Mechanical Stiffening of SRF niobium cavities by thermal sprayed coating

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Abstract

A new fabrication and stiffening method of SRF cavities is based on the addition of a thermal spray copper layer onto a thin wall niobium cavity. Mechanical properties evaluations of the copper coatings are mandatory for the feasibility studies of this technique. Numerical calculation were performed to analyse the cavity behaviour, showing the strong impact of the coating properties on the Lorentz forces detuning reduction. Important parametres, such as Young modulus, have been systematicaly measured and were correlated to RF measurements on bimetal cavity prototypes, proving the influence of thermal spray process upon cavity structure. At last, the thermal stress evaluations at low temperatures were developed since the niobium thermal expansion ratio is very different from the this of copper.

1 Introduction

The SRF cavities stiffening problem is mandatory for accelerators working at high accelerating gradient, like TESLA . The Lorentz forces detuning is function of the square of the accelerating gradient and the mechanical stability problems could be critical if the SRF cavities structure were not rigid enough. The actual stiffening system of TESLA was made of welded niobium rings, they were not only expensive and difficult to realize but also no more efficient when the accelerating gradient exceeds the 27MV/m, while the TESLA project aim is to achieve an ultimate E_{max}= 34MV/m. Numerical simulations were performed to analyse the cavity stiffening behaviour, it constitutes a strong mean for new stiffening system elaboration since Lorentz forces detuning could be computed from electromagnetic field distribution for each accelerating gradient, this for different stiffening system.

A new stiffening method of SRF cavities was studied since last three years, it was based on the addition of a thermal spray copper coating onto a niobium cavity. An important investigation of computation was done to compare this new stiffening method to welded niobium rings method, for TESLA cavities. To guarantee the eventual success of this new stiffening method, some mechanical experimental characterizations were performed, they indicated clearly a strong impact of thermal spray process in mechanical properties of the copper coatings and the difference between a bulk copper and a copper coating realized by thermal spray process. The thermal spray process optimization has been investigated and very interesting comparative results were obtained and correlated to SRF cavities computations and prototypes measurements. Numerical simulations and investigations on thermal spray technique could be interesting for superconducting RF technology for high-power proton-linacs applications, [1]. At last, a new phenomenon of thermal stress generation at low temperatures was analyzed for the niobium cavities coated by copper since the niobium thermal expansion ratio is very different from this of copper, the predicted thermal stress were compared to the results of an in-situ measurements.

2 SRF CAVITIES STIFFENING

The actual TESLA cavities, fig. 1, working at 25MV/m, used the Nb welded rings on the 2.5mm wall thickness niobium cavities to assure the mechanical stability, since the frequency shift Δf must be lower than the cavity bandwidth. The bandwidth could be calculated from Q_0 and Q_{ext}, for TESLA , $Q_0 = 5.10^9, Q_{ext} = 3.10^6$ [2], the bandwidth was 434Hz.

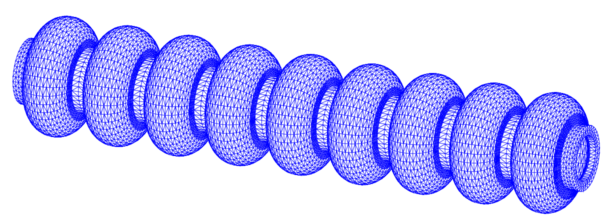


Figure 1: TESLA cavities with welded stiffening ring

To control the mechanical stability without prototype or tests, the numerical simulation is a very powerful tool. It shows (cf. fig. 4) that if the TESLA cavities should attain 27MV/m, the actual stiffening system is not more valuable. Naturally, we could propose a first method which consists in increasing the thickness of the niobium wall. The computation results show that this solution was not very efficient. Another new concept was proposed to add a copper coating onto the 2.5mm niobium cavities by thermal spray process. The calculations show that this solution could be very interesting if the mechanical properties of the copper coating realized by thermal spray were close to these of forged copper.

