INERT GAZ PLASMA SPRAYING FOR CAVITY STIFFENING USING COPPER COATING

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Abstract

Superconducting cavities required a high mechanical stability not to be affected by Lorentz forces detuning or by external mechanical vibrations which could induce large frequency changes. One possibility to improve the mechanical stability of SRF cavities is to coat the external cavity surface with an appropriate material. Since a few years, we have studied different coating techniques and materials, which could be used for this stiffening method. The thermal and mechanical properties of the different coatings obtained have been systematically measured and compared. An interesting process, the inert gas plasma spraying has been recently investigated: the copper coating obtained is characterized by a low porosity and a reduced oxidation. Measurements performed on samples showed that the coating meet the required thermal and mechanical performances. From the industrial feasibility point of view, this method is fully realistic and brings interesting performances at moderate costs.

1 INTRODUCTION

Future superconducting linear accelerators such as TESLA, the 500/800 GeV e+/e-linear collider or the Spallation Neutron Source (SNS) are designed to operate in a pulsed mode with pulse length in the millisecond range. Mechanical stability of the Superconducting Radio-Frequency (SRF) cavities is then a key issue for operating properly the cavities at high accelerating gradients. Lorentz forces or mechanical vibrations could induce an important shift of the cavity resonant frequency, resulting in an accelerating field (E_{acc}) decrease. RF feedback is used to compensate the E_{acc} drop by means of an increasing input RF power. Usually, the additional RF power is limited to 10 % of the nominal power for cost reasons so the acceptable cavity detuning has to be small enough to be compensated with RF feedback. As summarized in Table 1, depending on the application, different solutions could be foreseen, but have a limited efficiency, or are very costly.

A few years ago, we have started to study an alternative solution to stiff SRF cavities. The proposed solution is based on the coating of the external cavity walls with a copper layer [1]. An interesting technique to realize the copper deposition is the thermal spraying, a process widely used in the industry today for various applications.

Table 1: Limitation of the usual possible solutions for cavity stiffness increase.

Cavity Type	Problem	Possible cure	Limitation
TESLA Deep-drawn + EB welding	Lorentz Force Detuning	Stiffening rings	Not efficient for high gradients
PROTON (low β)	Any mechanical disturbance	Increase Nb thickness	Cavity fabrication cost
SEAMLESS Hydroforming Spinning	Variable Thickness	Use thicker initial Nb tube or sheet	Still able to fabricate ?

2 WHAT WE HAVE LEARNED FROM PREVIOUS EXPERIMENTS

Thermal spraying is a generic name including a lot of very different techniques such as flame spraying, plasma spraying, arc spraying... In fact, the coating properties are strongly depending on the spraying process, and even for a given process, the numerous deposition parameters could induce drastic changes on the coating properties [2].

The copper layer we need for our application has to be characterized by both good mechanical and thermal properties. The coating mechanical quality is important to obtain a sufficient stiffening effect with the lowest possible layer thickness, and good thermal properties (i.e. low coating thermal resistance) are mandatory not to affect the cavity thermal stability and performances.

An important part of the work was to perform numerical simulations to find a efficient stiffening design and to evaluate the effect of the coating on the static Lorentz force detuning [3]. A finite element code (CAST3M) associated with electromagnetic calculations (SUPERFISH) have been used to calculate the Lorentz forces on the cavity wall, then the cavity geometric deformation in order to compute the frequency change using the Slater theorem.

Several designs of cavity stiffening (Fig. 1) using different copper layer geometry (homogeneous or variable thickness) have been studied and compared with the cavity without reinforcement or with the cavity equipped with the stiffening rings.

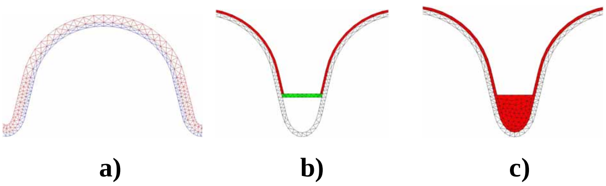

Figure 1: Possible stiffening design: **a)**: homogeneous Cu layer 2mm thick, **b)**: Nb Stiffening rings and Cu 2 mm, **c)**: Cu layer 1.6 mm and iris reinforcement 23 mm.

The first study was to quantify the copper coating young modulus influence on the stiffening efficiency. As we have measured on different samples, the Young modulus strongly depends on the spraying process, and could vary by a factor 5 ! On the figure 2 is plotted the computed detuning of a TESLA 9-cell cavity copper covered using the design quoted **c)**, as a function of the copper coating Young modulus, and for several accelerating field E_{acc} (35, 37 and 40 MV/m).

