ADVANCES IN SUPERCONDUCTING RF CAVITY STIFFENING BY THERMAL SPRAYING

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Abstract

Mechanical stability of SRF cavities is an important issue for future pulsed high-energy e+/e- colliders like TESLA or for high intensity proton linacs using SRF cavities. The French collaboration IPN/LAL/CEA is studying since 3 years now a new stiffening method based on the addition of a copper layer on the cavity outer walls by thermal spraying. Several 3 GHz and 1.3 GHz prototypes have already been realized and prove the feasibility and interest of the technique. Numerical simulations have been performed to study the mechanical and thermal behaviour of this bimetal cavity to define the characteristics needed for the copper coating. Different thermal spraying methods are now investigated by means of mechanical and thermal characterization of sample and also by prototypes cavities RF tests in order to reach the best coating properties suitable for SRF cavities.

1 INTRODUCTION

The main advantage of superconducting RF cavities is the very small power dissipation as compared to normal conducting copper cavities, leading to high quality factor Q_0. As a consequence, the frequency bandwidth Δf_{BW} of such devices are very narrow, according to the relation $\Delta f_{BW} = f_0/Q_l$ (f_0 is the cavity resonant frequency and Q_l the loaded quality factor). For f_0 in the GHz range and Q_l equal to a few 10^6, the bandwidth is typically a few hundreds of Hertz. Due to the high frequency of SRF cavities, a variation of only 1 µm of one cavity dimension could induce a frequency shift of several tens of Hertz. So SRF cavities are very sensitive to geometrical perturbations and require a high mechanical stability. Several phenomena could induce cavity shape deformations such as vibrations, pressure variations of the cryogenic fluids, over pressure during cavity cool-down or Lorentz forces originated by the high electromagnetic fields in the cavity.

An alternative stiffening scheme based on the addition of a thermally sprayed copper layer on the cavity outer walls could be a solution to increase the mechanical stability of SRF cavities. This method could be used for TESLA cavities as well as for lower frequency cavities used in proton linacs. This solution could also be very complementary with seamless cavity fabrication processes (spinning or hydroforming).

2 STIFFENING REQUIREMENTS

2.1 TESLA cavities

In the TESLA project [1], the 500 GeV e^+/e^- center of mass energy is reached by means of high gradient SRF cavities (E_{acc}=22 MV/m) operated in the pulsed mode. One difficult challenge is to reach the TESLA design luminosity ($L = 3.1\times10^{34}$ cm^{-2} s^{-1}) needed to have a reasonable event rate for particle physics. Such luminosity could only be obtained with small spot sizes at the interaction point. This requirement is fulfilled providing that the energy spread is kept at a very low level. Mechanical disturbances induce cavity detuning and hence variations of the cavity accelerating voltage, resulting in an increase of the energy spread.

For pulsed machine and high gradients as for TESLA, the most important source of frequency variation is originated by Lorentz forces (Fig. 1). The important surface electromagnetic fields E_S and H_S create a radiation pressure P on the cavity wall:

$$P = \frac{\mu_0 H_S^2 - \varepsilon_0 E_S^2}{4}$$

The cavity geometry is slightly altered by the radiation pressure and the volume variation results in a frequency shift, according to Slater's theorem [2].

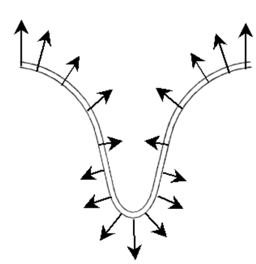

Figure 1: Repartition of the radiation pressure induced by Lorentz forces on a multicell cavity.

For small deformations, the volume variation is proportional to the radiation pressure and therefore the Lorentz force detuning Δf is proportional to the square of the accelerating field:

$$\Delta f = K E_{acc}^2$$

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The detuning factor K quotes the sensitivity of a cavity to Lorentz force detuning.

