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SEAMLESS 1.5 GHz CAVITIES OBTAINED BY SPINNING A CIRCULAR BLANK OF COPPER OR NIOBIUM

V. Palmieri, R. Preciso, V.L. Ruzinov* , S.Yu. Stark*,

INFN Laboratori Nazionali di Legnaro
Legnaro (Padua), Italy

ABSTRACT

A new technique to produce seamless resonators is presented. By means of a collapsible mandrel, Copper and Niobium monocell cavities complete with cut-off tubes have been spun starting from planar blanks. Costly and time-consuming Electron Beam welds can be avoided at least at the resonator equator level. The technique is relatively simple, costs little, does not require large equipment investments, and has been proven to be applicable in the forming of multicell cavities.

INTRODUCTION

With the application of high beta superconducting radiofrequency cavities in large accelerators such as those built at CERN, DESY, KEK and CEBAF, important investments in both human and financial resources have been made over the last fifteen years in the field of RF superconductivity.

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* On leave from Moscow Institute of Steel and Alloys, Moscow, USSR

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The progressive achievement of higher and higher accelerating fields at low rf losses and the need to transfer know-how from scientific laboratories to firms for industrial cavity production have contributed to the establishment of more or less universal fabrication technology standards. Over years of research, various criteria proven to improve resonator rf performances has been codified as guide-lines or canons in the fabrication process.

Nevertheless, the simple transfer of the technology developed so far is no longer sufficient for the new generation collider cavities. Further increase of the energy gradient values routinely achievable is a necessity. A drastic reduction in production costs (K$ per MV/m) is an even more important *conditio sine qua non* for the feasibility of building more and more powerful accelerators.

In this context, a significant savings in manufacture costs could be achieved if seamless cavities were produced by means of a simple and cheap fabrication technique. Let us consider the TESLA nine-cell cavities. Regardless of whether they are made of bulk Niobium or Niobium-coated Copper, if fabricated in the traditional way by spinning (or deep drawing) two half-cells and then Electron Beam (EB) welding them together, each resonator requires nineteen EB welds in critical regions. Occasionally, two other welds are required to connect the resonator body to the U.H.V. flanges. Therefore, the Electron Beam machine must be opened twenty-one times and each time the parts to be welded must be positioned within strict tolerance values. High vacuum must be created twenty-one times, and this takes time. At best, welding times can be limited to ten pumping runs, when it is possible to align all the nine cells welded at the equator, and then execute the welds at the iris in only one run.

Moreover, the welded region is often suspect whenever the final rf performances of the resonators do not correspond to the desired values. In the case of bulk Niobium, the RRR values at the weld strongly depend on the vacuum reached inside the electron beam machine. Niobium purity is jeopardized just in the most critical regions - the iris and the equator - where the electric and the magnetic fields reach their maximum. The EB welding of OFHC Copper is, however, not entirely free from problems, due to the presence of

Copper protrusions projected by the beam or by void bubbles in the weld that are invisible after welding and can open during chemical polishing.

Because the execution of the weld from the resonator exterior can cause cracks or other surface irregularities, it is generally preferable to execute all the Electron Beam welds by an internal gun. This poses a severe limitation on the construction of high frequency cavities due to the difficulty of inserting the welding gun in a narrow bore.

Last but not least, the amount of scrap material in the preparation of eighteen half-cells and cut-off tubes is not small, and especially in the case of bulk Niobium resonators, contributes to increased manufacture costs.

The a.m. considerations impelled us to develop seamless cavities; the first step consisted in experiments with monocell fabrication.

THE SPINNING OF SEAMLESS MONOCELLS FROM CIRCULAR BLANKS

Several different techniques (as opposed to the classical Niobium or Copper hydroforming and Copper electroforming approaches) have been considered for the production of seamless cavities. Among the following techniques taken into consideration: a) the explosive formation of resonators starting from seamless tubes; b) the preparation of a complex shape resonator by excavating a bulk cylinder, through either numerical control machining or electro-erosion and recovering the swarf in the case of Niobium; c) resonator forging by material deformation under plastic flow (by either intervening on internal stress tensile plasticity or on externally-applied stress tensile plasticity); d) the forming of the entire cavity by spinning planar blanks or by directly spinning seamless tubes.

