CAVITY CONSTRUCTION TECHNIQUES

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ABSTRACT
The materials, joining techniques, fabrication methods and cooling schemes that are normally used in the construction of radio frequency cavities for high energy particle accelerators are described. The processes are illustrated by examples taken from present day accelerators.

1. INTRODUCTION

This paper describes for those with little or no experience in the design of RF cavities the materials, joining techniques, fabrication methods and cooling schemes that are normally used to construct and cool them. The aim is not to give a rigorous presentation of each process but rather to unveil the panoply of possibilities that exist by first describing the process in a simple way and then by giving at least one example taken from present day accelerators.

2. MATERIALS

Copper is the preferred RF surface for room temperature applications and niobium for low temperature superconducting structures. For strength reasons the copper is often deposited onto, or attached to, a stronger material such as steel. Aluminium has been used but aluminium cavities tend to suffer from multipactor problems since the oxidised surface has a high coefficient of secondary emission. To reduce multipacting in the PEP cavities for example the inside surface had to be covered with 10-20 nm of titanium nitride [1].

The most commonly used materials are given below. The names of some of the machines with cavities made from these materials are given as examples in brackets.

- Bulk OFHC-type coppers (SLAC, DORIS, PETRA, LEP....)
- Copper-electroplated steel (KEK APS, GSI UNILAC...)
- Copper-clad steel (SPS, .......)
- Aluminium (PEP)
- Niobium or niobium-sputtered copper (TRISTAN and LEP SC cavities).

The important material properties are:

(i) electrical conductivity
For a given geometry and frequency this determines the max. possible Q

(ii) thermal conductivity
For a given power dissipation this determines the temperature levels

(iii) mechanical stiffness
This is characterised by Young’s modulus and determines (a) the minimum thickness to prevent collapse due to buckling (b) the elastic deformation of the cavity under external atmospheric pressure and hence the frequency change

(iv) vacuum outgassing rate
For a given installed pumping speed this determines the static pressure
(v) coefficient of secondary emission of the surface - number of electrons produced per incident electron - this influences the degree of multipacting

(vi) formability or machinability
(vii) weldability or brazability
(viii) cost.

The following material properties are not usually important but may be in special circumstances - see examples:

(ix) mechanical creep resistance
This may be important to prevent the buckling of thin-walled structures during bakeout: example - the OFHC copper of the LEP storage cavities which have a diameter-to-thickness ratio of 200 contains 0.1% Ag which increases the creep resistance by a factor 5 or more.

(x) mechanical fatigue
In certain circumstances this may determine the lifetime of the cavity: example - in the new generation of high gradient pulsed accelerating structures for linear colliders there is a danger of surface fatigue damage due to RF impulse heating and cooling - see for example Ref. [2].

(xi) magnetic permeability
This is important only if the cavity is subject to external magnetic fields.

Typical values for electrical conductivity, thermal conductivity and mechanical stiffness are given in Table 1 for the most commonly used materials at room temperature.

<table>
<thead>
<tr>
<th>Material</th>
<th>Electrical conductivity ($\Omega^{-1} \text{cm}^{-1}$)</th>
<th>Thermal conductivity ($W / \text{cm} / ^\circ\text{C}$)</th>
<th>Young's Modulus (daN / mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFHC copper</td>
<td>$5.8 \times 10^7$</td>
<td>$4.0$</td>
<td>$1.20 \times 10^4$</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>$1.5 \times 10^6$</td>
<td>$0.2$</td>
<td>$2.10 \times 10^4$</td>
</tr>
<tr>
<td>Mild steel</td>
<td>$5.5 \times 10^6$</td>
<td>$0.5$</td>
<td>$2.10 \times 10^4$</td>
</tr>
<tr>
<td>Aluminium</td>
<td>$3.7 \times 10^7$</td>
<td>$2.2$</td>
<td>$0.72 \times 10^4$</td>
</tr>
<tr>
<td>Silver</td>
<td>$6.2 \times 10^7$</td>
<td>$4.1$</td>
<td>$0.76 \times 10^4$</td>
</tr>
</tbody>
</table>

Material in the as-cast state is not recommended for cavity construction. Cast billets should be mechanically worked by forging, rolling or extruding to eliminate porosity and reduce grain size. Small grains reduce the risk of crack propagation along grain boundaries when the metal is plastically deformed.