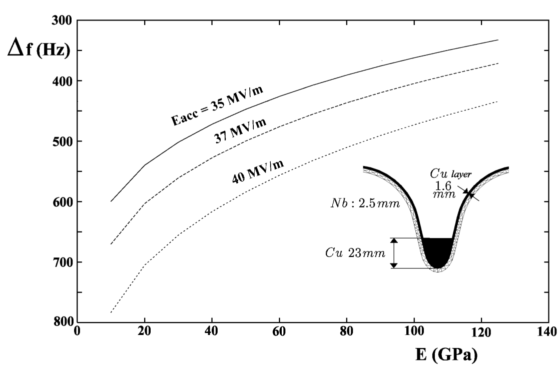

Figure 2: Simulations of the cavity detuning as a function of the copper layer Young modulus for different accelerating gradients.

In order to achieve efficient TESLA cavity stiffening at 40 MV/m, which means keeping the frequency shift at a reasonable value (lower than 500 Hz), a copper coating Young modulus of almost 95 GPa should be achieved. But one has to keep in mind that other mechanical parameters are also very important. Ultimate tensile strength (UTS), bond strength between the copper and the niobium, and maximum elongation are important parameters in order for the layer to sustain thermal shocks and mechanical stresses due to the cold tuning (initial tuning and field flatness could be done prior to the copper deposition). Reasonable values are above 50 MPa for the UTS and bond strength, and a maximum elongation above 0.1 %.

Besides the mechanical behavior, the others important parameters are the coating thermal properties. Covering a cavity with a copper layer could change its thermal stability because a new thermal barrier between the niobium and the helium bath is added. If the coating thermal resistance is important, the cavity performance will be lowered (maximum achievable accelerating gradient).

Thermal simulations of the bi-material cavity have been performed [4] to quantify this effect on the cavity defect-free case (global heating), our ultimate goal. The consequence of the coating on the cavity performances is shown in the figure 4, where the Q_0 vs E_{acc} curve has been computed for several copper layer thickness.

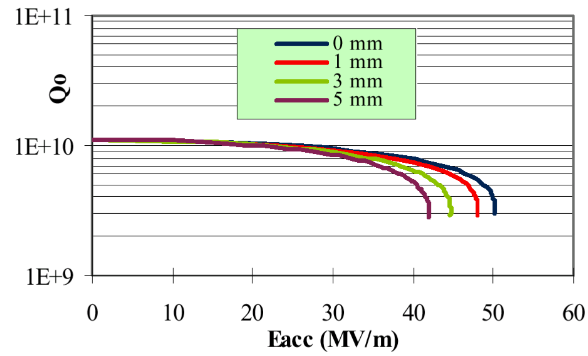

Figure 4: Computed cavity performances for different copper layer thickness (0 mm stands for the non coated cavity) in the defect-free case.

The result of these simulations is to find a criteria on ΔR_{th}, the increase of the thermal resistance due to the copper layer in order to reach the TESLA-800 goal (Q_0 = 5 10^9, E_{acc} = 40 MV/m). So the maximum acceptable increase of ΔR_{th} is 4.2 10^{-4} $K.m^2.W^{-1}$ at 2K, which corresponds to 3 times the thermal resistance of a 3 mm thick niobium plate (RRR 150).

During our previous study, several spraying processes have been investigated: atmospheric plasma spraying (APS), basic and optimized, and high velocity oxy-fuel spraying (HVOF). Mechanical and thermal properties of the copper layer have been systematically measured on samples. The results showed that none of these methods were able to produce copper coatings characterized at the same time by the desired mechanical and thermal properties.

Recently, another thermal spraying process has been investigated: the plasma spraying under inert gas (IPS).

3 INERT GAS PLASMA SPRAYING

One conclusion of the previous study was that the in-flight oxidation of the copper melted particles during the deposition process is an important phenomenon which is probably the main cause of the poor copper coating thermal conductivity (compared to the bulk) and also the layer fragility. The Inert gas Plasma Spraying (IPS) is based on the classical plasma spraying, and the whole process takes place in a sealed chamber (Fig. 5) filled with inert gas (argon).

Figure 5: Chamber used for Inert gas Plasma Spraying.

IPS spraying on a 1.3 GHz prototype cavity and on niobium rectangular samples was performed in the specialized C2P laboratory of the "Ecole des Mines de Paris" located in Evry (France). A preliminary study allowed to set up the best spraying parameters. Some of them are shown in the table 2.

Table 2: IPS spraying parameters.