Fast RF feedback allows to control the amplitude and phase of the cavity accelerating voltage, providing that the frequency shifts are not too large. The RF control system acts back on the incident power to compensate a decrease of the accelerating voltage induced by a cavity resonant frequency shift. To keep the required extra RF power to reasonable values, TESLA nine cell cavities need to be stiffened. Additional niobium rings, electron-beam (EB) welded between the cells, allowed to reduce by a factor 2 the detuning factor K, down to 1 Hz / $(MV/m)^2$. For TTF, the obtained amplitude and phase stability ($\sigma_V/V < 10^{-3}$ and $\sigma_\phi < 0.005°$) proved that Lorentz force detuning could be kept within acceptable limits [3].

An upgrade of TESLA-500 to an energy of 800 GeV (and $L = 5\times10^{34}$ cm^{-2} s^{-1}) is considered and could be achieved with an increase of the accelerating gradient up to 34 MV/m. For such electromagnetic fields, and despite the presence of the stiffening rings, Lorentz force detuning becomes too large to be controlled by an RF control system because the extra peak power required would be too high. With the TTF RF control, detuning of the cavity by one bandwidth increases the required power @ 25 MV/m by 25 % [4]. However, for short pulses as for TESLA (1.3 ms long with a flat top of 800 µs), the frequency shift computed in the steady state case differs from the effective real detuning because the cavity mechanical deformation is not instantaneous. Dynamic cavity behaviour submitted to Lorentz force detuning could be simulated [5] and introduces an important parameter, the cavity mechanical time constant τ_m, which is the cavity response time to a mechanical perturbation.

On the figure 2 is plotted the results of the simulated effective frequency shift for a typical TESLA cavity after the RF pulse of 1.3 ms, using the following parameters: E_{acc} = 25 MV/m, K = 0.9 Hz / $(MV/m)^2$, I_b = 8 mA. For an increasing τ_m, the effective detuning is reduced and becomes much lower than the steady-state value (Δf = 560 Hz).

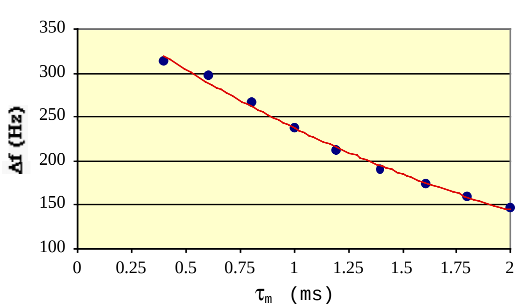

Figure 2: Effective frequency shift after 1.3 ms as a function of the mechanical time constant for a typical TESLA cavity at 25 MV/m.

Note that experiments on TTF allowed to measure τ_m for TESLA cavities in the range 200 - 400 µs [4].

2.2 Proton cavities

Several designs of high-intensity proton linacs are based on low-frequency SRF cavities (350 - 700 MHz). The peculiar shape of these cavities ("pizza-like"), with lateral walls almost parallel, make them very sensitive to any mechanical perturbation. Most of the applications requires a CW operation (nuclear waste transmutation or tritium production), but other projects could use a pulsed regime (neutron spallation sources for instance) and again Lorentz force detuning could be a major problem, even if the designed peak surface fields of such machines are lower than TESLA.

But, even in the CW regime, the low-beta proton cavities need to be stiffened to sustain mechanical perturbations. For instance, a 2 bar over-pressure might occurs at the beginning of the cavity cool-down when the cavity is still at the room temperature. Numerical simulations have shown that in that case, and even for a 5 mm thick 700 MHz (β = 0.5) cavities, the induced stresses in the cavity niobium walls could be higher than the niobium yield stress (60 MPa @ 300 K) resulting in a non-reversible cavity plastic deformation.

2.3 Seamless cavities

Seamless cavity efforts have common goals to avoid EB welding and to simplify the fabrication process as compared to the classical one (deep drawing and welding) [6]. Independent of the technique used (spinning or hydroforming), the most difficult task is to reach a uniform wall thickness all along the cavity. Moreover, the difficulty to produce seamless cavities increases with the niobium thickness. Therefore, stiffening by thermal spraying could be very complementary with thin-wall spun cavities (a few tenths of millimeter thick) or hydroformed cavities, easy to produce and already available.

3 CAVITY STIFFENING BY THERMAL SPRAYING

Since three years, a collaboration between three French laboratories IPN, LAL and CEA/DSM/DAPNIA is studying a new stiffening method for SRF cavities.