In the mechanically worked condition, chemically cleaned surfaces of the metals given in Table 1 have all approximately the same outgassing rate of $1.5 \times 10^{-11}$ (unbaked) and $1.5 \times 10^{-12}$ (baked) Torr l s$^{-1}$ cm$^{-2}$ after 100 h pumping at 20 $^\circ$C. The value for electrolytically deposited copper may be as much as a factor 10 worse depending on the process.
The oxygen content of OFHC copper is normally restricted to 5 ppm but the BE 58 electronic copper which is de-oxidised with phosphorus and has up to 30 ppm of oxygen has also been successfully used - for example in LEP accelerating cavities.

Copper-clad steel is produced by explosion bonding or hot rolling. The explosive bonding of copper to niobium has been used extensively at Argonne National Lab. [3].

3. FORMING TECHNIQUES

3.1 Machining

For cavities made by machining it is recommended that wherever possible axisymmetric geometries be used so that the components can be turned on a lathe. Turning is one of the cheapest and most accurate machining techniques. Table 2 gives the tolerances and surface finishes that are normally associated with the various classical machining processes. As a general rule of thumb the finish required is \( Ra = \frac{\text{skin depth}}{4} \) where \( Ra \) is the mean arithmetic distance of the true profile from the average profile. Whenever possible final machining of the internal vacuum surfaces of cavities should be dry or with alcohol as the cutting fluid. Otherwise the fluid should be water-based as opposed to oil-based and for cutting copper in particular should be sulphur-free.

For applications requiring the very best dimensional accuracy and surface finish use is made of mono-crystal diamond cutting tools. Such tools used in conjunction with sophisticated lathes (see below) are capable of machining components to tolerances of a few \( \mu m \) with surface finishes better than N1.

<table>
<thead>
<tr>
<th>SURFACE FINISH</th>
<th>N8</th>
<th>N7</th>
<th>N6</th>
<th>N5</th>
<th>N4</th>
<th>N3</th>
<th>N2</th>
<th>N1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ra (( \mu m ))</td>
<td>3.2</td>
<td>1.6</td>
<td>0.8</td>
<td>0.4</td>
<td>0.2</td>
<td>0.1</td>
<td>0.05</td>
<td>0.025</td>
</tr>
<tr>
<td>PLANING</td>
<td></td>
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<tr>
<td>DRILLING</td>
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<td>TURNING</td>
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<tr>
<td>DIAMOND TURNING</td>
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<td>MILLING</td>
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<tr>
<td>LAPPING</td>
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<td>POLISHING</td>
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</tbody>
</table>

Roughness obtained with usual workshop practice
Roughness obtained with special care

The copper cups in Fig. 1 for example were machined, to the dimensions shown, on a Pneumo MSG 325 lathe for the CLIC 30 GHz prototype accelerating sections and represent the state of the art in diamond machining. Tolerances of \( \pm 2 \mu m \) were obtained with a surface finish \( Ra = 15 \) nm. These Pneumo machines have CNC control, closed-loop laser interferometric feedback with 25 nm resolution, vibration isolation and air bearing spindles...
and slides. The diamond tool for this application was lapped to a form precision of < ± 0.5 μm over an angle of 100°.

![Diagram of diamond-machined copper cups for CERN Linear Collider accelerating structures.]

Fig. 1 Diamond-machined copper cups for CERN Linear Collider accelerating structures

For non-axisymmetric geometries, as a complement to CNC milling machines, a relatively new technique "electro-erosion wire machining" is well worth mentioning since accuracies of one hundredth of a millimetre with surface finishes around N5 can now be obtained. In this process material is eroded away by striking an electrical discharge between the workpiece and a continuously moving wire. This technique is very useful for making sharp-cornered slots or holes.