3 NUMERICAL COMPUTATIONS

Numerical calculations were performed with the finite element code "CASTEM 2000 " [3] in order the compare the new stiffening concepts to actual stiffening system. First, the resulting cavity shape change is computed for a given stiffening scheme with "CASTEM 2000 ", then a special module is necessary to compute the cavity volume change ΔV and the resulting frequency shift according to Slater's formula:

$$\frac{\Delta f}{f_0} = -\frac{1}{4W} \int\int\int_{\Delta V} (\mu_0 H^2 - \varepsilon_0 E^2) dV \qquad (1)$$

where: W is the total electromagnetic energy stored in the resonator, E and H are the electromagnetic surface fields and f_0 is the fundamental mode of the unperturbed cavity. A very high numerical precision is required at this step because the cavity deformation ($\Delta l = 0.2\mu$m) was very small compared to the cavity scale (1m), as well as frequency shift: 300 Hz for Δf and the 1.3Ghz for f_0. To preserve the double precision of "CASTEM 2000 " computing results, the special module is developed inside the "CASTEM 2000 ". The first "CASTEM 2000 " computing results concerning the actual TESLA niobium cavities have successfully compared to experimental measurements and other computing results realized in DESY, [4].

Then, special modelizations of copper coating stiffened niobium cavity was realized, it permits the comparison of such new cavities with the actual bulk niobium cavities equipped with welded rings.

3.1 *Limit of the actual welded ring stiffening system*

The figure 2 show the actual TESLA stiffening system, a niobium ring was welded between two cells.

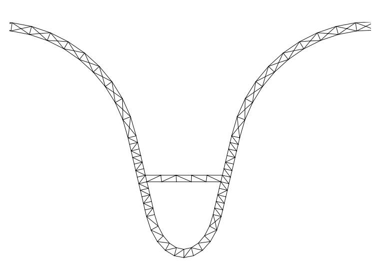


Figure 2: Actual stiffening system using Nb welded rings

The figure 3 shows the cavity deformation under the Lorentz forces:

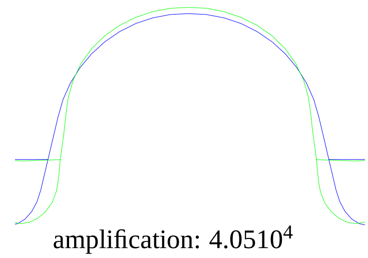


Figure 3: Deformation of TESLA cavities

The fig. 4 shows the Lorentz forces detuning of TESLA cavities with the actual stiffening system welded on a 2.5mm niobium wall. We could see that frequency shift should go out of the bandwidth if the accelerator field exceed the 27 MV/m.

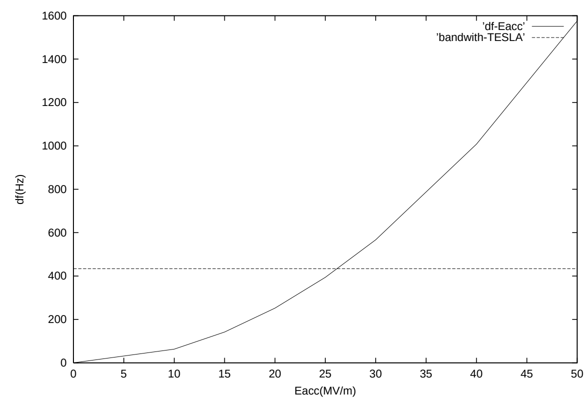


Figure 4: Bandwidth and frequency shift versus accelerator field

A remedy could be the increase of the niobium wall thickness, but it is very expensive and not a very efficient solution: to reach 30MV/m, at least 5mm niobium wall is necessary.

3.2 *Perspectives of a new stiffening system*

A new proposed stiffening method consista in adding a copper coating onto the 2.5mm wall niobium cavities by thermal spray process. The sketch of the copper deposition is shown in figure 5.

