IN-VACUUM TEMPERATURE MEASUREMENT OF NIOBOIUM COMPONENTS USING INFRARED PYROMETRY DURING ELECTRON BEAM WELDING PROCEDURE

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Abstract

Electron beam welding (EBW) is widely used in the construction of Niobium Superconducting RF cavities. The welding sequence of such a complex structure, foresees many welding operations. The welding parameters depend on many variables as the material thickness, but also on the component temperature before each weld.

This paper presents a technique to measure the temperature of Nb components in vacuum during the EBW operation using an IR pyrometer placed outside the vacuum chamber through an appropriate vacuum viewport. With the current configuration the system can measure temperatures up to 350 °C in the vacuum conditions of the EBW vacuum chamber (10^{-5}-10^{-6} mbar).

The technique was used to optimize the time interval between each subsequent equatorial weld during Nb cavities production at Ettore Zanon, increasing the welding procedure reliability and decreasing the waiting time by control of the temperatures in the weld region.

Moreover this technique can be generally used for in vacuum measurements of components from room temperature up to about 350 °C. Future developments are under way to make this technique compatible with UHV and increasing the measurement range.

INTRODUCTION

In view of the mass production of components for the upcoming large superconducting accelerator facilities, a big effort has been spent to transfer to Industry the necessary know out, developed in several years of R&D in Research institutes. In the context of the European XFEL construction, the production of the 800 1.3 GHz Nb SuperConducting (SC) cavities has been shared between two Companies (Ettore Zanon and Research Instruments). DESY and INFN share, within WP04 of XFEL [1], the responsibility for the production of all SC cavities, from raw materials, till the cavity integration into the He tank, passing through all surface treatments.

For the welding of all Nb and Nb-Ti parts, Electron Beam Welding (EBW) is used in several steps of the cavity fabrication process, such as for the assembly of subcomponents and for the cavity equatorial welding.

The required tight production rate of SC cavities to respect the overall time schedule of the accelerator must be in accordance with the high quality of the final products to guarantee the performance of the resonators once in operation.

INFN, together with Ettore Zanon (EZ), started an activity to optimize the EBW operation and to increase the reliability and the final quality of the cavities welds. An outcome of this activity is the assembly of a system for the in-vacuum temperature measurement of Nb components during EBW.

In this paper we present, after a short description of the requirements for EBW of Nb components, the hardware and the experimental set-up realized for the in vacuum temperature measurement. Results obtained on a Nb dummy cavity and also during the production of series cavity components at EZ are also presented.

SET-UP REQUIREMENTS

The choice of hardware and of a suitable experimental set-up has been done based on constrains imposed by the EBW machine layout and the welding process.

Prescription for EBW of Nb and Nb-Ti used in the production of XFEL cavities are described in the specifications for the mechanical fabrication of the SC 1.3 GHz series cavities for the European XFEL [2]. During EBW operation, the vacuum pressure must not exceed $5 \cdot 10^{-5}$ mbar (Nb RRR 300). The venting of the EBW machine can be done below 150 °C with N_2, and below 100 °C with air to avoid any reactions of the hot material with gases that could degrade the cavity performance. Moreover, the cleanliness of the EBW vacuum chamber must be guaranteed to avoid inclusions of foreign materials in the welds.

Together with EZ we designed an apparatus whose goal is the in vacuum temperature measurement of both subcomponents and cavities during the EBW operation. EBW constrains suggest a system able to measure the temperature of components inside the vacuum chamber, without any mechanical contact with the working piece and compatible with its movement during welding. The set-up consists of an IR pyrometer (3MH-CF4 by OPTRIS, λ = 2.3 μm, T = 50 °C ÷ 600 °C) that through a Zinc Selenide UHV viewport, transparent both to visible light and to IR (80% at 2.3 μm), gauges temperature of components during weld operation, measuring the power emitted from the hot body [3, 4]. The IR pyrometer signal U is related to the object temperature by Stefan-Boltzmann law that can be extended in the relation:

$$U = C\left(\varepsilon T_{obj}^4 + (1-\varepsilon)T_{amb}^4 - T_{Pyr}^4\right)$$

where ε is the emissivity of the investigated object and T_{obj} its temperature, T_{amb} the surrounding ambient

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temperature, T_{Pyr} the self-radiation of the pyrometer and C a device specific constant.

Moreover, since most metals have no transmissivity in the IR range, the relation between the reflection ρ of the body under investigation and its emissivity is $\rho = 1 - \varepsilon$.

A low emissivity value ε transfers into the risk of inaccurate measuring results. This is the case of Nb with $\varepsilon = 0.1 \div 0.2$ for T = 20 ÷ 300°C [5]. To overcome this possible risk, we installed special calibrated high emissivity ($\varepsilon = 0.95$) Kapton stickers called "emissivity dots" located on the Nb sample surface (ACLSED by Optris, T_{max} = 380 °C, ϕ = 25 mm) [3].

We tested the set-up at LASA with an apparatus in good vacuum (< 10^{-7} mbar), equipped with the ZnSe UHV viewport, heating a sample of Nb up to 300 °C. The calibration of the system was done measuring the temperature using both a K thermocouple in contact with the sample and the pyrometer. The maximum error in the range between 20 °C ÷ 250 °C was of ± 5 °C.

