Proceedings of the 1999 Particle Accelerator Conference, New York, 1999

SEAMLESS SUPERCONDUCTING RF CAVITIES

Vincenzo Palmieri

ISTITUTO NAZIONALE DI FISICA NUCLEARE
Laboratori Nazionali di Legnaro
Legnaro (PD), ITALY

Abstract

Electron beam welding is a well-established technique for superconducting cavity fabrication. Nevertheless it is not free from problems and its main drawback is cost. The paper reviews the most common techniques explored by who is running after the research of seamless cavity fabrication. In the end, it follows a brief overview of some unconventional forming techniques by the hidden potentialities.

1. INTRODUCTION

More than any other project, TESLA with the related proposal of 20.000 superconducting cavities has pointed out all the problems under a possible mass production.

Welds and all the related work of trimming, tolerance respect, alignment accuracy, etc. appear to consume great fractions of the production costs and to create more of the expected production difficulties. The main percentage of cavity failures indeed occur at the welds at the cavity equator, since this is the highest stress point and therefore the weakest point of the assembly.

However the standard technique used for fabricating nine-cell resonators works fine, but it suffers of the drawback to be absurdly expensive for that amount of pieces. At the end, as in many other fields, the machine feasibility is only determined by a mere cost problem!

The problem does not lie in the weld itself, since 20.000 pieces (at least 180.000 welds only for the resonator bodies) is a relatively small number for the production world. The real cost levitation is given by all the phases of piece preparation that are preliminary to the weld.

In such a framework the development of low fabrication cost alternative technologies becomes a need [1].

2. WHICH PROBLEMS UNDER ELECTRON BEAM WELDING

Electron Beam Welding (EBW) is the preferred technique for refractory metals. It consists into a high energy density fusion process that is accomplished by bombarding the joint to be welded with an intense strongly focused beam of electrons. The instantaneous conversion of electrons kinetic energy into thermal energy, as they impact and penetrate into the surface where they impinge, cause the weld-seam interface surfaces to melt and produce the weld-joint coalescence desired.

During EB welding, the thermal cycles produced by the rotation of the piece respect to the beam, cause physical state changes, metallurgical phase transformation, and transient thermal stress and metal movement. After welding is completed, the finished product may contain physical discontinuities, such as protrusions, material microprojections, craters, cracks or voids in the welds. These are mainly due to excessively rapid solidification, or altered microstructures due to the non uniform cooling or principally to residual stress and distortion due to plastic strains.

The perfect weld should be indistinguishable from the surrounding Niobium material. Instead, what one finds is the formation of three metallurgical zones upon completion of the thermal cycle: the Weld-Metal Zone (WMZ), the Heated-Affected Zone (HAZ), and the Base-Metal Zone (BMZ). The peak temperature and the subsequent cooling rates determine the HAZ structures, whereas the thermal gradients, the solidification rates, and the cooling rates at the liquid-solid pool boundary determine the WMZ structure. The size and flow direction of the melting pool determines the amount of dilution and weld penetration.

Two thermal states, quasi-stationary and transient, are associated with the welding process. During the welding, one assists to the formation of a transient thermal state in the weldment. At some point after weld initiation but before weld termination, the temperature distribution is stationary, or in thermal equilibrium. Hot cracking usually begins in the transient zone, because of non-equilibrium solidification of the base material. A crack that forms in the source-initiation stage may propagate along the weld if the solidification strains sufficiently multiply in the wake of the melting beam. Cracks generally appear in the weld craters and may propagate along the weld. The majority of the thermal expansion and shrinkage in the base Niobium occurs during the quasi-stationary thermal cycles. Residual stresses and weld distortion are the thermal stress and strain that remain in the weldment after completion of the thermal cycle. Moreover excessive grain growth in the weld HAZ and fusion zones can produce cracking during the weld.

Almost 20 years of EB practice have taught to limit defects formation probability by full penetrating welds and by means of a beam raster. The beam oscillation capability indeed allows wider welds, slower cooling rates and more uniform weld shapes without necessarily using beam defocusing. Also beam oscillations capability reduces the need for accurate beam-to-seam alignment and makes precise joint tracking less crucial.

