (x, α, β, γ) are calculated by a PC on basis of the theoretical cavity geometry and are adjusted to the actual position of the different welding seams. Those are determined after the mechanical alignment of the instrument along the horizontal axis given by a He-Ne laser beam. Small deviations due to manufacturing tolerances and the tuning procedure are thereby taken into account. Defect recognition is not automated but relies on the expertise of the operator. Pictures in different magnification of detected surface irregularities are output on a video image printer and, digitized, on the PC for image treatment and storage in an inspection database. The support frame for the object handling was designed to fit bare cavities as well as fully equipped module units.

2b. Temperature mapping

The invention of temperature mapping by carbon resistors plunged in subcooled helium was an important step in the development of superconducting cavity technology [2]. By measuring the temperature profile on the outer surface during RF power input this method provides information on areas with higher losses in the superconducting Nb layer. Such an area is counted as hot-spot if the difference to the temperature background values in the cavity acceptance test (vertical test) exceeds 100 mK. In almost all cavities with insufficient performance at least one hot-spot, sometimes up to 6, can be blamed for the increased losses. All those hot-spots could be reliably related to visible Nb layer defects in the visual inspection (s. 3a,b).

2c. Inspection Database

Inspection results are organized on a PC server as database for public access via the CERN computer network. It contains images, position and description of the different observations on the cavity surface. A report output as service to the manufacturer is foreseen as well as special queries for relating observations on different inspected units.

3. RESULTS

3.1 Classification of defects

Up-to now we have inspected 62 Nb layers in 350 MHz cavities, corresponding to 340 m^2 cavity surface, since the initial operation of our system. Two cavities had Q-factors better then specification values for comparison. Every inspection was undertaken under special consideration of zones that have been marked as "hot-spots" (see 2.b) in the vertical RF test. Interestingly, there is little difference in optical aspects of the layer between cavities of different manufacturers. This proofs a high coherence in the transfer of the recipe to the firms [3]. The reflectivity of the surface seems to be slightly company specific though and certain structural irregularities without clear influence on the performance can also serve as production "fingerprints". Defects causing hot-spots instead are, apart from their geometry, of more general nature. All three industry firms as well as the CERN production had to cope with them in different frequencies of appearance.

3.1.a Defects at the interface - the copper surface preparation

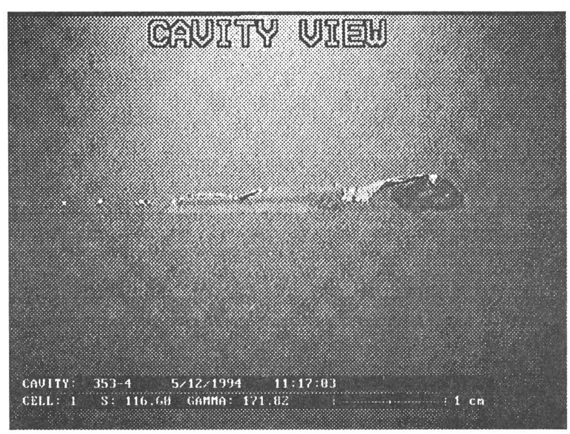

fig. 3.1: detachment with detrimental effect on the cavity performance. (oriented along the cavity axis)

In this class of defects we can condense many different possible production failures since they are causing the same type of visible layer fault: a lack of coating adherence that leads to the heat-up of the concerned area, the melting of the Nb, sometimes explosive eruption by vaporization of chemical residues and eventually the denudation of the copper substrate. In fig. 3.1 we show one characteristic example. We can clearly observe a copper oxide trace caused by a liquid running from a zone of non-uniform Cu chemical polish downwards (the cavity is in a vertical position during chemical processing and baking).

Different failures can lead to a perturbation of the chemical polishing: stains of chemical products sticking on the surface, insufficient degreasing, liquid retention in pits [4], areas with varying copper structure introduced during the lathe-spinning or the electropolishing of the copper half-shells or mechanical damage of the surface. Clearly, during all different liquid processes (for details see [3]) non-homogeneous flow, gas bubbles on the surface or splashes have to be avoided. The possibility of foreign material inclusion in the copper sheets has been addressed using surface analytical tools. Apart from small traces of iron in a defective surface area of 3 cavities [5], no other observations compatible with inclusions have been made. For fully understanding the various defect mechanisms one needs a very detailed knowledge of the initial production steps and the manufacturing installations. However, a significantly decreased defect frequency was obtained by selectively adding more chemical polishing cycles in case of any doubts about the surface uniformity and by the systematic chemical rinsing of the chemistry installations. Additionally, the statistical analysis of production data has also given some hints on degrading processes or installations [6] as reasons for a defect formation.