3.2 Rolling

This is a cheap and simple way of producing cylinders. There are drawbacks however. After rolling and welding, the tolerances on diameter are no better than a few tenths of a millimetre at best and in general the cylinders are then machined. Welding these cylinders to other components produces a potential weak spot for leak tightness at the double-weld crossover point.

Rolling and welding copper-clad material is possible but is complicated by the fact that the weld seam is composed of two overlapping materials. The SPS travelling wave cavities for example (4 m x 750 mm ID) were fabricated from 20 mm thick normal steel with a 5 mm thick cladding of copper using this technique (the tolerance on the finished diameter was 1 to 2 mm).

3.3 Forging

This technique is in itself not sufficiently accurate to make finished RF components. It is used to economise material by pre-forming pieces to approximate dimensions before final machining. Forging can be used in particular to make seamless cylinders thus eliminating the double-weld problem associated with rolling, the billet is first pierced to make a hole and then the wall thickness is reduced by successive hammerings to obtain the final diameter.

The disks and seamless cylinders for the LEP 352 MHz accelerating cavities were all pre-formed by this process.
3.4 Spinning

This fabrication method involves pushing a thin flat disc of ductile material onto a former whilst the whole assembly is rotating. The process is therefore only applicable to axisymmetric shapes where the diameter-to-thickness ratios are relatively large. Compared to other sheet metal forming processes spinning produces a more uniform thickness distribution and for cavity work has the advantage that the reference surface is the inside surface of the component.

Fig. 2 LEP storage cavities

The 1.2 m diameter copper hemispheres for the LEP 352 MHz storage cavities which are shown in Fig. 2 were spun from 8 mm thick sheet. In order to obtain the tight tolerances imposed (radius ± 1.2 mm and minimum thickness 5 mm) the copper was heated to temperatures between 400-480 °C during the forming process. The resonant frequency of the sphere was adjusted prior to welding by machining off material from the base of the hemispheres to reduce their height.

3.5 Pressing and deep drawing

Pressing sheet metal into moulds is a technique which is used extensively in the automobile industry for mass production. The relatively large initial investment in the
development of suitable tooling makes this method less attractive than others for the fabrication of a few cavities. The reference surface provided by the surface of the mould is in this case the outside surface of the cavity. Ports for tuners and other accessories are easily made in the main wall of the cavity by pressing or drawing a hemispherical tool through a pre-cut hole as shown in Fig. 3.

![Fig. 3 Forming outlet ports in cavity walls by pressing](image)

The SPS single-cell 200 MHz copper cavities for LEP operation were constructed from two such half-shell pressed parts for which tooling was available in industry (pressure vessel standards). The main dimensions are given in Fig. 4. Overall tuning of the cavity after final assembly welding is made by stretching or compressing the cavity to produce plastic deformation in the longitudinal direction.

![Fig. 4 Fabrication of SPS cavities from two half-shell pressed parts](image)
General rules for the deep drawing of niobium based on experience at Cornell for the fabrication of superconducting cavities are given in Ref. [4].

3.6 Hydroforming

Hydroforming, in which the metal is forced into an external die by hydraulic pressure, has been successfully used at CERN to produce multi-cell copper cavities from a single seamless tube [5]. Several examples are shown in Fig. 5 for frequencies from 352 MHz - 2.1 GHz.

![Image of hydroformed cavities]

**Fig. 5** Single piece multi-cell hydroformed cavities

Since the ultimate elongation of annealed copper is around 50% and deformations of typically 200% are required to produce these cavities, the forming process is in fact a multistage operation including preliminary swaging and several expansions with intermediate annealing. The principle of swaging is shown in Fig. 6. - reductions of 40% were obtained with pressures of 650 bars.