Atmosphere	Argon
Spraying distance	140 mm
Cu powder size	> 45 µm and < 90 µm
Powder feed rate	30 $g.min^{-1}$
Plasma gas flow rate	Ar: 80 and H_2: 10 $l.min^{-1}$

Before spraying, the cavity (or the sample) is degreased and sand blasted with 300 µm sized white corundum. It is then pre-heated in the chamber filled with argon with the plasma torch, without copper powder injection, up to a temperature of about 150-200°C. While the spraying is performed, the substrate temperature increases and could lead to niobium pollution and superconducting properties degradation. To avoid this phenomenon, an argon cooling using 2 external nozzles was installed on each side of the plasma gun. A pyrometric system is used to monitor the cavity wall temperature and Ar flow rate is set up to keep the substrate temperature below 150°C. A picture taken during the deposition process on the cavity is shown on the figure 6.

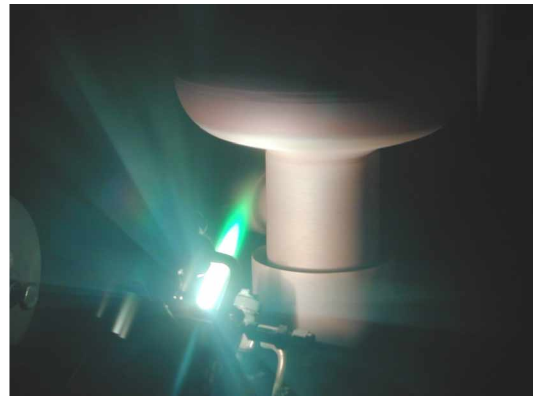

Figure 6: 1.3 GHz cavity during copper deposition in the IPS chamber.

4 CHARACTERISTICS OF THE IPS COPPER COATING

Several samples of niobium copper coated were fabricated in order to perform mechanical and thermal measurements to characterize the copper layer quality, and to compare the results with the values already obtained with the others spraying methods [5].

4.1 Mechanical Properties

The coating porosity was first measured using picture analysis: 8 % porosity and very low oxidation is revealed by the picture (Fig. 7).

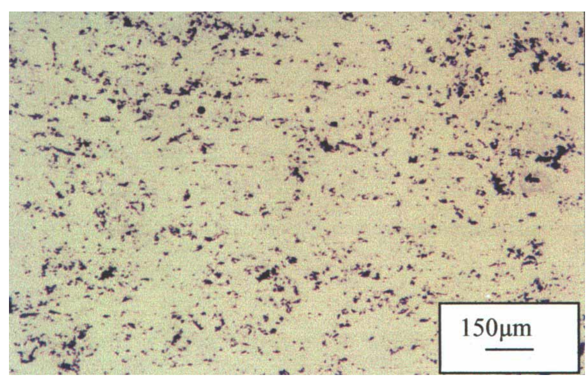

Figure 7: Microprobe picture of the IPS copper coating.

Elastic properties of the copper layer were measured using several methods: X-ray diffraction (XRD) was performed to evaluate the residual stress between the Cu layer and the niobium substrate. Usual tensile measurements were carried on with a special traction device equipped with a precise extensiometer. Vicker's microhardness was measured using a microdurometer to evaluate the microstructure anisotropy. These techniques and the results have been recently published [6], and some are presented in Table 3.

Table 3: IPS elastic properties measured on samples.

Young Modulus	72 GPa
UTS	124 MPa
Porosity	8 %
Maximum elongation	0.2 %
Bond strength	51 MPa

An automated 3 points bending device was developed at the IPN laboratory to perform Young Modulus measurements of copper samples (Fig. 8). This device is adapted for macroscopic measurements of fragile layers. The same apparatus was used for each copper samples, so the obtained values could be confidently compared.

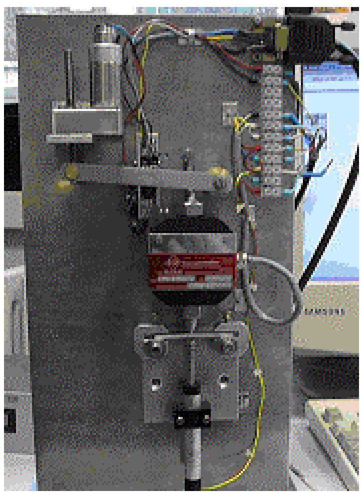

Figure 8: IPN apparatus for Young modulus measurement using the 3 points bending method.

The measured Young modulus is 72 GPa, a value lower than the bulk (130 GPa), but 3 times higher than the one obtained with the non optimized APS process.

4.2 Thermal Properties

Thermal properties of copper coated niobium samples were measured at the IPN laboratory [7]. On the figure 9 is plotted the measured copper layer thermal conductivity and is compared with other materials. The conductivity improvement of the copper layer deposited with the IPS is very clear as compared with the HVOF process.

This result is confirmed by the overall thermal resistance measurement on samples: for a bi-metal cavity (Nb RRR 140, thickness 2.5 mm, and IPS copper layer of 3.5 mm thickness) this parameter is only multiplied by a factor two as compared to the naked cavity made of the same niobium. Thermal properties of this copper layer are very good as compared to the copper obtained with other spraying techniques. This result confirms the important role of the oxidation on the layer thermal behavior. Low oxidation is mandatory to achieve high thermal conductive copper coatings.