The parts to weld must be scrupulously assembled and point welding is performed in order to clamp the structure before the effective weld. The cost of joint preparation is higher than that encountered with other techniques, because the relatively small electron beam spot size requires a maniacal precision for the preparation of the joint gap and the accuracy of the alignment. In addition starting and stopping the weld are not operations that can be undervalued, since low uniformity and possible metal melt-through can occur at the end of the joints.

Before welding, the parts must be properly cleaned, since inadequate surface cleaning of the weld metal can cause weld flaws, a deterioration of superconducting properties of the weld, reducing also pumpdown times and gun operational stability. The Residual Resisitivity Ratio (RRR) of the weld critically depends on the grade of vacuum achieved in the chamber during the process, since this directly affects the interstitial impurity content in the weld.

3. BEFORE TO DECIDE FOR SEAMLESS CAVITIES, ARE WE SURE THAT EBW IS THE ONLY SUITABLE WELDING TECHNIQUE?

One of the advantages of EBW is the ability, with a lower total heat input, to make welds deeper and narrower than by other techniques.

The superiority of the EBW over other techniques lies in the fact that the kinetic energy of the electrons can be concentrated onto a small area on the workpiece. Power densities higher than those possible by any known continuous beam, including laser beams can be obtained. The high power density plus the extremely small intrinsic penetration of electrons in Niobium results in almost instantaneous local melting and vaporization of Niobium. That characteristic distinguishes EBW from other welding techniques in which the rate of melting is limited by thermal conduction.

On the other hand, EBW is expensive, both for manufacture time and for equipment. The capital cost of an EBW system can be close to $1 million. Note that the capital cost includes only the energy source, control system, fixturing, and material handling equipment. It does not include operating maintenance or inspection costs, which can vary widely depending on the amount of pieces to weld.

In the author’s opinion a not detailed investigation has been done up to now about alternative techniques for welding Niobium. Laser Beam Welding for instance has unexplored resources and it could deserve interesting surprises whenever investigated for the application to Niobium.

In addition a less-known technique, but not for this less powerful, is the Ultrasonic Welding (USW). It consists in a quasi-solid state process that produces a weld by high frequency vibration shear forces at the interface between the two held under moderately high clamping forces. The resulting internal stresses result in elastoplastic deformations at the interface.

In particular the advantages of ultrasonic welding are that: i) permits to join materials independently of the respective thickness; ii) provides joints with good thermal and electrical conductivity; iii) it does not require terribly expensive tooling and particularly trained personnel.

4. SEAMLESS CAVITIES

You wont have to worry about anyone of the above mentioned problems about the obtained weld structure, when switching to seamless cavities.

Moreover, the fabrication time needed for fabricating a nine-cell resonator by the current EBW technology is of few weeks. The fabrication time of a seamless tube from a Niobium planar blank is around a few tens of minutes, while by seamless forming (either by hydroforming or by spinning) the same time becomes curtailed to only some hours.

The main research activity in this field is carried by several groups respectively in France (hydroforming and hot forming), Germany (hydroforming), Italy (spinning) and Japan (hydroforming and explosive forming).

As it will appear in the following, except the spinning that can start from a planar blank, all the below reported forming techniques require Niobium seamless tubes. Three techniques exist for producing such tubes: deepdrawing, flowturning and backward extrusion. Each one of these techniques work satisfactorily and can provide mechanically perfect tubes. The problem however lies in reducing contamination and trapped lubricant among grains during the application of plastic deformations.

4.1 Hydroforming

Tube hydroforming is a pressurized hydraulic forming process used to produce complex shapes as the cavity one in tubular components. Pressure can be applied by compressing a fluid, by pressing rubber, usually polyurethane, while the shape is determined by an external die. The drawback of hydroforming lays in the difficulty to achieve an expansion over 200% without intermediate annealings. In order to keep annealings to the minimum, the tube diameter has an intermediate size between the iris diameter and the equatorial one. The tube is initially swaged at the iris, then expanded under an additional axial compressive force. The effect of the tube shrinking during bulging results in a more uniform wall thickness of the cavity.