The last two techniques are currently under investigation at our laboratory. Spinning has given us satisfactory results, and proven easy and economical to perform. With minimum effort, we have modified the well-known spinning technique currently used for the production of half-cells. Seamless 1.5 GHz monocells have been spun from Copper, Aluminum and Niobium planar blanks. The technique has been described in detail in a previous paper [1] and primarily consists in pressing a metal disk against a mandrel rotated by the headstock of a lathe (fig. 1).

This technique is ordinarily applied in the production of aircraft and aerospace components such as rockets and missile heads, parts of musical instruments, or bells, etc. Virtually any metal ductile enough to be cold-formed can be spun without applying heat to the work metal. Sometimes preheating or intermediate annealing increases ductility and reduces the strength of hard-to-form refractory metals and permits greater thicknesses to be spun. The manual spinning of approx. two meter-diameter, 3 mm thick low-carbon steel is not uncommon. The maximum practical diameter is more often limited by the availability of equipment. Due to the demand for large components in the aerospace engineering sector, literature refers to the successful power spinning of blanks even as large as six meters in diameter and blanks 14 cm thick [3]. Nothing seems to prevent the spinning of double-curved revolution surfaces for monocell cavities, or even multi-curved revolution surfaces for multicell cavity fabrication.

First, cavity prototypes were manually spun using a small lathe as sketched in fig. 1. Then we used a semiautomatic lathe, with hydraulically-driven spinning tool. In this case, the spinning tool used is not of the friction type, but a steel roller. In our experience, good results from the mechanical point of view can be obtained with both manual and semiautomatic spinning. Of course, the greater the automation of the lathe is, the more uniform the thickness profile along the resonator axis will be. However, when measuring the resonant frequency of the cavities, we observed that the degree of automation did not affect reproducibility. The spinning procedure and the sequence of the different operations seem to have greater influence.

Fig. 1 schematically displays the tooling and the workpiece set-up for the manual spinning of a monocell cavity.

The mandrel is mounted on the headstock of a lathe. A Copper or a Niobium circular blank is clamped to the mandrel by the follower block. The tool rest and pedestal permit the fulcrum to be moved to various positions by swinging the tool rest and moving the support pin from one hole to another as needed. Spinning is done by pulling and pushing the tool against the workpiece, pivoting around the support pin.