3.1 Principle

The principle of the method is to coat the outer cavity wall with a metal by thermal spraying. The objective is to increase the cavity stiffness without lowering RF performances. Therefore, the following requirements should be fulfilled to become a good technical solution:

- High mechanical stability to overcome microphonics and Lorentz force detuning at high fields

(E_{acc} > 25 MV/m) where other solutions (stiffening rings for TESLA cavities) are not efficient any more [7].

- Good coating thermal properties that does not affect the cavity thermal stability to keep the RF performances at the same level.
- Lower cavity fabrication costs by reducing the niobium thickness and avoiding any further EB welding.

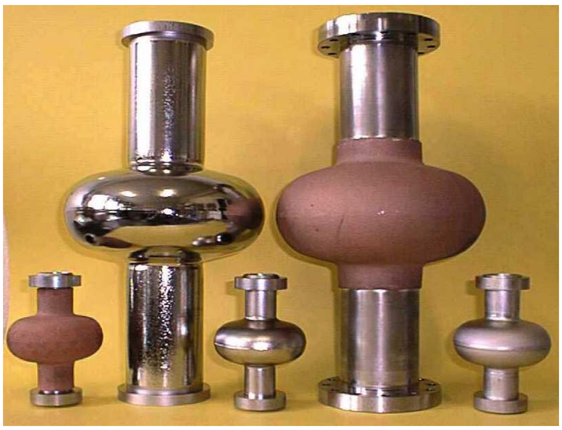

Figure 3: 1.3 and 3 GHz bulk niobium and niobium copper coated cavities at.

Almost any kind of coatings could be obtained by this technique. Our first investigations were directed towards copper coating, in order to take advantage of its good thermal properties. Some prototypes of niobium cavities covered with copper are shown on Fig. 3

As the most difficult requirements are for the TESLA cavities at high gradients, our studies are mainly directed towards TESLA cavity stiffening, because any solutions suited for these cavities would also be adapted to other applications.

3.2 Mechanical properties requirements

To evaluate the stiffening capabilities of the method, numerical simulations were performed with the finite element code CASTEM 2000 to compute the Lorentz force detuning on a cavity stiffened by a copper layer. First evaluations showed that the best stiffening solution is to cover the cavity with a uniform h = 0.5 to 2 mm thick copper layer and an additional H = 10 to 20 mm at the iris between two adjacent cells (Fig. 4).

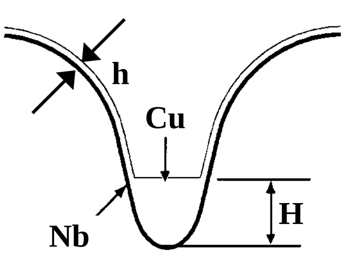

Figure 4: Stiffening scheme parameters definition.

An optimization of the required heights h and H could be done, depending on the coating characteristics (Young's modulus) and on the objective on the accelerating field [8]: the criteria is to obtain a frequency shift lower than the cavity bandwidth.

The coating's Young's modulus is the most important parameter for the stiffening effect. The bonding strength between the niobium and the coating should also be high enough (> 80 MPa) to avoid any detachment. The ultimate tensile strength has to be sufficient to withstand the stresses imposed, for instance, by cold tuning.

3.3 Thermal property requirements

The copper coating could increase the overall thermal resistance, R_g, between the niobium RF surface and the liquid helium bath by an amount ΔR_g. The cavity thermal behaviour (Q_o level and maximum attainable field) should not be affected by this effect. Thermal simulations of a defect-free TESLA cavity, taking into account the overall thermal resistance increase ΔR_g due to the copper layer, showed that the cavity thermal stability is not affected for E_{acc} = 40 MV/m if $\Delta R_g < 4.2\ 10^{-4}$ K.m^2.W^{-1} (i.e. about 3 times a typical Kapitza Nb/HeII resistance R_k = 1.4 10^{-4} K.m^2.W^{-1}) [9].

For 700 MHz proton cavities, the coating thermal property requirements are a slightly less drastic, due to the lower operating gradients and lower frequencies.

