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ELECTRON BEAM WELD PARAMETER SET DEVELOPMENT AND COST CAVITY*

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Introduction

Various methods have recently been considered for use in the cost-effective manufacturing of large numbers of niobium cavities. A method commonly assumed to be too expensive is the joining of half cells by electron beam welding (EBW), as has been done with multipurpose EBW equipment for producing small numbers of cavities at accelerator laboratories. We have begun to investigate the advantages that would be available if a single-purpose, task-specific EBW processing tool were used to produce cavities in a high-volume commercial-industrial context. For such a tool and context we have sought to define an EBW parameter set that is cost-effective not only in terms of per-cavity production cost, but also in terms of the minimization of quench-producing weld defects. That is, we define cavity cost-effectiveness to include both production and performance costs. For such an EBW parameter set we have developed a set of ideal characteristics, produced and tested samples and a complete cavity, studied the weld-defect question, and obtained industrial estimates of cavity high-volume production costs. The investigation is ongoing. This paper reports preliminary findings.

Electron Beam Weld (EBW) Parameter Set

The cost of joining half cells by EBW is multiplied prohibitively if there is a requirement for machining the joint edges to enhance alignment. Therefore we sought to define a parameter set in which machined joint edges are not needed. The niobium is formed and then simply sheared, with alignment accomplished through recycled fixturing.

Integrally related to that production-cost issue, however, is an important cavity-performance issue: the effect of weld defects left on cavity inner surfaces. Understanding of the effect of manufacturing and processing methods on cavity performance is incomplete, but it has been demonstrated that heat treating cavities will, on average, increase the limiting fields at which they quench. [1] Cavities that have not been heat-treated have achieved gradients near the theoretical limit. A reasonable model for this would be weld defects randomly scattered, occasionally resulting in an isolated cavity producing very good results.

Therefore we defined the EBW parameter set as applying to sheared, unmachined joint edges in 3 mm niobium sheet and needing the following properties:

- High tolerance of joint variations—cracks, burrs, and other irregularities—so that irregularities in edge preparation do not lead to weld defects or vacuum leaks.
- Full electron-beam penetration of the niobium from outside the cavity, such that the inside weld bead supporting RF current is flat and smooth, with no surface ripple or protruding structure that could cause local magnetic field enhancement.

- A residual resistivity ratio (RRR) of the niobium in or near the weld that is not degraded by the welding process.

One way to achieve these characteristics is by using the electron beam to simulate the surface heating characteristics of a Tig weld. The moving molten zone is relatively quiet in such a case, and the surface tension of the metal can produce a smooth underbead as it solidifies.

The technique derives from the rhombic raster technique developed over a decade ago at Cornell for welds of machined joint edges. [2] That technique focused sequentially on individual rhombus-shaped weld areas of several square millimeters. It was used very successfully on a number of cavities. The joint was prepared by machining the 3 mm niobium sheet to a total of 1.5 mm in the region of the weld in the form of two overlapping niobium edges, such that a cavity half cell was either male or female.

Using that basic rhombic raster technique, a weld parameter set was developed here which can be used to join 3 mm niobium without edge preparation or machined overlap. In fact, the parameter set works equally well with a gap of 0.25 mm. Samples having only sheared edges were joined in a butt-weld configuration with a very smooth underbead. An interesting feature of this parameter set is that there is minimal weld shrinkage. Another interesting feature is that the weld is not affected by the temperature of the part as the part heats up. The following parameters have good results on 3 mm sheet:

Beam Voltage:	50 kV
Beam Current:	43 mA
Weld Spread:	15 cm/min
Focus:	Sharp
Rhombic Raster:	9 kHz & 10 kHz axes

The gun was pointed down on the work in each case. A profilometer trace over the weld surface of a typical sample shows an average surface roughness of 3.2 microns. One minute of etching in BCP (1:1:1) will remove about 13 microns.

<u>Cavity Preparation</u>

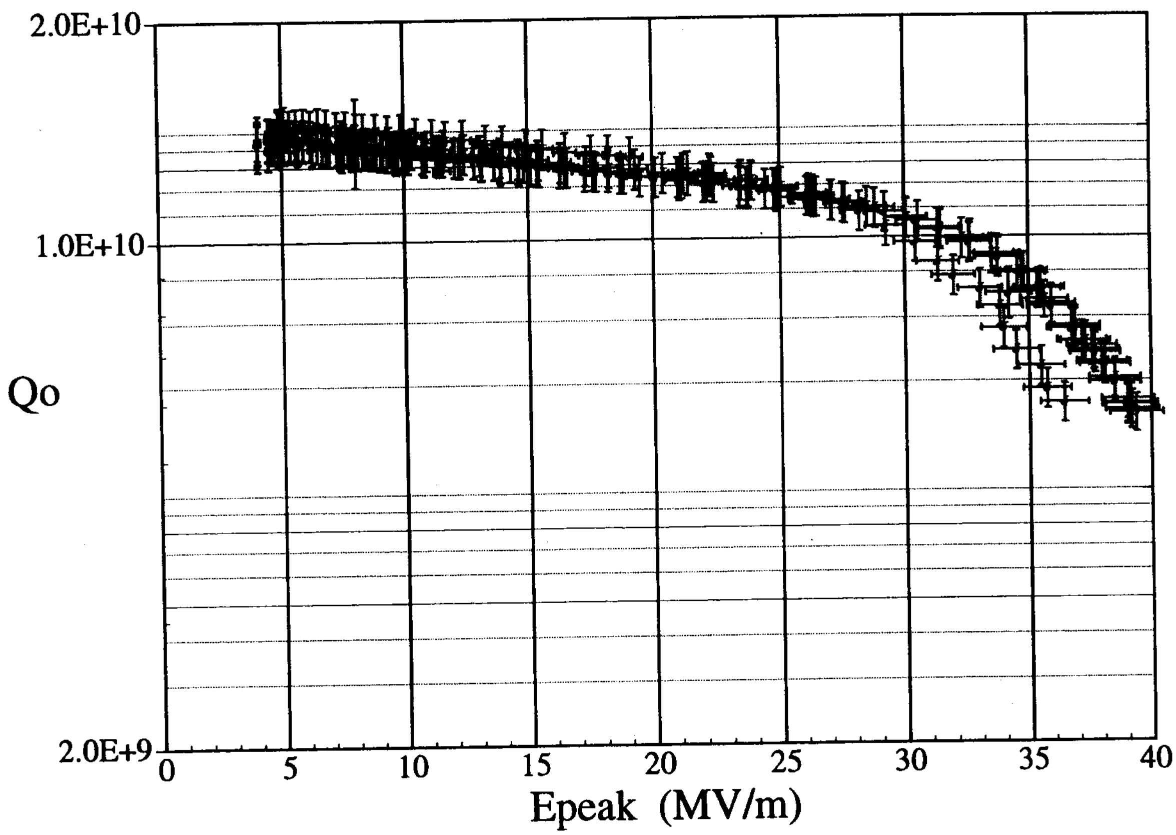
A 1500 MHz single cell was formed from 3 mm niobium having an RRR of 200. The half-cell edges were trimmed in a milling machine without deburring. Niobium parts were cleaned before welding in BCP (1:1:1) for one minute. After welding, the complete cavity was etched in BCP (1:1:1) for a total of 12 minutes in four successive 3 minute exposures.