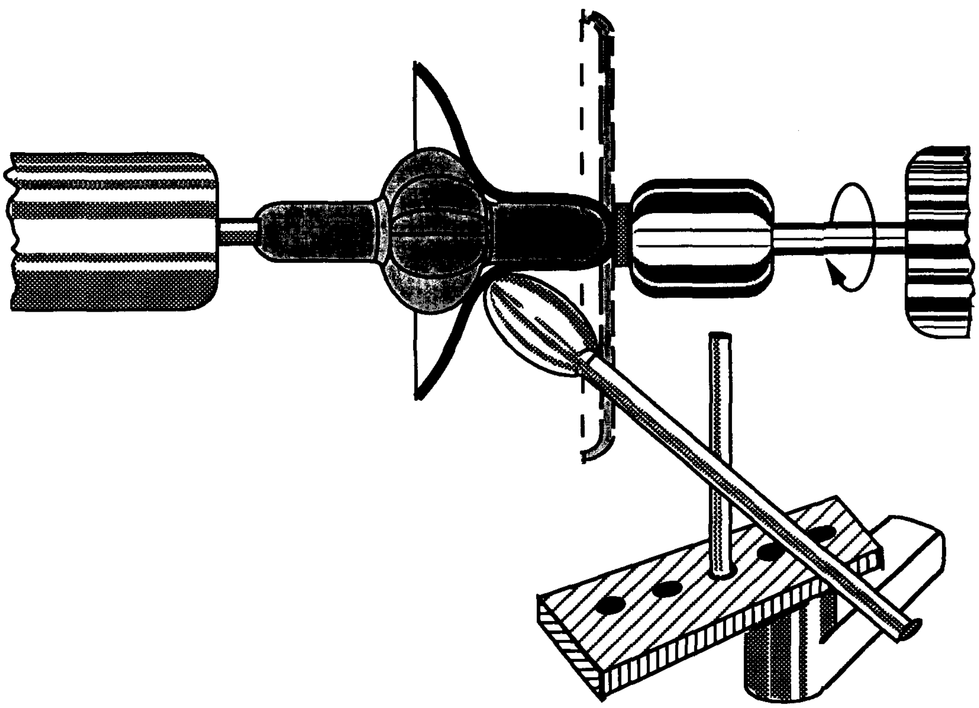

Fig. 1 Set-up for monocell cavity spinning using a simple hand tool applied as a pry bar.

The spinning of a monocell is performed in two set-ups and requires the use of two mandrels: a truncated cone pre-form mandrel and the final mandrel in the shape of the finished resonator. The latter is a collapsible mandrel, consisting in an assembly of sectors held in place by two key-sectors. When the keys are removed, the mandrel collapses and the remaining sectors can be removed from the spun resonator one by one [1].

Another variant has been also tested. We moulded the mandrel by pouring a low-melting alloy (around 130°C) into a die. After spinning, the workpiece was heated, and the mandrel melted. Our experience leads us to consider this low-melting mandrel technique to be costly and time-consuming for production quantities and offers no significant advantage even in multicell fabrication.

Aluminum, Copper and Niobium 1.5 GHz monocell cavities complete with cut-off tubes have been successfully spun from around 400 mm diameter circular blanks. An intermediate annealing after pre-forming is required for OFHC Copper. It is more difficult to spin Copper than pure Niobium (250 RRR), which is very ductile and does not harden. On the other hand, we observed Niobium elongation to be somewhat less than that of Copper. Significant differences in ductility were found between Niobium of the same RRR from different suppliers.

Maintenance of dimensional accuracy, internal surface quality and the absence of wrinkles and scratches depend on a plethora of parameters, each correlated with the others. Internal surface "orange peels" at the level of the irises and the second half-cell appeared in the first prototypes , but this problem was successfully dealt with by modifying the process parameters and finding the right sequence of operations.

The crucial parameters that influence the final result are:

A) **Peripheral Spinning Speed**. Speeds of the order of magnitude of 1 sms (surface meter per second) are acceptable. Using a variable-speed drive, the speed must be changed according to the resonator diameter in the zone being swept by the tool.

B) **Spinning Feed**. This determines the fit of the resonator against the mandrel, hence the precision of resonator frequency. It significantly influences the finish of the resonator internal surface. Depending on the force applied onto the workpiece, safe feed rates correspond to fractions of a millimetre per revolution. This is one of the main parameters and is determined by the geometry of the piece and the roller shape. Spinning feed must be carefully controlled at the level of the resonator iris, and in general whenever a workpiece must be spun with small curvature radii.

C) **Intermediate annealing temperature**. Only one intermediate annealing in U.H.V. is necessary in the spinning of Copper monocells. We tried annealings at different temperatures from 400°C to 700°C and observed that while keeping other factors constant in the forming process, higher temperatures caused higher degrees of ductility due to material stress relaxation, but also gave rise to progressively greater "orange peel" phenomenon.

The intermediate annealing necessary for Copper, was suppressed when spinning 250 RRR Niobium after the first few tests. Pure Niobium can be cold-worked to a considerable degree before it work-hardens appreciably. Tensile and plastic elongation properties depend greatly on material purity and on temperature. However, Niobium ductility at the RRR values required for cavity fabrication and from -50°C up to 600°C, is practically not affected by temperature [4-6] as shown in fig. 2.