![Image of swaging operation]

**Fig. 6** The swaging operation
The expansion phase, using pressures up to 200 bars, is shown schematically in Fig. 7 - the tube is put into a multipart die which is initially open but which closes progressively during expansion as the length of the tube decreases.

![Diagram of multipart die expansion](image)

Fig. 7 Expansion in a multi-part die

The absence of welds which are normally associated with surface irregularities and hence sources for electron emission makes these multi-cell structures particularly attractive for use as substrates for the fabrication of niobium-sputtered superconducting cavities.

### 3.7 Electroplating

This is the standard method for putting thin coatings (say up to 100 µm) of high conductivity material (usually copper or silver) on steel surfaces which would otherwise see RF fields in cavities. At one time avoided for justified complaints of low conductivity and high outgassing rates, this technique can now produce copper qualities which rival those of the best OFHC-type coppers. In the case of stainless steel a pre-plating with a 4-5 µm nickel layer before copper plating is normally necessary to obtain a satisfactory adhesion - note however that nickel is magnetic!

The GSI at Darmstadt in particular has invested considerable effort in the copper plating of mild steel for the fabrication of their Wideroe and Alvarez tanks [6]. Considerable expertise and care is needed for a successful application of this technique which is often quite long and involved - the GSI plating process for example has 16 steps but produces a copper with a conductivity of $58 \times 10^{-4} \Omega^{-1} \text{cm}^{-1}$ and an outgassing rate of about $3 \times 10^{-10} \text{Torr s}^{-1} \text{cm}^{-2}$ after 100 h pumping at 20°C.

Both the 508 MHz disk-and-washer and 508 MHz aperiodic structures (APS) for TRISTAN at KEK have used this method. The APS cavities are made from low carbon steel with a 200 µm copper surface layer deposited using a pyrophosphoric acid bath. The measured Q values of the cavities corresponded to 89% of the calculated SUPERFISH value.

### 3.8 Electroforming

In the electroforming technique the main body of the cavity is produced by building up a thick layer of electrolytically deposited material onto a metal mandrel which is...
subsequently removed in the case of steel for example or dissolved out in the case of aluminium.

The main advantages of this technique are:
- High purity and good characteristics of deposited material
- Ability to produce complicated shapes
- Dimensions of the mandrel are reproduced exactly
- Single piece cavities can be made without brazed or welded joints
- Cooling ducts can be incorporated into the walls.

The disadvantages are:
- Tends to be expensive
- Relatively slow rates of deposition (30-50 μm/h)
- Unless made in two halves each cavity requires a former
- Difficulties in brazing and welding electroformed copper.

The Daresbury Laboratory 500 MHz single-cell copper cavities shown in Fig. 8 for the 2 GeV electron storage ring were made by this process [7]. The cavity consists of an inner, single-piece electroformed shell surrounded by two electroformed half shells which are EB welded together to form the water cooling jacket. Four machined copper outlet ports for tuners and other accessories were fixed onto the aluminium mandrel and became incorporated into the main body of the cavity as the electrodeposited layer was built up to 13.5 mm. After electroplating of the inner shell was finished cooling channels were milled into its walls and the mandrel etched out chemically. The half shells were electrodeposited onto a steel mandrel from which they were released by heat after completion.

![Diagram of the Daresbury Laboratory 500 MHz electroformed cavity](image)

**Fig. 8** The Daresbury Laboratory 500 MHz electroformed cavity
Cooling channels can also be built into the cavity walls by putting wax beading onto the partially formed wall and then plating over it to complete the process.

### 3.9 Sputtering

Traditionally superconducting cavities are made of high purity Nb sheets by spinning and welding. This type of cavity suffers from the relatively poor thermal conductivity of Nb at liquid helium temperatures which is often insufficient to prevent the inner surface from exceeding the critical temperature due to local heating at surface defects.

The alternative solution in which a 1 μm Nb layer is sputtered onto OFHC substrate cavities has the advantages of higher thermal stability, elimination of macroscopic resistive inclusions at the surface and lower cost.