During tests with "emissive dots" the quality of vacuum was monitored with a RGA spectrometer, revealing no degradation due to degassing of the "emissive dot" glue. To verify the compatibility of "emissive dots" in a particle free environment, as required for the cavity fabrication, at DESY was performed a test in clean room (ISO4 class) showing that these dots are particle free and can be used for Nb components in the EBW machine.

TEST ON COMPONENTS AT EZ

Once calibrated and tested at LASA, the system was moved to EZ and installed in the EBW machine (Fig. 1).

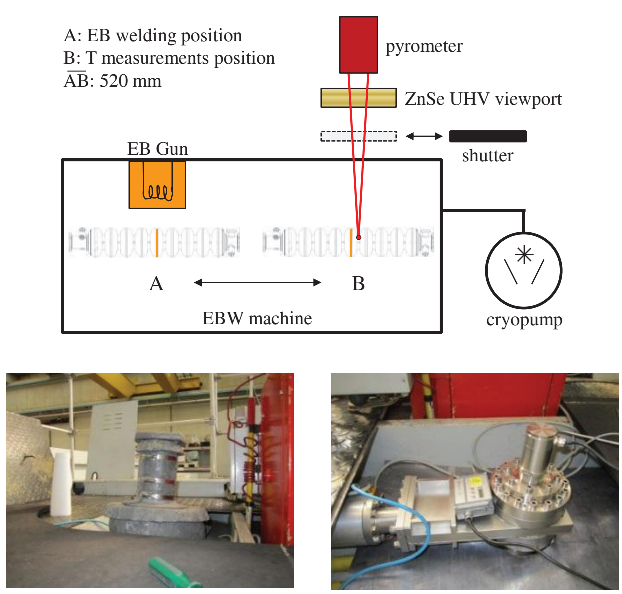

Figure 1: Sketch of the experimental setup and photos of the pyrometer, mounted on a gate valve, with and without X-ray shielding.

The ZnSe UHV viewport was installed in one of the top apertures of the vacuum chamber and a support was built to hold the pyrometer head. To avoid a decrease of the viewport transmission due to Nb evaporation during welding, a gate valve was installed between the viewport and the chamber acting as a shutter. The vacuum condition was monitored using a RGA spectrometer.

During EB welding the component is located in position A, and the shutter is closed. Once the welding process stops, the shutter is opened and the component is moved in position B (distance 520 mm) for temperature measurements. The adjustment of the positioning of the IR sensor on the emissive dots is done moving the component, using the pyrometer laser aimers (see Fig. 1). Before starting the EBW operation, an X-ray shield (Pb) was installed around the pyrometer head and the viewport. Its shielding efficiency was measured performing an EB weld on a Nb sample at the maximum power of the machine obtaining dose values within the natural background.

Two-Cell Cavity (dummy)

The first set of measurements was done on a 1.3 GHz two-cell dummy cavity prepared and assembled for this investigation, applying the same equatorial welds procedure used for the XFEL cavity production. The dummy cavity consists of two Nb cells (ϕ_{eq} = 210 mm, ϕ_{ir} = 78 mm, 2.8 mm thickness) and one stiffening ring welded between the two cells, with a total weight of about 4100 g (see Fig. 2).

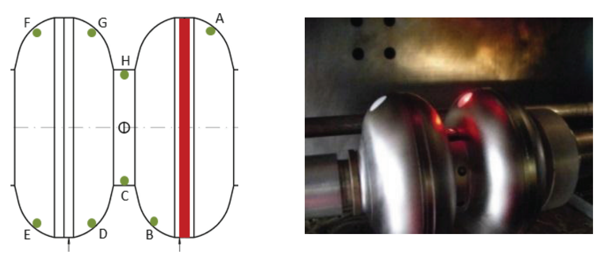

Figure 2: Positions of the "emissive dots" and photo during measurement: red laser beams are used for alignment.

The temperature measurements of the dummy cavity started at the end of each weld step in several areas, at different distances respect to the equator under weld operation (dots position are shown in Fig. 2). This was done not only to study the temperature behaviour of the piece after weld and during cooling, but also to identify the best area of the component to be used as a temperature reference during production.

Fig. 3 shows the temperature measured in several areas of the dummy cavity after the final equatorial weld. The electron beam power during the welding was 2.25 kW, with incident energy of 190 kJ. The time t=0 corresponds to the end of the weld procedure. At the end of the weld, the emissive dot A appeared partially damaged and burnt giving an underestimation of the temperature.