4 THE DIFFERENT THERMAL SPRAYING TECHNIQUES

Thermal spraying is a generic term gathering different techniques. Each of them are able to produce coatings with specific properties, and one of the main difficulty is to find the right process for a given application. The spraying techniques differ mainly in the heat source (plasma or chemical combustion) and in the environment (under air, inert gas or vacuum). A summary of the different techniques with their main parameters and typical achievable coating properties is given in Table 1.

The coating characteristics depend strongly on the spraying process but also on the deposition parameters which number about 50, and are more or less important, such as particle velocity, gun-substrate distance, powder-particle size distribution, substrate temperature, angle and velocity of the powder injection, etc... For a given substrate, coating material and spraying process, each of these parameters has to be optimized to obtain the best coating characteristics. Techniques such as atmospheric plasma spraying (APS) or high velocity oxy-fuel spraying (HVOF) could give interesting properties for the deposited layer. Generally, the best properties are obtained with more complex processes performed under a controlled

Table 1: Main parameters and coating properties of different thermal spraying techniques [from 10, 11]

Process	Flame Spraying (FS)	High Velocity Oxy-Fuel (HVOF)	Atmospheric Plasma Spraying (APS)	Controlled Atmosphere Plasma Spraying (CAPS)	Vacuum Plasma Spraying (VPS)	Arc Spraying (AS)
Heat source	Combustion of fuel gas in oxygen	Combustion of fuel gas in oxygen at high pressure	Plasma (mixture of Ar/H_2, Ar/He or Ar/N_2)	Plasma (mixture of Ar/H_2, Ar/He or Ar/N_2)	Plasma (mixture of Ar/H_2, Ar/He or Ar/N_2)	Arc heating (consumable electrodes)
Heat source temperature	3000 - 3500 K	3000 - 3500 K	10000 K - 15000 K	10000 K - 15000 K	10000 K-15000 K	-
Exhaust jet speed	80 - 100 m/s	1500-2000 m/s	500 - 800 m/s	500 - 800 m/s	1500 - 3000 m/s	particle speed < 150 m/s
Particle size	Powder: 5-100 µm Wire diameter 3-6 mm	5 - 50 µm	5 - 100 µm	5 - 100 µm	5 - 20 µm	Wire diameter: 2 - 5 mm
Atmosphere	Air	Air	Air	Inert Gas Ar, He, N_2	vacuum (50 mbar)	Air
Porosity	10 - 20 %	< 5 % < 1 % possible	1- 10 % typical	1- 10 %	< 2 %	10 -20 %
Bonding strength	30 MPa typical 70 MPa max.	> 60 MPa typical 100 MPa achievable	20 - 80 MPa	20 - 50 MPa 80 MPa achievable	> 80 MPa	10-30 MPa typical
Remarks	Industrial, high oxidation	Industrial, high bonding strength, High oxidation	Industrial, high oxidation	Low oxidation homogeneous coating	Low oxidation, high bonding strength	Industrial, poor coating properties

environment, like the controlled atmosphere plasma spraying (CAPS), or the vacuum plasma spraying (VPS).

Due to the lack of data on the copper spraying onto niobium and more generally on the coating characteristics at cryogenic temperatures, the choice of a method from previously published results was not possible.

Up to now, two spraying techniques have been fully investigated: the APS and HVOF methods. Investigations on the VPS and on the CAPS also gave some interesting preliminary results.

5 RESULTS ON PROTOTYPE CAVITIES

Five prototype cavities (3 GHz and 1.3 GHz) have already been coated with copper using different thermal spraying methods.

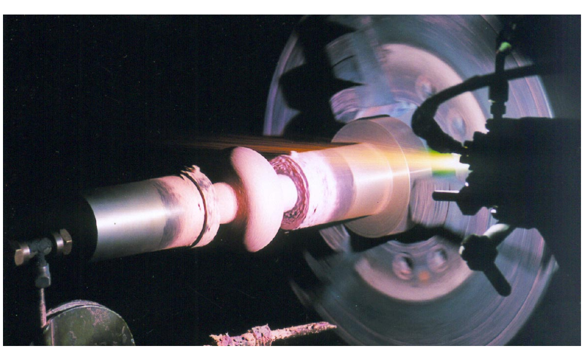

Figure 5: the non-optimized APS copper coating of a 3 GHz single-cell cavity.