This method consists of producing an argon gas plasma at a pressure of about $5 \times 10^{-2}$ Torr and using the impact of the positive argon ions driven onto niobium cathodes by electric fields to sputter off niobium atoms which condense on the cavity walls.

Two four-cell 352 MHz superconducting cavities for SPS/LEP injector operation were made by this technique [8]. A schematic drawing of the set-up for magnetron sputtering is shown in Fig. 9. The time to deposit 1 μm of niobium was 1 h.

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**Fig. 9** Schematic assembly for magnetron sputtering
3.10 Explosion forming

Explosion forming is a little known and, to-date, unused technique for fabricating cavities. The principle is shown in Fig. 10. A shock wave is created in an underwater vessel by detonating an explosive charge. The force of the wave is used to deform sheet metal blanks into external dies.

![Diagram of explosion forming](image)

Fig. 10 Explosive forming

The advantages claimed for this process are:
- Ability to exceed the limits of conventional forming processes
- Excellent dimensional conformity to the die
- Conservation of internal surface finish
- Low tooling costs
- Particularly suited to one-off large dimension components.

The technique is apparently suitable for copper components - an offer was made to CERN by the Societe Nationale des Poudres et Explosives in Paris to fabricate the LEP 352 MHz storage cavities in this way. For niobium however it was concluded from tests made at Cornell [4] that the high stress rate during explosive forming was disadvantageous from the point of view of formability compared to techniques where the force is applied slowly.

4. JOINING TECHNIQUES

4.1 Brazing

Brazing is one of the most common ways of assembling cavities - as an example the SLAC two-mile linac was made this way.

Brazing is a joining technique in which, through heating to a certain temperature, a filler metal or alloy, having a lower melting point than the base materials, melts and wets the former, flows by capillary action through a defined gap and solidifies on cooling.

In order to wet well, a molten metal must be capable of alloying with some of the metal on the surface and this is only possible after elimination of grease and oxide films. Recommended cleaning procedures for OFHC copper and stainless steel components are given in Appendix 1.

The size of the gap in which the braze flows is typically a few hundredths of a millimetre. Some recommended joint geometries are shown in Fig. 11. The brazed joint should be
designed if possible such that on cooling it is under compression rather than in tension. For cylindrical components the material with the higher coefficient of expansion should therefore be on the outside.

![Fig. 11 Some recommended joint geometries for brazing](image)

Some of the commonly used brazing alloys and their brazing temperatures are given in Table 3 for the base metals indicated. Filler alloys containing metals such as Zn and Cd which have high vapour pressures should not be used to braze components which will eventually form part of the cavity vacuum surface.

**Table 3**
Commonly used brazing alloys

<table>
<thead>
<tr>
<th>FILLER ALLOY</th>
<th>TYPICAL BRAZE TEMP. (°C)</th>
<th>BASE METALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>92.5Ni/4.5Si/3B</td>
<td>1175</td>
<td>SS/SS</td>
</tr>
<tr>
<td>35Au/65Cu</td>
<td>1030</td>
<td>Cu/Cu</td>
</tr>
<tr>
<td>50Au/50Cu</td>
<td>990</td>
<td>Cu/Cu</td>
</tr>
<tr>
<td>76Ni/14Cr/10P</td>
<td>1065</td>
<td>SS/SS</td>
</tr>
<tr>
<td>80Au/20Cu</td>
<td>960</td>
<td>SS/Nb</td>
</tr>
<tr>
<td>80Au/20Cu</td>
<td>910</td>
<td>metalised ceramic/Nb</td>
</tr>
<tr>
<td>20Ag/60Au/20Cu</td>
<td>865</td>
<td>Cu/Cu</td>
</tr>
<tr>
<td>59Ag/31Cu/10Pd</td>
<td>860</td>
<td>Cu/Cu</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cu/SS (Ni plated)</td>
</tr>
<tr>
<td>68Ag/27Cu/5Pd</td>
<td>817</td>
<td>Cu/Cu</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cu/SS (Ni plated)</td>
</tr>
<tr>
<td>72Ag/28Cu</td>
<td>790</td>
<td>Cu/Cu</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cu/SS (Ni plated)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>metalised ceramic/metal</td>
</tr>
</tbody>
</table>