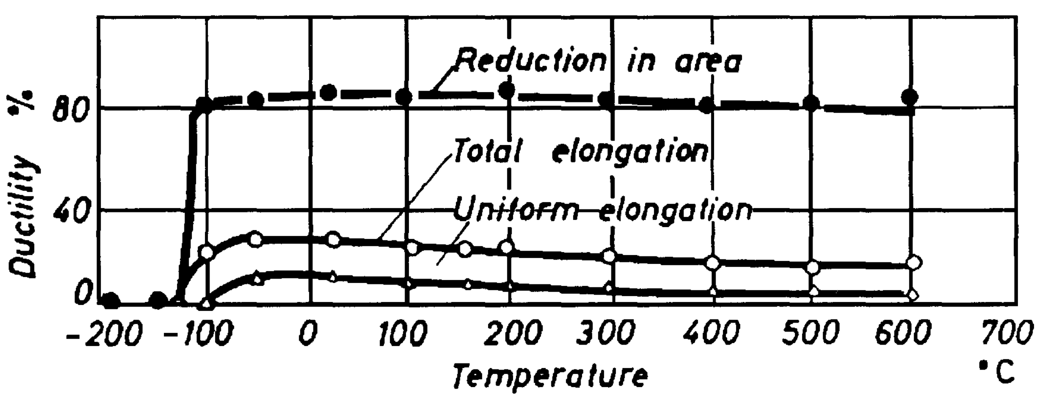

Fig. 2. The effect of Temperature on Niobium tensile properties (After Wessel and Lawthers [3]).

D) **Workpiece lubrication**. The quality of the final result depends on the tenacity and viscosity of the lubricant used and its ability to adhere to the rotating blank. The lubricant is applied to the blank with a swab or a brush before loading it into the lathe. Additional lubricant is added during spinning as judged necessary to avoid the tool from scraping the surface or jamming, and to limit the amount of heat generated. Motor oil, animal fat, soaps, tallows and waxes are traditionally used as lubricants [7]. Literature extols the lubricant properties of a colloidal suspension of Zinc in Lithium soap, Molybdenum disulfide paste diluted in different fluids, and light oils mixed with paraffin oil (kerosene).

Parameters A), B) and C) must be assigned every time as a function of the metal, the blank thickness, diameter, and microstructure. Spinnability [1], as most cold-working operations depends on metal grain size.

On the other hand, spinning has a marked effect on the mechanical properties of the work metal. Grain size is redefined and made oriented depending on the pressure applied [2]. Moreover tensile and yield strengths increase while ductility decreases. It is not really clear if such strength increase is an undesirable phenomenon. In fact, increased mechanical rigidity would permit the fabrication of resonators of thinner thicknesses. This would offer the twofold advantage of faster heat removal by the helium bath and important cost savings when using bulk Niobium. On the other hand if stress and dislocation deteriorate thermal conducibility too much, the hardening of the workpiece can be modified as much as desirable by annealing the resonator after spinning.

With regard to hardening, fig. 3 displays the hardness distribution in the deformation zone in a Copper slab cross-section [3]. The example provided is very similar to the spinning of a Copper resonator at the first iris when the first cut-off tube has been spun and the first half-shell is still taking form.

It is interesting to note that the area in contact with the tool has higher hardness than on the mandrel side. There are no evident reasons why this should not hold true for Niobium as well. On the contrary this would be even more favourable, since Niobium single-crystals experience no strain-hardening at room temperature.

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1 We define spinnability as the maximum percentage reduction a metal can withstand before failure.

2 The deformation texture of Niobium is essentially a single {110} fibre, being {110} the plane of slip.

Literature documenting etching patterns on Niobium surfaces and studies by X-ray or stereographic projection analysis of slip traces show that for a given plastic elongation of Niobium, main crystals are observed to deform to an extent comparable with the total elongation measured. As expected, the cleavage occurs in the neighbourhood of a grain boundary [8].