The equatorial weld on this cavity was not as smooth as on the flat weld samples or cylindrical samples. The 3 mm sheet had thickened at the equator to 3.3 mm in the drawing process. It is not yet known whether intolerance to sheet thickness variations or an anomaly produced by the EBW equipment was responsible for the irregular weld. A beam profile monitor is being installed to characterize the beam before or after welding.

Cavity Testing

Although the equator weld on the complete test cavity did not achieve the same quality as on 3 mm samples, the test results were nonetheless reasonable. The cavity was limited by quench at a peak field of 39.2 MV/m (Fig. 1). Tests will continue with the same weld parameter set using a fully characterized beam profile to ensure repeatability as well as a consistent niobium sheet thickness.

SINGLE CELL 1500MHz CAVITY WITH CRACK TOLERANT BEAM WELD



Cost of Forming and Joining Cavity Parts

We have obtained commercial estimates for forming and joining nine-cell cavities in quantities of 20,000. Our model was the TESLA cavity with two HOM parts and one FPC port and stiffiners between each cell. We have not included material or material inspection costs. Flange costs have also been omitted, but flange welds to the cavity have been included. Both beam pipes are drawn from cups with additional draws for coupling ports. All squared edges are sheared, including all port openings.

Commercial estimates for forming are very straightforward, since similar shapes are produced daily by many companies in much larger quantities. Therefore the following estimates are considered conservatively high.

The forming estimates, include tooling, labor, and a 20% vendor profit, were:

- Half cells for 20,000 cavities: 1,360K $
- HOM beam pipe with 2 ports: 169K $
- FPC beam pipe with 1 port: 142K $
- Stiffeners: 160 K $

We also examined the cost of welding formed cavity parts in a dedicated production tool rather than using the general-purpose electron beam welder currently used in small-quantity production.

The production joining tool considered here is a continuous load-locked electron beam welder containing three automated electron beam guns operating simultaneously in a common vacuum envelope which is never let up to atmosphere. The cylindrical chamber is approximately 15 m in length with a load lock at each end. The design vacuum during e-beam welding is 1×10^{-8} Torr. This is an arbitrary pressure which costs very little to achieve in this type of machine. The effect of beam welder vacuum on cavity performance is generally not well known except for degradation of the RRR welds made in very poor vacuum.

A continuous production tool of this sort having multiple electron beam weld guns and designed to perform a specific task is not unusual; but, to our knowledge, none have been made for cavity fabrication.

Electron Beam Welding Estimates

Process assumptions to produce 5000 cavities/year:

- Three shifts.
- Production rate of 1.5 cavities per hour (load-lock cycle time is three cavities every 2 hours).
- 1 FTE required per shift for fixture loading and operation, 1/2 FTE for maintenance and support.
- Capital cost of EBW tool and fixturing: 3,500K $.

Cost of forming and welding per cavity for a quantity of 20,000 is approximately $320 per cavity. (EBW costs include capital and labor but do not include vendor profit.)

Conclusion

The unit cost in a typical manufacturing process taken to extremely large numbers of units, will generally approach asymptotically the cost of material from which the unit is made. Because of the high cost of niobium this limit would be relevant for quantities as small as 20,000 and substantial reduction in cavity costs beyond those described here will not be achieved through further efforts to reduce manufacturing costs. Substantial cost reductions in dollars per volt achieved can be obtained however by understanding the relationship between EBW technique and quench producing weld defects. The fact that isolated cavity tests exhibited near theoretical performance with equator welds and without heat treatment demonstrate that this is possible. Future work will focus on this relationship.

Acknowledgment

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[1] W. Möller, "Quest for High Gradients," Proceedings of the 7th Workshop on RF Superconductivity, Gifsur Yvette, France, Oct. 1995.

[2] J. Kirchgessner, "Forming and Welding of Niobium for Superconducting Cavities," Proceedings of the 3rd Workshop on RF Superconductivity, Argonne National Lab, 1987, 533.