The first tests were performed on 3 GHz cavities made from reactor-grade niobium (RRR = 30), heat treated at 1200 °C with Ti gettering, and then coated (Fig. 5) by a non-optimized APS process (manual procedure, use of an intermediate Al/Cu bonding layer). The results proved the feasibility and interest of the method [12]: accelerating fields of 14 MV/m were achieved and almost no degradation of the performances was observed after the copper deposition.

Experiments on a 1.3 GHz cavity tested before and after copper deposition by the same non-optimized APS process showed almost no degradation (Fig. 6) of the 28 MV/m maximum accelerating field achieved in this cavity (limited by a quench).

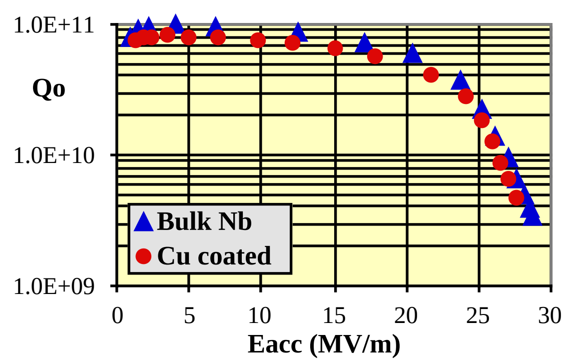

Figure 6: 1.3 GHz cavity performances before and after copper coating using the non optimized APS technique.

Moreover, the stiffening effect of the copper coating was quantified with the help of the Δf vs E^2_{acc} measurement: a reduction of the detuning factor K by a factor 1.6 was obtained as shown on the figure 7.

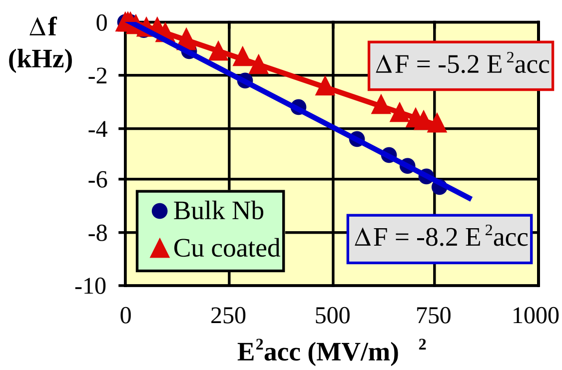

Figure 7: Measured detuning factor before and after copper coating by the non-optimized APS process.

Another 1.3 GHz high-field cavity has been recently copper coated by the HVOF technique. A picture taken during the spraying process is shown on the figure 8: the cavity is mounted on a rotating axis and the torch delivering the copper jet follows a trajectory similar to the cavity shape, almost always perpendicular to the cavity surface. Two CO_2 cooling nozzles are placed from each side of the torch, in order to keep the substrate at a low temperature (less than 70 °C), measured by a monochromatic infra-red optical pyrometer.

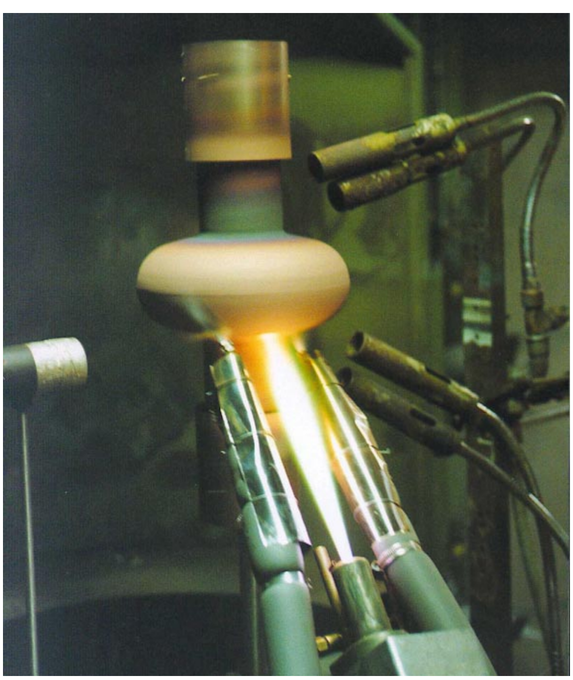

Figure 8: HVOF copper spraying on a 1.3 GHz cavity.