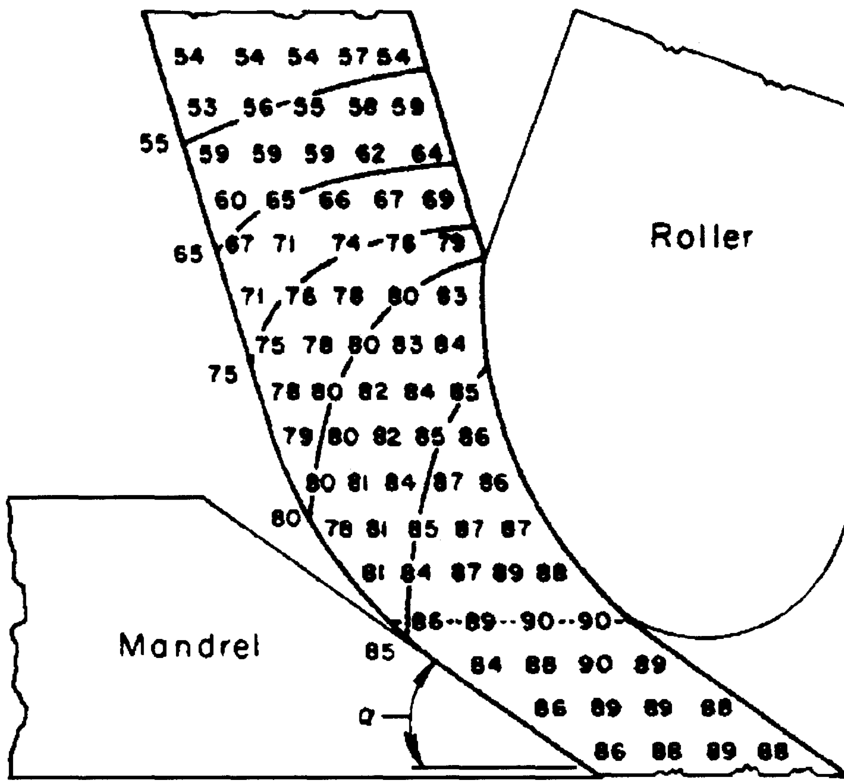

Fig. 3. Hardness distribution in a Copper workpiece reduced 43% by spinning (After ref.3).

CONCLUSIONS

Aluminum, Copper and Niobium 1.5 GHz monocell cavities complete with cut-off tubes have been successfully spun from approx. 400 mm diameter circular blanks by means of a collapsible mandrel. The surface finishing of these spun resonators, both on the internal and external sides, is good enough to be chemically or electrochemically processed, so that no further machining is required after spinning.

An overreduction of the final resonator thickness was found at the level of the second iris, where an anomalous thinning of the resonator wall was observed. However, such overreduced thickness is only half of the maximum thickness. This 1:2 ratio is much better than what can be obtained by hydroforming. We are confident that greater control and reduction of thickness disuniformity can be achieved. A deep investigation into the compressive and tensile stress, strength, ductility, strain hardening and strain-rate sensitivity in Copper and Niobium is certainly the key to the improvement of our present results.

A initial prototype of an Aluminum four-cell 1.5 GHz resonator has already been produced. Starting from a 2.5 mm blank, we had a 2.1 mm thickness on the first cut-off and 0.9 mm on the second even after curving the blank eight times on the mandrel. The second prototype had even more uniform thickness.

In our tests on monocells, we found that pure Niobium was easier to spin than OFHC Copper. A Niobium monocell can be formed in less than two hours, and the amount of scrap Niobium cut in the manufacture operation is less than 10%. This percentage can be lowered. Moreover, the rejected Niobium was recycled by Electron Beam remelting.

Spinning a multicell cavity by starting from a cylinder instead of a blank is currently under investigation in parallel. Our positive results with blanks, however, have encouraged us to believe that multicells could be spun satisfactorily without necessarily starting from a cylinder. Although extended experimentation is required to obtain reliable seamless spun multicell cavities, it is now already possible to conceive of multicells composed by seamless monocells EB-welded only at the iris. The elimination of the equatorial welds would lower manufacture costs considerably.

Of course, in order to be competitive, seamless monocells must meet the challenge of the final rf test, and achieve accelerating field values at low power losses comparable to those currently obtainable. If this occurs we must bear in mind that spinning offers the following advantages compared to traditionally welded and hydroformed cavities:

a) Lower tooling costs, and relatively smaller capital and equipment investment;

b) Shorter set-up time;

c) Design changes in resonator shape can be made at minimum expense;

d) Changes in work-metal or thickness require a minimum of tool changes.

On the other hand, there is the drawback that skilled operators are required, because the quality of the result often depends on operator experience. This aspect could be in any case overcome after the manual spinning of a few dummy prototypes. Automatic equipment capable of reading all the manoeuvres executed by the operator could be devised to repeat the entire process faithfully step by step.

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