As foreseen, the maximum temperature of about 230 °C was recorded for emissive dots (A,B) closer to the welded equator. These data were acquired 73 s (dot A) and 93 s (dot B) after the end of the weld operation, due to the time spent to move the cavity in the correct

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position for the temperature measurement. While the temperature recorded at dots closer to the welded equator (A,B) and on the stiffening ring (C,H) continuously decreased in time, temperatures for farther dots (D,G,E,F) started to increase as the heat diffused in the cavity, reaching maximum temperatures of about 120 °C (D,G) and 90 °C (E,F) at later times. The measurements done of all dots at about 630 s, show that the entire cavity is thermalized and it starts cooling down following a similar behavior on all dots. Moreover, since till the end of the cooling down the highest recorded temperature corresponds to the stiffening ring (C,H), we decided to monitor only this temperature until the venting of the EBW machine. Once the temperature reached 80 °C, the EBW machine was vented with air, as prescribed by the XFEL specifications.

Based on these results and also considering that emissive dots close to the welding area can be damaged, the stiffening ring has been identified as the more appropriate region to follow the temperature of the entire object.

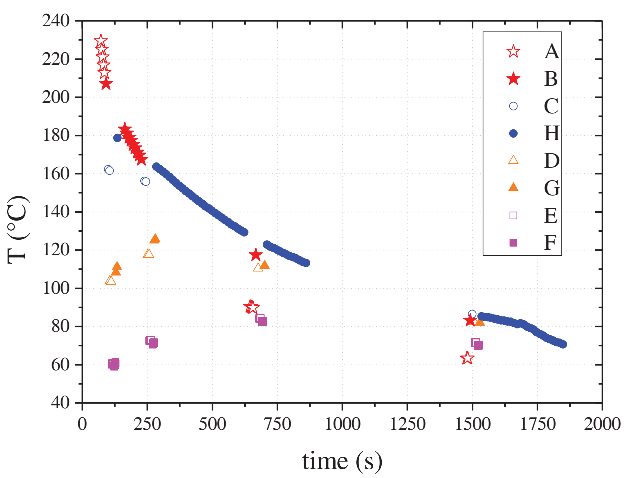

Figure 3: Temperature at different locations of the two-cell cavity. For dot positions see Fig. 2.

End Cell Unit, Dumb Bell and 9-cell Cavities

This method has been applied both on subcomponents and on cavities of the XFEL series production. The usage of this technique has given important information relative to the waiting time before N_2 venting, reducing considerably the production time.

For End Cell Unit (ECU), measurements were done after the welding of End Half Cell with the Connection End Tube, with a power of 3.3 kW, using one emissive dot at about 80 mm from the welding area. In Fig. 4, the measurements done on two ECUs are shown. The green curve is relative to an ECU during the natural cooling down in vacuum. After 500 s from the end of the welding, the measurement started with an initial recorded temperature of 142 °C that decreased to 55 °C in about 3000 s, reaching room temperature in 25000 s (about 7 h). The red curve is relative to a second test with an ECU where we used the temperature measurement to start the N_2 cooling. In this case the measurement started after about 70 s since the end of the weld process. Due to the reduced delay between the end of the weld and the start of the temperature measurement, it was possible to observe also the expected increasing of the temperature (up to 160 °C) due to the heat diffusion, followed by the cooling in vacuum to 150 °C in about 300 s. Afterwards, N_2 venting started with a rapid decrease of temperature from 150 °C to 55 °C in 1000 s when the chamber was finally vented with air. From the plot it is clear the advantage of this technique for starting the N_2 inlet and, consequently, reducing the cooling time by a factor 3.

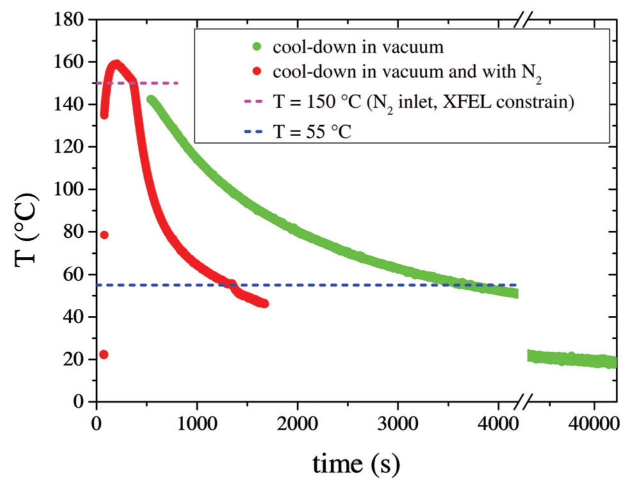

Figure 4: ECU cooling without and with N_2. Magenta line represents the XFEL prescription for starting venting the EBW machine with N_2.

The same procedure has been applied on the production of other subcomponents like the iris weld of Dumb Bells and on the equatorial welds of the 9-cell cavity, with a reduction of the needed cooling time to about 50 % (Dumb Bells: 30 min instead of 1 h; cavity: 2 h instead of 4 h). For the 9-cell cavity, only one "emissive dot" was used, placed on one of the stiffening ring.

CONCLUSION

An in-vacuum temperature measurement technique has been implemented and applied to control and optimize the EBW procedure of Nb components for the production of XFEL cavities. Measurements done on a dummy two-cell cavity, on subcomponents and on the XFEL cavities show the usefulness of this technique in decreasing the waiting time after welding procedure of about 50 %. This technique is a powerful tool for improving the reliability of the welding procedure and reducing the time interval between each subsequent equatorial welds.

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