Suitable choice of filler alloys allows multiple brazes at successively reduced temperatures to be made on the same component. In some circumstances where the composition of the filler is changed (alloying with the base metal) it is even possible to make more than one braze at the same temperature without melting the previous brazings.
The brazing process is usually carried out either under vacuum (10^-6 Torr minimum) or in an atmosphere of hydrogen. Under vacuum, surface contaminants are removed (at least at elevated temperatures), and the hydrogen content of the base materials and hence their subsequent outgassing rate is significantly reduced. A hydrogen atmosphere produces a more rapid and uniform heating of the components but can cause embrittlement in some materials due to its strong reducing properties.

Advantages of brazing:
- Little or no distortion of the components
- Dissimilar materials can be joined (metals to ceramics)
- Multiple joints can be made in one operation.

Disadvantages:
- Possible reduction of strength and grain growth due to relatively high temperatures.

Whenever possible the components to be brazed should be self-aligning and self-supporting. External alignment or support devices tend to create constraints on the free expansion and subsequent contraction of the brazed joint due to differential heating and cooling rates, and material mismatches.

The heating rates and temperature stabilization times are chosen according to the masses to be heated. A typical heating cycle is shown in Fig. 12.

![Temperature vs. Time Diagram](image)

\[(dT/\text{dt})_1 = 200 - 500 \, ^\circ\text{C}/\text{h}\]
\[(dT/\text{dt})_2 = 100 - 400 \, ^\circ\text{C}/\text{h}\]
\[\Delta t_1 = 10 \text{ min} - 2 \text{ h}\]
\[\Delta t_2 = 1 \text{ min} - 40 \text{ min}\]

Fig. 12. A typical heating cycle for brazing.
4.2 Diffusion bonding

This technique has been used to assemble the copper cups that form the travelling wave accelerating sections of the LIL (LEP Injector Linac). The surfaces to be joined were first coated with a 6 μm layer of silver and then pressed together for 1 h with a pressure of 1.3 daN/mm² at a temperature of 350 °C. The bond is formed by diffusion of the silver into the copper.

If the contacting surfaces are very clean and very flat a diffusion bond can even be obtained on copper surfaces without the silver. This observation has been used in the fabrication of the CLIC prototype accelerating sections [9]. Although the cups for the sections are brazed together, a direct copper-to-copper diffusion bond has been used to prevent the flow of excess braze material into the very small 30 GHz cells. The scheme is shown in Fig. 13.

A 1 mm wide diffusion-bonded annular surface at the inside edge of the discs provides electrical contact and blocks the flow of the brazing alloy. The diffusion bond between the clean mirror-finish contacting surfaces (Ra = 0.025 mm) is made during the normal brazing cycle under slight pressure. A similar ring at the outer surface prevents braze leakage to the outside. Q-values of 95% of theoretical have been obtained using this technique.

4.3 Joining by electroplating

This technique was used to make the travelling wave accelerating sections for the 2.5 GeV electron linac of the Photon Factory at KEK [10]. The diamond-machined disks and cylinders of the disk-loaded waveguide structure were stacked together and consolidated by electroplating an external envelope of copper as shown in Fig. 14. The advantage claimed for this cold joining method is that the overall geometry is so well defined that no allowance for tuning is necessary.
4.4 Electron-beam (EB) welding

The welding agent for this technique is a finely focused beam of high-speed electrons which gives up its energy to the workpiece in the form of heat. Although electrons only penetrate for a distance of a few atomic diameters into solid material, the energy density of the electron beam is so high that it pierces the material being welded by vaporisation rather than by melting. The vapour filled hole has liquid walls which close in on themselves as the electron beam is moved along the joint.