3.1.b "Surface" defects

A completely different mechanism of defect creation is the sticking of foreign particles on the Nb surface, i.e. after the coating. It can be dust particles introduced during the manipulation or operation of the cavity but also metallic splinters from joints or tooling. If adsorbed in regions of high field values this particles heat-up under RF power and migrate into the active layer under local melting. Once fixed, they can provoke thermal quenching due to a reduced thermal conductivity towards the substrate (see fig. 3.2). Defects of this type can be cured by the video controlled removal of the foreign particle, grinding of the melted zone (fig.3.3) and additional high pressure/low pressure water rinsing. After such a treatment of the defect shown in fig. 3.2 the "quench" was shifted to electric field gradients much higher then the design value, the cavity was therefore recovered without stripping of the Nb layer/new coating.

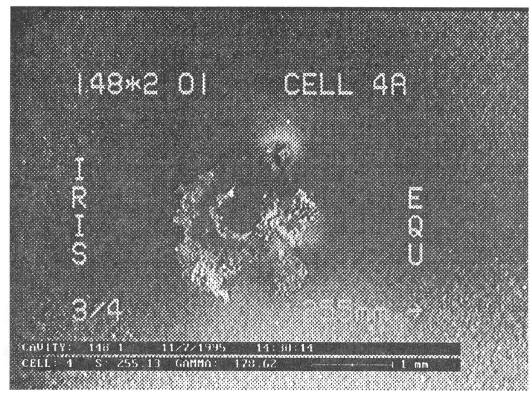

fig. 3.2: surface defect related to a thermal quench.

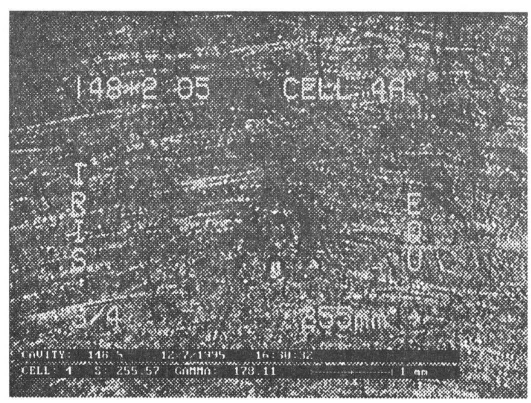

fig. 3.3: same area after grinding before the high pressure water rinsing.

A fully equipped cavity that had suffered of a degrading performance during the module operation was treated like described above. A defect that was supposed to be a source of electron emission affecting other areas of the layer, was removed by a controlled grinding, the whole cavity high pressure rinsed afterwards. That way, the initial performance of the cavity of the vertical test was reached again by relatively simple intervention.

3.2 Statistics on defect appearance

Now that we know about the main defect types and their possible ways of build-up it is interesting to find out, if certain sectors on the cavity surface are more susceptible for defect formation. In that respect, we first evaluate the hot-spot (>100mK) occurrence in the different cells from all cavity acceptance tests (vertical tests). It is obvious from fig. 3.4 that there is a top-down tendency (vertical position) from cell 4 to 1 for the defect probability in cavities from all manufacturers. Company 3 seems to have overlapping of an additional defect source in cell 1.

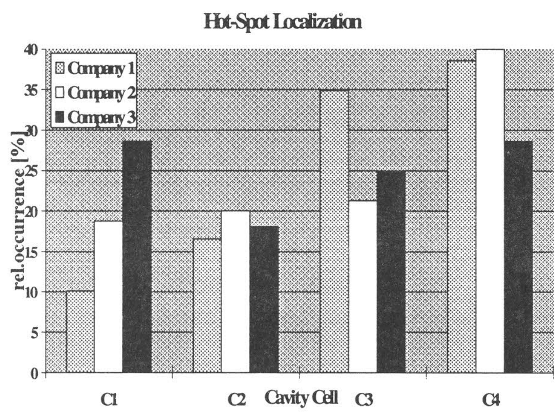

Fig. 3.4: Rel. occurrence of observed hot-spots (>100 mK) in different cells of the cavity. C4 is the upper cell (B-side) in the vertical chemical processing.