Prior to coating, the cavity is degreased and sand-blasted to increase the surface rugosity and therefore the bonding strength between niobium and copper. The 3 mm thick homogeneous copper layer was deposited in 1h35min.

Before coating, the maximum accelerating field was 31 MV/m. The cavity was then tested after Cu deposition, only with a light integrated chemistry. During the test, heavy field emission occurred and we did not succeed in completely processing out the emitters. The maximum field was then 19 MV/m, limited by a quench (fig. 9). Changes in the experimental observations (apparition of field emission) and suspicions about a cavity contaminated with dust coming from copper residues did not allow us to conclude that the degradation of cavity performances was due to the copper layer. A new test performed after a careful cleaning of the beam-tube outer surface to avoid contamination during assembly should help to clarify the results observed.

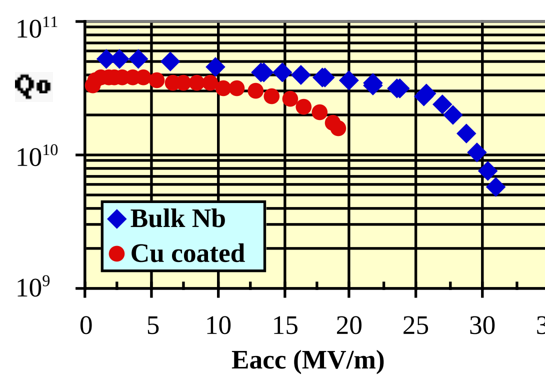

Figure 9: 1.3 GHz cavity performances before and after copper coating using the HVOF technique.

However, the measurement of the Δf vs E^2_{acc} curve clearly showed the important increase of the cavity mechanical stiffness: the detuning factor K was strongly reduced by a factor 4.2 with the additional copper laye, as shown on Figure 10.

Table 2: Coating mechanical and thermal characteristics (X means no sample available for measurement).

Process & Provider	RRR Coating	Young modulus (GPa)	Porosity	Δ Rg @ 2K ($K.m^2/W$)	ΔRg/Rk	Conductivity @ 2 K (W/m.K)	UTS (MPa)	Limitation & Estimated E_{acc} max
Cu APS *Mallard*	3	25	≈20-30%	$4.0\ 10^{-4}$ (2 mm)	3	1.55	≈ 75	Stiffening 33 MV/m
Cu CAPS *CEA*	X	≈ 60	9.8 %	$3.9\ 10^{-4}$ (2 mm)	3	X	≈ 100	Stiffening > 35 MV/m
Cu HVOF *Sevenans*	3	53	2.6 %	> $1.43\ 10^{-3}$ (3 mm)	> 10	0.19	≈ 100	Heat transfer < 30 MV/m
Ti APS *SICN*	3	18	≈20-30%	$5.0\ 10^{-4}$ (2 mm)	3.5	X	X	Stiffening < 32 MV/m
Cu APS *Evry*	4	60	1-2 %	> $1.8\ 10^{-3}$ (3 mm)	> 16	0.22	≈ 100	Heat transfer < 25 MV/m
Ultimate Goal		**95**		**$4.2\ 10^{-4}$**	**3**	**4.8** for e_{Cu}=2mm, no He penetration	**80-100**	**40 MV/m**

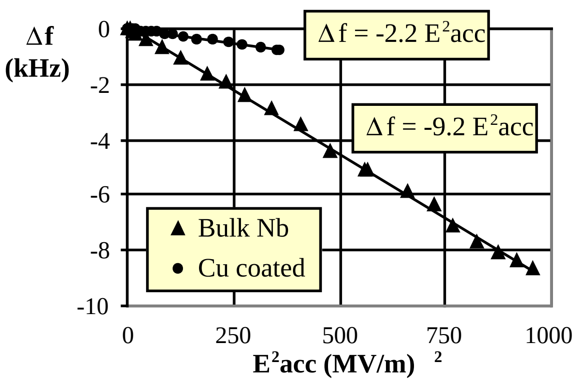

Figure 10: Measured detuning factor before and after copper coating by HVOF spraying.