Hydroforming has been certainly the most investigated among the seamless cavities forming technologies. Copper cavities for Niobium sputtering were hydroformed at CERN by Hauviller, with only two intermediate annealings. Recently Kaiser at DESY has succeeded in hydroforming a Niobium tube jacketed in Steel liners. Antoine at Saclay has also hydroformed a monocell cavity starting from a seamless Niobium tube of low RRR. Both grups have reached Q values over 1e+10 and accelerating fields around 20 MV/m. The results are very encouraging and they will certainly improve a lot after that enough good quality seamless tubes will be available. Hydroforming is also investigated by Saito at KEK, with the idea of applying it to Niobium clad Copper tubes.

4.2 Explosive Forming

Explosive forming is a high-velocity process in which the punch or diaphragm is related by an explosive charge. The tube is water filled and the explosives utilized are generally highly explosive chemicals, gaseous mixtures, or propellants. One of the most common explosive is Pentaerythritol tetranitrate (PETN) or Trinitrotoluene (TNT) and are placed into the tube center. Water is generally used as the energy transfer medium to insure a uniform transmission of energy and to muffle the sound of the explosive blast. After detonation a pressure pulse of high intensity is produced. A gas bubble is also produced which expands spherically and then collapses until it vents at the surface of the water. When the pressure pulse impinges against the workpiece, the metal is displayed onto the die with a velocity up to 100mt /sec). In order to ensure the proper die filling, it is important that air is evacuated from the die. This brings a little complication to the equipment, because this makes not easy the axial shortening of the tube during expansion, as it happens in hydroforming.

The main results on explosive forming have been obtained at KEK by Saito that succeeded in explosively forming a Copper three cells in only two steps, so only one intermediate annealing. In particular for explosive forming, the availability of good tubes is compulsory for the achievement of good results.

4.3 Hot forming

The formability at high temperature below the recristallization point, gives the possibility to increase formability of the material and to deform without riskof failures regardless of the pressure and load applied. Hot forming of Niobium 3 GHz two cell cavities has been proposed by Grandsire from LAL Orsay. The process is done in two steps, with 40 % of deformation in the first step, an annealing (900 °C, 2 hours), and another 90 % in a second step. The results are very promising, since once the proceedure is set up, large numbers of resonators can be produced in short time with high reliability. Obviously, the higher the forming temperature is, the higher formability is. This is an advandage but has the related drawback to need refractory material dies and Ultra High Vacuum.

4.4 Spinning

Spinning has been proposed by the Author, since it is a chipless production method of forming axially symmetrical hollow parts of almost any shape. It is a point deformation process by which a metal disc, or a cylindrical preformed hollow component is plastically deformed by axial or radial motions of a tool or rollers acting onto a workpiece clamped against a rotating chuck. It is a characteristic of this process that the movement of tools onto a rotating piece, acts upon a very localized area where plastic flow takes place. The chuck is made collapsible in order to be extracted from the interior, once the cavity is ready.

The parameters that more than other influence the forming process are the roller feed speed, the angular speed of the rotation chuck and the roller shape. Besides these fundamental importance is hold by the role of intermediate mandrels, that permit to spin a full nine-cell resonator from a planar blank without any intermediate annealing and with the actual rate of one-cell per hour.

Q values over 1e+10 and gradients up to 25 MV/m have been found by Pekeler at DESY, on the Niobium monocells spun at LNL. Niobium clad Copper has also no particular problems for spinning, since a monocell spun by the author at LNL and processed by Saito at KEK reached the 25 MV/m goal. Interesting results has also give the collaboration, with P. Kneisel of Jefferson Lab. Over seven cavities have been fabricated and characterized. The highest value of the field reached was 33 MV/m over 5e+09. Fivecells have been already produced and ninecell cavities, will not delay to come.

5. UNCONVENTIONAL METAL FORMING TECHNIQUES:

Besides the above mentioned techniques for seamless cavity forming, there are several unconventional ones, that even if at the moment are unexplored by our scientific community, are not less powerful than the previous.