A typical large EB machine using 150 keV electrons can produce 75kW of heat energy at the workpiece - enough to weld 200 mm of steel - with spot sizes down to 0.2 mm.

Advantages of EB welding:
- Extremely narrow fusion and heat affected zone
- High quality welds with good joint strengths
- Low total heat input resulting in virtually no distortion
- Welding almost inaccessible places (line of sight only needed)
- High penetration single pass welds at high speeds
- Chemically pure welds due to the vacuum environment
- Can weld dissimilar materials (SS/Cu for example)
- Good reproducibility (fully automatic process)

The main disadvantages of EB welding is that in situ welding is not possible because a vacuum is necessary.
Plain butt-weld or lap butt-weld geometries as shown in Fig. 15 are usually preferred for cavity work.

Fig. 15 EB butt-weld geometries for cavity work

The 352 MHz copper cavities for the LEP main ring were assembled by this technique. The geometry of the joint between the disks and cylinders of the cavities is shown in Fig. 16 (a). Since full penetration EB welds in copper tend to splash through into the cavity leaving a very rough and irregular surface the weld is fired into a "stopper". This stopper (see Fig. 16) also ensures that the small zone of porosity present at the root of copper EB welds is kept safely away from vacuum surfaces. The pieces were first tack welded together (one third of full penetration) to minimise distortions and then welded. After the full penetration weld a very superficial cosmetic pass is necessary to produce a smooth surface at the outer edge of the cavity. Weld shrinkages of about 0.5 mm were measured for this geometry. Typical dimensions of the EB weld are shown in Fig. 16 (b).

Fig. 16 Geometry of EB weld for LEP 352 MHz accelerating cavities
Typical welding parameters for this weld are:

- Gun voltage \( U = 150 \) kV
- Welding current \( I = 58 \) mA
- Welding speed \( v = 10 \) mm/s
- Working distance \( d = 560 \) mm
- Weld thickness \( t = 1.3 \) mm.

For constructions requiring both EB welding and brazing operations it is recommended that the EB weld be made last to avoid cracking the weld by thermal stress as occurred in the SPS 200 MHz cavities for injection into LEP.

In superconducting cavities where it is very important to have smooth defect-free internal surfaces, EB welding can, when space permits, be made from the inside. This has been done at CERN for 352 MHz niobium cavities.

4.5 Inert-gas arc welding

In this process the heat for welding is produced by striking an arc between the workpiece and an electrode using a constant or pulsed voltage supply. For high quality work TIG (Tungsten Inert Gas) and PLASMA welding are normally preferred. Both techniques use a non-consumable tungsten electrode which in the plasma process has a high-speed gas flowing around it to produce a constriction of the arc. Argon or helium gas is used to shield the weld area from the normal oxidising atmosphere.

Advantages of TIG or Plasma welding:
- High quality welds with good joint strengths
- Low cost process
- Ability to do in situ welds
- Process can be fully automated.

Disadvantages:
- Poor penetration power
- Multiple passes required for thick components
- Large heat affected zone
- Deformations in thick components can be large
- Dissimilar metals cannot be welded.

The disks and cylinders of the 353 MHz aluminium cavities for PEP at SLAC were joined together by this technique.

4.6 Shrinking

This method was used at Stanford to construct the original 1 GeV (MARK 3) accelerator [11]. The discs of the disk-loaded waveguide structure were mounted on an invar mandrel and after cooling to liquid nitrogen temperature were put into the steam heated outer waveguide tube. The resulting interference fit at room temperature was about 0.5% of the diameter. For later constructions this technique was abandoned in favour of brazing.

5. COOLING

The design of the cooling system for RF cavities must take into account not only the total amount of heat which has to be carried away, but also the increase of surface temperature that can be tolerated without creating an unacceptable loss in shunt impedance that results from the temperature-dependent variation in electrical conductivity. This problem has been analysed in detail in Ref. [12]. It was found in PETRA for example that the operational
shunt impedance was 18.9% lower than the assumed room temperature value due to thermal effects [13].