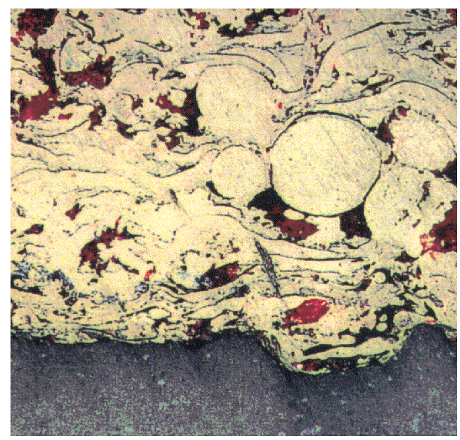

Figure 11: Optical microscope picture of the non optimized APS copper coating (× 200).

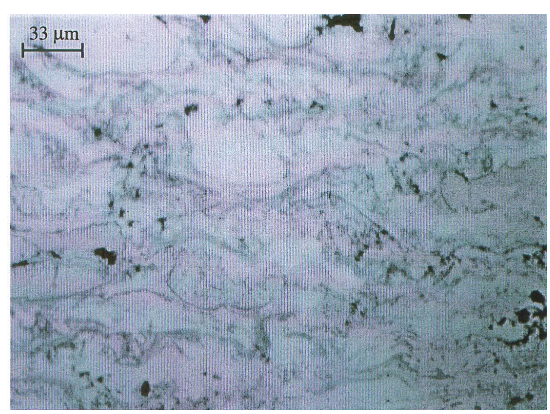

Figure 12: Optical microscope picture of the HVOF copper coating (× 200).

6 MECHANICAL AND THERMAL PROPERTIES OF COATINGS

In order to choose the most suitable spraying process, the coating properties should be measured, and an assessment of the quality be made.

6.1 Optical microscope pictures

At first, optical microscope pictures are used to give an evaluation of the porosity, the unmelted particle number, the oxide content to therefore have an estimate of the coating quality. Characterization of the niobium - coating interface quality is also possible. The two following pictures (fig. 11 and 12) show the difference between a highly porous coating (20 to 30 % with the non optimized APS, fig. 11) and a dense one (2 to 3 %, with HVOF, fig. 12)

6.3 Mechanical and thermal measurements

Mechanical and thermal characterizations have been performed on samples. Their preparation (Fig. 13, 14) was done by: niobium and stainless steel rectangular plates are placed on an cylinder, forming an eight-side polygon (the so-called "praying wheel"). After the thermal spraying, the plates are removed and samples are machined at the right size for the different characterizations.

Young's modulus, porosity and ultimate tensile strength (UTS) were measured by several methods [8]. Thermal properties like conductivity and overall thermal resistance were measured at low temperature at the IPN Laboratory using dedicated test cells [13].

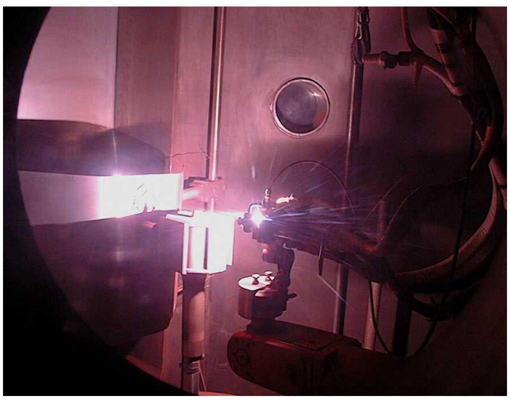

Figure 13: Samples fabrication: the copper deposition process on the "praying wheel" by the APS technique.

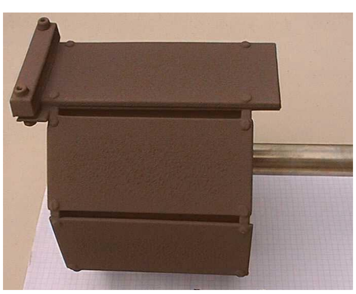

Figure 14: The obtained "praying wheel" after the coating with the APS technique.