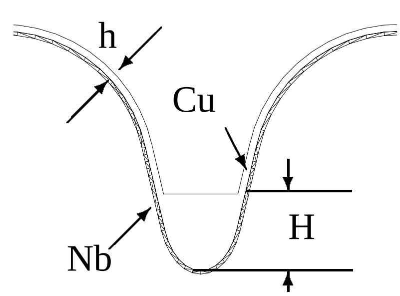


Figure 5: Proposed stiffening system

Three parameters could be optimized: the niobium wall thickness, the homogeneous copper coating layer (h) and the iris fill up height (H). The choice of these parameters offered the different possibilities to keep the frequency shift below the cavity bandwidth for each accelerating field. The better choice for some E_{acc} is illustrated in table 1,

E_{acc}(MV/m)	Concept	Δf(Hz)
25	Nb2.5mm, h=0.5mm, H=9mm	319
30	Nb2.5mm, h=1mm, H=11mm	342
34	Nb2.5mm, h=1mm, H=13.3mm	407

Table 1: Copper deposition results on cavity detuning

The computation results shows that the new stiffening system could be a very promising solution for reaching $E_{acc} > 25$MV/m. Of course, all this would be true only if the copper coating has the same Young modulus and Poisson ratio than the bulk copper and the bending strength has a high level. The mechanical properties evaluation is very important to perform calculations of the real stiffening effect of copper coating on cavities.

4 THERMAL SPRAY PROCESS AND MECHANICAL PROPERTIES OF COATING

The eventual success of the thermal spray coated cavities depends on mechanical properties of the coating. The mechanical properties of the coating depends strongly on thermal spray process, so several thermal spray process comparative studies and a series of mechanical properties characterizations were investigated simultaneously.

Mechanical properties of coating could be very different according to the thermal spray process and its conditions. Three thermal spray process have been investigated, the most industrial process APS (Atmosphere Plasma Spray) and the advanced VPS (Vacuum Plasma Spray) process and HVOF (High Velocity Oxy-Fuel) process. Two classical mechanical characterization methods, the traction and the flexion, on standard specimens were performed to give a global behaviour of each copper coating. The X-ray diffraction method was also used to evaluate the elastic constants (Young module and Poisson coefficient) under a goniometer with in-situ micro-traction tests. The X-ray diffraction permit also the residual stress distribution evaluation in the substrate and in the coating, [5].

4.1 Investigated thermal spray process

Actually, the most industrial process is the atmosphere plasma spray (APS), realized under ambient air, several specimens using APS process were realized by l'École Nationale Supérieure des Mines de Paris. This plasma spraying process was already elaborated by a French company "Mallard". In this case, the substrate surface is roughened and a bronze/aluminium thin layer is sprayed onto niobium prior to copper layer deposition so as to achieve a high bonding strength.

Another very interesting thermal process is vacuum plasma spray (VPS), realized under vacuum condition. The "Laboratoire d'études et de recherche sur les matériaux et les propriétés de surface" (France) is specialized in copper deposition using VPS process, very good mechanical and thermal properties were obtained, this process appears to be very interesting to solve the stiffening problems, but one of the projection conditions is the increasing of substrate (Nb) temperature, about 900 ˚ c. At that temperature, the oxygen diffusion in niobium substrate was favored and it damaged dramatically the niobium RRR (Residual Resistivity Ratio). All supplementary precaution would increase the cost of the projection.

The last process that we investigated was the High Velocity Oxy-Fuel (HVOF) process, the main advantage of this process for SRF cavities coating is that the temperature of the substrate (Nb) was kept low (about 100 ˚ C) during the projection. It avoided the oxygen diffusion in niobium and also limited the residual stress due to the difference of thermal expansion ratio between Nb and Cu during the refreshment after deposition.

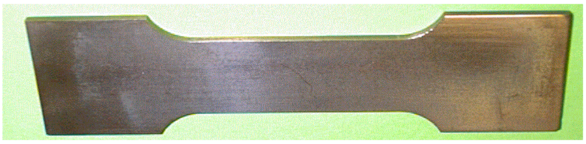
4.2 Specimens elaboration

The mechanical properties were measured with flat samples. To preserve the representativity of the specimens from the cavities axisymmetric geometry, the flat samples were fixed on a octogonal support for thermal spraying, figure 6.