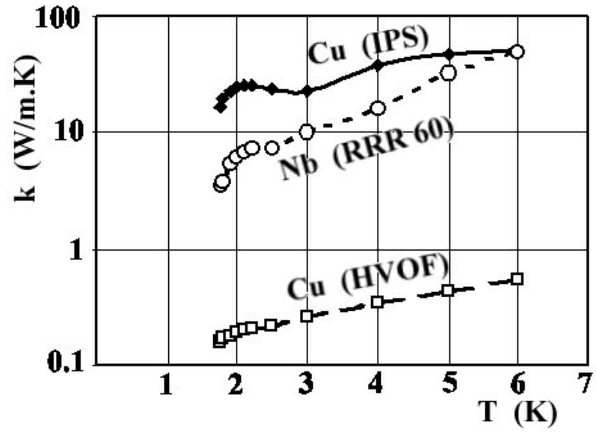

Figure 9: Comparison of the IPS copper layer conductivity with bulk niobium and HVOF copper.

5 PROTOTYPE CAVITY

A 1.3 GHz cavity was copper coated with the IPS technique. The copper layer thickness is 3.5 mm. A picture of the cavity before and after deposition is shown on figure 10.

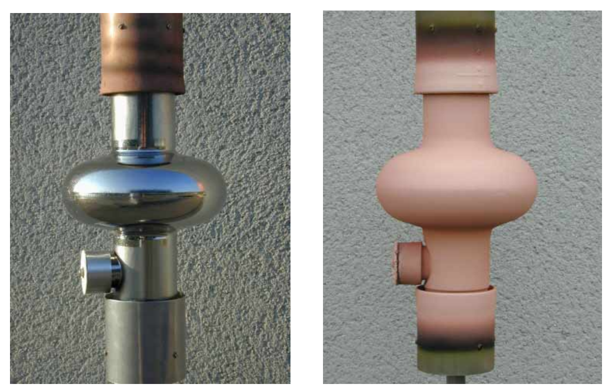

Figure 10: Monocell cavity before and after copper deposition with the IPS technique.

Before coating, the cavity reached 30 MV/m, limited by RF amplifier. A first test after coating was quite bad, the maximum accelerating field was 18 MV/m, limited by a quench. After another light chemistry (BCP 1:1:2), a second test was performed. This time the cavity reached 25 MV/m with important electron activity. Another interesting result is the effect on the frequency shift. The detuning factor K_L is decreased by a factor 3 when stiffened with the copper coating. These experimental results fit well (Figure 11) with the simulation performed using the copper Young modulus measured on the samples.

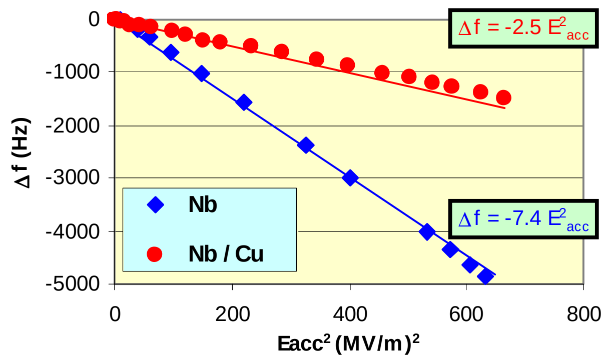

Figure 11: Experimental (points) and calculated (lines) frequency shift as a function of the accelerating field before (blue, square) and after (red, dots) copper coating.

6 CONCLUSION

Mechanical and thermal properties obtained with the IPS spraying process overcome the other deposition methods as showed on the Table 4 were the data are summarized.

Table 4: Summarized mechanical and thermal properties of the copper layers measured on samples and cavities.

Coating Process	Porosity (%)	E (GPa)	Thermal Resistance Increase $K.m^2.W^{-1}$	Measured K_L before/after Cu
APS	20...30	25	$4.0\ 10^{-4}$ (Cu 2mm)	-8.2 / -5.2
Optimized APS	5...7	63	>>$1.8\ 10^{-3}$ (Cu 3mm)	No data
HVOF	2...3	66	>>$1.4\ 10^{-3}$ (Cu 3mm)	-9.2 / -2.2
IPS	7...8	72	$4.7\ 10^{-4}$ (Cu 3.5mm)	-7.5 / -2.9

Cavity stiffening using copper coating sprayed using the IPS technique seems to be an alternative method to reduce the cavity sensitivity to any mechanical disturbance or to Lorentz forces detuning. A first cost estimation for small series (< 10) showed that less than only 10 % of the total cavity cost would be needed to coat a TESLA 9-cell cavity

7 REFERENCES

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