Table 2 gives the results for several coating material and techniques: industrial APS (Mallard and SICN firms). HVOF (LERMPS lab), CAPS (CEA lab) and optimized APS (Ecole des mines lab). A VPS coating was also performed on a niobium tube, but due to the high substrate temperature during spraying (above 800°C), the niobium was strongly polluted by oxygen: the RRR of niobium bars located inside the tube during the process were decreased from 140 to 15. Further investigations on the VPS process at low substrate temperature will be performed to determine what coating properties could be achieved in these conditions.

The last line of the Table 2 gives the requirements for a given stiffening scheme of a TESLA cavity (h = 2.5 mm and H = 20 mm, see fig. 4) to keep the frequency shift due to Lorentz forces (calculated in the steady-state case at 40 MV/m) lower than the cavity bandwidth. As mentioned in the Section 3.2, the effective detuning is lower than the one computed in the steady-state case: this positive effect will likely be enhanced for a copper-coated cavity since the additional layer will increase the cavity mechanical time constant τ_m.

Measurements reported in Table 2 showed that the coating's Young's modulus is divided by more than a factor 2 as compared to the bulk material (130 GPa). These values are consistent with the measured porosities, which depend strongly on the spraying process. Lowest porosity rates (< 3%) were obtained by optimized APS process and HVOF. Measurements of the coating RRR and electrical resistivity ρ at room temperature indicated that the copper layer has poor properties as compared to the bulk material (RRR < 4 and $\rho_{coating} < \rho_{bulk} / 4$ @ 300 K).

The last column of the table give, for each spraying process, what would be the limitation for a copper-coated cavity using the stiffening scheme described above. Due to the coating's low Young's modulus, the limitation is mainly the stiffening efficiency, but in the case of the optimized APS and HVOF spraying, the limitation is the heat transfer from the cavity RF wall to the helium bath.

To check if the porosity rate plays an important role in the coating thermal properties (i.e. to verify if superfluid helium is able to penetrate the microchannels), a porous coating of a poor thermal conductivity metal (Ti) was realized. The measured coating thermal resistance proved that superfluid helium penetrates the deposited layer and short-circuit the highly resistive coating. The copper layer appears to have a very bad thermal conductivity as compared to the bulk material. The requirements on the overall thermal resistance increase are fulfilled only providing that the porosity rate is high. The HVOF and optimized APS process showed that for such a high thermal resistance, we were not able to make a precise measurement and only a minimum value of the thermal resistance could be deduced (the test-cell was designed for lower thermal resistance samples) [13]. We suspect that the high oxide content of the APS and HVOF copper coatings is responsible for their bad thermal properties. Oxide content determination on the optimized APS copper coatings gives a value of 12 % (mainly Cu_2O).

Avoiding oxidation seems to be necessary to obtain good copper coating properties. The preliminary results on samples coated by the CAPS technique are very promising: thanks to a reduced oxidation due to the inert-gas spraying environment, the thermal resistance increase, ΔR_g, meets the requirements. Moreover, the Young's modulus seems sufficient to successfully stiffen the cavity for at least 35 MV/m, an accelerating gradient slightly above the TESLA-800 specifications (i.e. 34 MV/m).

7 CONCLUSION

SRF cavities are very sensitive to any mechanical perturbation. Cavity stiffening is necessary for TESLA cavities to overcome Lorentz force detuning in order to reach the high luminosity. Proton cavities need a large niobium thickness to withstand mechanical efforts, and for the low-β ones, an additional stiffening scheme will be necessary.

The proposed stiffening method based on copper thermally sprayed is very promising. Different spraying processes have been investigated and the mechanical and thermal properties of the coating were systematically measured. Prototype single-cell cavities proved the interest of the method and allowed us to quantify the stiffening effect.

Preliminary results on the copper layer obtained by the CAPS procedure are very interesting and seem to meet the requirements for a successful stiffening of TESLA-800 cavities (designed to operate at 34 MV/m). Further investigations on the CAPS procedure, and also on the VPS spraying at low substrate temperature will be performed in the near future.

To go on with the characterization of the coating, other experiments are planned: determination of the bonding strength between the niobium and the coating, fatigue tests of a bi-metal material submitted to successive cool-down and warm-up, and study of the tuning feasibility using a device made of two half-cell.

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