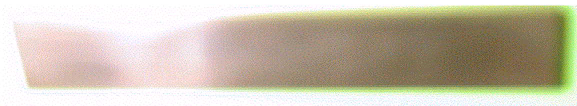
Figure 6: Cu deposition on specimens' support

After deposition, theses covered samples were machined with milling machine tool to have standard tensile specimens. For specific tests, the substrat was removed by milling.

Two types of specimens were elaborated, the first one has bar form, fig.7 b), it was destined to three points flexion, for comparison, the traction was also made on this samples. Another one was the standard tensile specimen, figure 7 a).



a) tensile specimen



b) bar specimen

Figure 7: Specimens

4.3 *Copper deposits behaviour evaluation*

The copper deposits realized by thermal spray process have the laminar structure since the deposition was made layer by layer, the thickness of each layer depends on thermal spray control process, it was generally about several microns. The copper powder could be melted or not depending on the process and the porosity level could be very different, some oxide could be included, as consequence, the deposit medium could be inhomogeneous and anisotropic.

4.3.1 *Micrographic Analysis*

The figure 8, 9 and 10 show the micrographic analysis images of the copper deposit for VPS, APS and HVOF process:

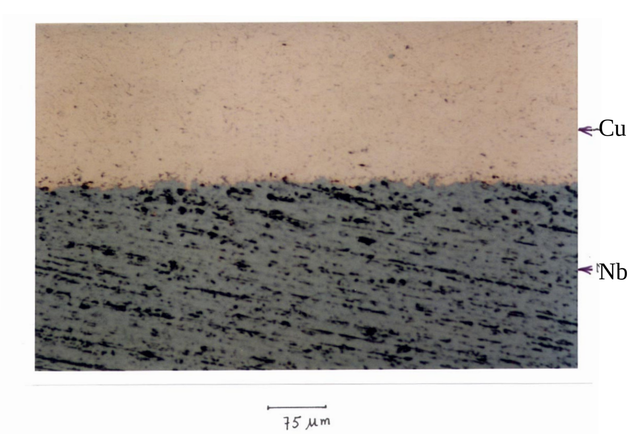
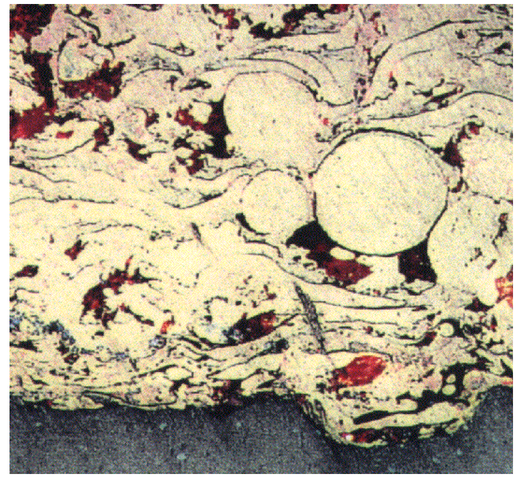


Figure 8: VPS copper deposit



50μm

Figure 9: Industrial Cu APS deposit

33μm

Figure 10: HVOF copper deposit

We can note that the VPS copper deposit has a more uniform structure with a very small porosity, the HVOF copper deposit has many oxide inclusions (dark trace) which made a very anisotropic structure, the industrial APS Cu deposit has the oxide inclusion and unmelted copper powder and a high porosity level.

The particularity of the copper deposit structure make the mechanical characterization of this material difficult. If one uses some classical methods of characterization, the essential problem was to interpret the measurements data. We could expect that some classical methods like the three points flexion or traction deliver some global informations about the copper deposit properties.