5.1 Electromagnetic forming

Electomagnetic Forming (EMF) can be applied to a cavity by simultaneous radial compression and expansion of a seamless tube. EMF works by the magnetic induction effect. When a coil or a solenoid is place near a metallic conductor and pulsed via an energy store like a capacitor bank, a magnetic field is generated between the coil and the workpiece. If done quickly enough, the magnetic field is excluded from penetrating into the workpiece for a short time period. During this time, a pressure is generated on the workpiece that is proportional to the magnetic flux density squared. This "magnetic" pressure is what provides the forming energy. The energy is usually supplied to the workpiece in the form of kinetic energy. The magnetic pressure pulse accelerates the workpiece up to a certain velocity (such as 200-300 m/s). This kinetic energy drives the material into the die, causing forming on impact. The problem of coil extraction after cavity forming is a false problem, since the internal coil could be disassembled in sectors.

EMF produces a phenomenon called Hyperplasticity. Hyperplasticity results from inertial stabilization of material failure modes and permits dramatic increases in strain to failure. Hyperplastic formability, via EMF, of structural aluminum alloys for instance can cause these alloys to have higher formability than drawing quality steels. One drawback of EMF instead lies in the different electrical conductivity of materials. Results obtained with Copper are not directly connected with what obtainable with Niobium.

5.2 Peen Forming:

Peen forming is a dieless forming process performed at room temperature. During the process, the surface of the workpiece is impacted by pressure from small, round steel shot. Every piece of shot impacting the surface acts as a tiny hammer, producing elastic stretching of the upper surface. The impact pressure of the peening shot causes local plastic deformation that manifests itself as a residual compressive stress. The surface force of the residual compressive stress combined with the stretching causes the material to develop a convex curvature on the peened side. Moreover it is well known that cracks do not propagate under compressive stresses. Peening forming is widely used in aeronautic industry for example for shaping aircraft wings. A possible application to cavities could be foreseen on a seamless tube of diameter equal to that of the cavity equator, rotating between headstock and tailstock of a lathe.

5.3 Laser Activated Stress Forming:

This technique is rather new and currently under research. Bellow-shaped components are easily formed.. The tube to be formed is stressed within 90% of its material yield point by a laser that induces temperature gradients activation. The piece rotates meanwhile laser irradiated and it is shortened under the application of an axial load.

5.4 Ultrasound Activated forming:

The ultrasonic-activated forming is a metalforming process that applies high-frequency vibrations to the workpiece through the tooling. The vibrations are usually greater than 15.000 cycles per second (cps) and are generally no more than a tenth of a millimeter in amplitude. Metalforming with the aids of ultrasonic energy dates back to the mid-1950s. Tests showed that when a wire was stressed in tension with ultrasonic activation, the yield strength of the material seemed to increase. It was also determined that this effect increased linearly with the increase in vibratory power and was independent of the frequency. This phenomenon was attributed to ultrasonically favored formation and movement of dislocations within the crystal lattice structure that assisted intercrystalline slip. The application of ultrasonic energy in the form of high-frequency vibrations during cold-forming operations reduces the forming force required, increases the deformation rate, decreases the total number of processing steps, and improves the quality of the finished product. Ultrasonic activation can be applied to both slow-speed and high-speed forming processes. In tube drawing operations, for instance, either the draw die or the plug can be ultrasonically activated. Activating the die is generally preferred since the effect of the vibration is greatest, the number of passes can be greatly reduced.

6. CONCLUSIONS

Aim of this work was only to offer a panorama of the forming technologies that can be applied to the problem of seamless cavity fabrication. Some techniques seem more easy and low cost than others, however, there is a not simple answer to the question: ”Which one will be chosen for TESLA cavities?”. The times are not ripe for a right evaluation of the problem. Too much experimental work has still to be done before than one technique will prevail on the others.

7. ACKNOWLEDGMENTS

The author is indebted toward L. Grandsire, L. Liljie, M. Pekeler, D. Proch, D. Reschke, K. Saito, P. Kneisel, F. Stivanello, W. Venturini.

REFERENCES

V. Palmieri, Particle Accelerators, vol. 61, 1998, [pp. 479-519]/215-255.