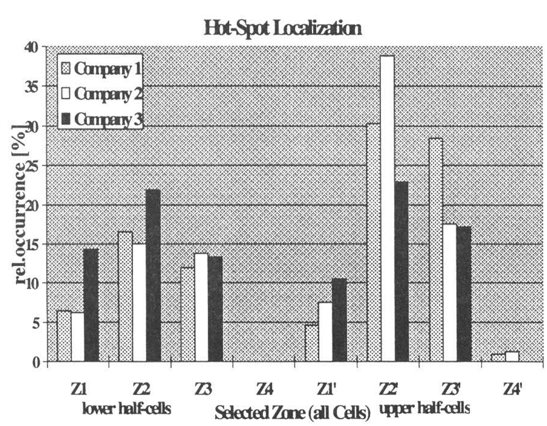

Fig. 3.5: Rel. occurrence of observed hot-spots (>100 mK) in specific zones of the active layer, distinguished between upper and lower half cell in the vertical position.

If we now analyze the hot-spot localization as function of their relative position to the equatorial welding for all cells (Z1: 0 - 70mm from the equatorial welding; Z2: 70 - 235mm; Z3: 235- 330mm; Z4: 330 - 368mm; Z'x are the corresponding zones lower than the equator) than we can note 3 basic results:

- almost no hot-spots in the iris region due to the low magnetic fields in that zone and a difficult resistor contact;
- upper zones are more affected than the corresponding lower zones, especially if combined with the result on different cells (s. above);
- company 3 has an increased defect probability in the areas closed to the equatorial welding may be due to the insufficient treatment of welding projections or the handling of the half-shells before and after welding.

The additional observation of a top-down tendency is well corresponding to the observation of preferential sticking of water and chemistry contaminants (algae, plastics) in the upper half-shells of the highest cells and to increased accumulation of bubbles close to the liquid surface. During the evacuation of the chemicals the flow is minimal when le liquid surface reaches the zone Z2 for every cell. We can therefore consistently connect the most frequent defect type to the preferential zones of appearance.

4. PERFORMANCE RECOVERY

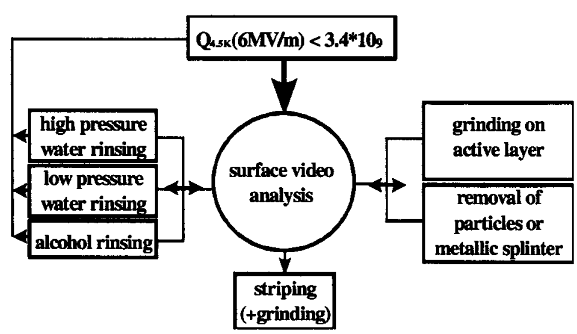

Fig. 4.1: possible recovery action depending on the specific inspection result

Based on the results of our analysis we now apply procedures shown schematically above for cavity/module recovery. A stripping and new coating should be done only when the Nb layer is detached on areas summing up to more than $1mm^2$. Strong profiles in the copper substrate have to be treated mechanically before the following chemistry/coating. In the other cases we first try to locally work on the defects and combine this effort with local/global high pressure water rinsing and water/alcohol rinsing for cleaning and drying.

5. CONCLUSION

Video surface inspection is essential for a systematic cavity performance analysis, the production quality control and in any performance recovery treatment. It has turned out that only two types of defects are relevant in terms of acceptance or rejection of industrially produced LEP2 cavities: I) Nb detachments due to a great variety of failures in the copper surface preparation for coating and II) an attachment and inclusion of foreign particles on an otherwise defect free Nb layer. Under II) we could also group tip like surface geometry acting as a electron field emitter.

Many other observed variations in the Nb layer morphology or chemical composition certainly play a role in the quest for highest cavity performance, but they usually do not appear as "hot-spots" in temperature mapping. In that context we should mention observations like stains of water rinsing without Nb detachment, impact of electrons on the surface followed by some recrystallization, covered non-uniform copper removal, traces of the copper mechanical abrasion, melted plastics and so on.

In contrast to class I can defects of class II, occurring on bare cavities or during module operation, be successfully cured by a combination of a local grinding with high pressure/low pressure water rinsing. Evidence was also obtained for the need of mechanically treating certain copper defect structures (class I) before a new chemistry/coating cycle.

The combined effort of defect analysis and regular intervention in the production cycles in industry, even on some parts of the production recipe [6], have helped to significantly increase the coating acceptance rate. We are now (1995) reaching 67% acceptance of the first Nb coating and values close to 100% for additional layers. In parallel have the mean values of cavity Q-factors increased to about 20% better than specification values [7].

6. ACKNOWLEDGMENTS

The effort of M. Karmarkar and G. Cavallari in developing the inspection system is gratefully acknowledged. We warmly thank D. Boussard for his support and for valuable discussion.

7. LITERATURE

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