4.3.2 *Three points flexion*

A flexion measurement system is investigated at IPN Orsay, the specimen was a rectangle 55mm$\times$10mm, the applied force by a press was calibrated with a spring, the maximum deflection was measured by a comparator with a sensibility of 0.01mm. If F is the applicated force, d the measured maximum deflection of the bar under the charge F, the Young modulus could be deduced by:

$$E = FL^3/4dbe^3$$

where L is the length, b the width and e the thickness. The range of applicated force was from 0 to 2.5N, the range of the maximum deflexion was from 0 to 0.07mm, since $dE/E = -\delta d/d$ and the precision about d was 0.01/0.07, the range of error dE/E was estimated about -0.14. The flexion measurement were performed on HVOF copper deposit and a no industrial APS copper deposit, the measured Young modulus of HVOF copper deposit was 53 GPa and the measured Young modulus of APS copper deposit was 60 GPa.

4.3.3 Traction

A traction machine was investigated at LAL Orsay, the force range is from 3000 Newton to 150 KN, a special extensometer is equipped with a precision of 1 μm or 0.03%. The measurements were performed at first on the same bar specimen used for flexion. The Young modulus measured on the bar specimen was estimated to 55 GPa for HVOF copper deposit and 63 GPa for APS copper deposit. We can note that these results are very closed to flexion measurement results.

The maximum elongation was also measured, we have obtained 0.28% for the HVOF bar specimens and 0.16% for APS bar specimens. It signifies that the HVOF and APS copper deposits were very brittle, the chemical analysis has shown a very high content of oxide in the deposit, the principal reason was that the copper deposition was executed at air environment.

The ultimate tensile stress was also measured, the results were 152 MPa on the HVOF bar specimen and 120 MPa on the APS bar specimen.

The traction was also performed on tensile specimens, fig. 7 a). The measurement results were slightly different from these of bar specimen, the Young modulus measured on the tensile specimens was estimated to 41 GPa for HVOF copper deposit and 46 for APS copper deposit, the ultimate tensile stress was estimated to 60 MPa for HVOF copper deposit and 80 MPa for APS copper deposit, the maximum elongation was estimated to 0.14% for HVOF copper deposit and 0.2% for APS copper deposit. The dispersion can come from the machining of the special shape of the tensile specimen and the precision of the force measurement of the traction machine.

4.3.4 X-ray diffraction

To take into account the anisotropic characteristics of the thermal spray coating, the X-ray diffraction (XRD) method has been used to evaluate, in situ, the stress values of studied specimens in $\{311\}$ directions as a function of applied external deformation and charge. In the other hand, with the same measurement data, the radiocrystallography elastic constant (REC) in $\{311\}$ directions (micro REC) could also be precisely obtained. The stress values in $\{311\}$ direction should not be the same level than applied macro stress. The X-ray diffraction was nearly the only method to measure the micro REC.

The used X-ray is a characteristic K_α Manganese irradiation. XRD stress analysis is realised according the French XRD stress analysis standard (AFNOR XPA09-285, may 1999). With a charge sensor on the micro-traction setting and a strain gauge on the studied specimen surface, we could obtain a strain-stress curve like macro mechanical tests.

With the use of measured micro REC, the precise XRD stress values can be evaluated from the real XRD stress-strain curves, Young modulus and Poisson coefficient were obtained in $\{311\}$ directions for 2 copper coatings. The obtained elastic constants are closed to macroscopic mechanical values because what we realised are the pseudo-macro-tests according the experimental conditions. The real micro elastic constants could be evaluated from REC values but they were difficult to be compared with macro values, [5].

The Young modulus measured on the tensile specimens was estimated to 51 GPa for HVOF copper deposit and 41 for APS copper deposit, the ultimate tensile stress was estimated to 105 MPa for HVOF copper deposit and 98 MPa for APS copper deposit, the maximum elongation was estimated to 0.2% for HVOF copper deposit and 0.23% for APS copper deposit.

4.3.5 Experimental results analysis

The results of different measurements mentioned previously were compared to get more certitude on mechanical properties that we want to know.

We could note that the Young modulus values obtained from different measurements were very similar, close to 50 GPa, this value was less than a half of the forged copper. Another major defect of studied HVOF and APS Cu deposits was the fragility, the properties of the studied HVOF and APS Cu deposits were not good enough for our applications.

However, a very interesting copper deposition process is the VPS, it avoids the oxidation during the deposition since the deposition was executed at vacuum condition. The mechanic properties were very similar to the forged copper, the only precaution is to avoid the oxygen diffusion in niobium during the deposition if the temperature of the substrate exceeds the 800 ˚C, this process should be optimized in the near future. Anothee controled atmosphere plasma spray process (CAPS) using inert atmosphere during the process will been studied also in the near future .

5 THERMAL STRESS ANALYSIS OF A NIOBIUM CAVITY WITH COPPER COATING AT LIQUID HELIUM

A new problem should be analyzed concerning the copper coated niobium cavity during the cooling down since the thermal expansion of the niobium was very different to the thermal expansion of the copper. An analytical thermal stress calculation and an in situ thermal stress measurement are developed from room temperature to liquid helium temperature, [7].

The calculated prediction of thermal stress is verified by measurement, the figures 11, 12 and the table 2 show a very good agreement between the calculation and the measurement.

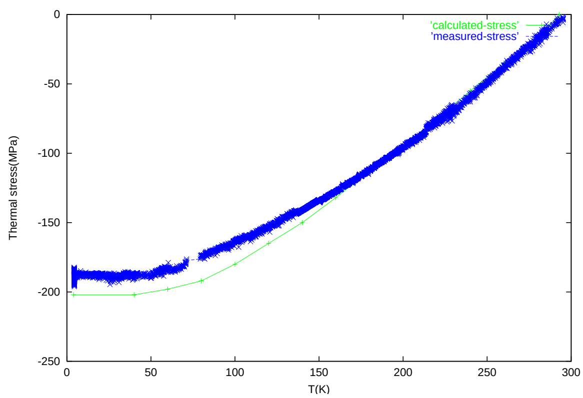


Figure 11: Stress at inner Nb surface

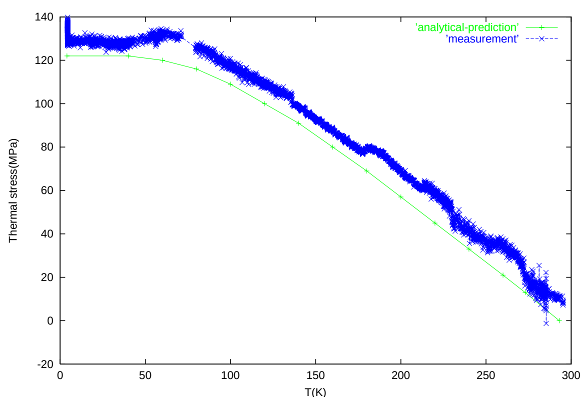


Figure 12: Stress at outside Cu coating surface

	Measurement	Calculation
Nb inner surface	**σ_{4K}=190MPa**	**σ_{4K}=201MPa**
Cu coating surface	**σ_{4K}=130MPa**	**σ_{4K}=122MPa**

Table 2: Measured and calculated thermal Stress

As the elastic limit of niobium increases very much as the temperature decrease, reaching about 600MPa at 4K as compared to 70MPa at 293K, there was no particular danger to damage the niobium, the measurement doesn't show any inelastic deformation. But important geometrical modifications should appear, a new device correcting the cavities volume change must be investigated to keep the functional frequency of cavities.

6 CONCLUSION

Numerical simulations were performed for SRF cavities' mechanic stability on pulsed mode. The cavities stiffening problems were largely studied, the performance of a new stiffening method using thermal spray technique to add a copper coating at niobium cavities were analyzed, a series of material characterization methods was investigated on different thermal spray deposits. The development and optimization of an adapted thermal spray process for SRF cavities stiffening requirement continuous, it constitutes a real technical and economical challenge. The application of this technique was not limited to TESLA project, it has been also proposed low beta SRF cavities fabrication for high-power proton-linacs. The cavities tuning feasibility study should be investigated in the near future, on a welded 1.3 GHz two half cells specimen, the vibration mode calculation should be also investigated. The numerical simulation has contributed also to the design of SRF cavities for high-power proton-linacs [1] and this contribution should continue in next steps of the demonstrator realization for nuclear waste transmutation.

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