The basic theory governing thermal flow in water-cooled solids is given in Appendix 2.

Normal conducting sheet metal cavities are usually cooled by water flowing through pipes which are fixed to the external surface by brazing (example - LEP storage cavities) or by soft soldering (example - SPS LEP single-cell cavities). The very unorthodox technique of interference clamping by shrinking of a pre-formed array of pipes onto the cavity wall via a heat-conducting paste was used at the Lawrence Radiation Laboratory in Berkeley to cool a pre-stripper tank [14]. Copper pipes have also been attached to prototype copper cavities at CERN by metal spraying.

For effective cooling the water flow should be turbulent (Reynold's number > 2300). Typical values for surface heat transfer coefficients for water at 25 °C in round pipes are given in Fig. 17 using the empirical relationship given in Appendix 2

\[
N_{Nu} = 0.023 \cdot N_{Pr}^{0.4} \cdot N_{Re}^{0.8}
\]

For more solid pieces such as forged discs or nose-cone blocks, an internal cooling channel can be created by an interconnecting series of drilled holes as shown in Fig. 18.

Jacket cooling is also used (see for example the Daresbury electroformed cavity) but requires some form of channeling to be effective and submits the inner shell to much higher external pressures.
Fig. 18 Interconnecting drillings for cooling water in LEP 352 MHz accelerating cavities

REFERENCES

APPENDIX 1

RECOMMENDED CLEANING PROCESS FOR OFHC COPPER

1. Degrease in perchloroethylene
2. Ultrasonic clean in an alkaline detergent solution (pH = 9.7) at 60°C for 5-10 mins. The detergent NGL 17.40 supplied by Cleaning Technology SA (Geneva) and used in a concentration of 10 g/l of demineralised water has proved very effective at CERN
3. Rinse in cold demineralised water
4. Deoxidise in a 50% by volume hydrochloric acid bath at room temperature for 5-15 mins depending on the thickness of the oxide layer to be removed
5. Rinse in cold demineralised water
6. Passivate in a solution containing 80 g/l of chromium trioxide and 3 cc/l of sulphuric acid
7. Rinse in cold demineralised water
8. Air dry after rinsing in hot demineralised water or alcohol at room temperature

In order not to deteriorate the very high surface finish on diamond-machined components steps 4-6 should be omitted.

RECOMMENDED CLEANING PROCESS FOR STAINLESS STEEL

1. Degrease in perchloroethylene
2. Ultrasonic clean in an alkaline detergent solution (pH = 9.7) at 60°C. The detergent P3 VR 580 17 supplied by Henkel and Co. SA (Pratteln, Switzerland) and used in a concentration of 20 g/l of demineralised water has proved very effective at CERN
3. Rinse in cold demineralised water
4. Dry in hot air
APPENDIX 2

THERMAL FLOW IN WATER-COOLED SOLIDS

The heat that is dissipated within the very thin surface layer at the inside surface of the cavity walls is transported
(i) by conduction throughout the cavity,
(ii) by forced convection to the bulk of the cooling water, and
(iii) by natural convection and radiation to the atmosphere.

Steady state conduction and radiation present no difficulties since they can be expressed exactly by the mathematical laws of Fourier (1822) and Boltzmann (1884) respectively. Forced and natural convection on the other hand involve the exchange of heat due to the complicated mixing motion of fluids for which there is no complete mathematical description. A differential equation describing the law of convective heat transfer therefore does not exist and this has necessarily led to the accumulation of vast amounts of empirical data covering an equally vast range of variables. This data is in general rationalised by expressing the empirical relationships in terms of dimensionless groups which establish a certain logical grouping of the variables. Most of the groups encountered in convective heat transfer analysis are given in Ref. [15] together with their physical significances. In the special case of heat transfer between a moving fluid and a solid surface the following simple relationship proposed by Newton in 1701 is used:

\[ q = h (T_1 - T_2) \]

where \( q \) heat flow per unit area
\( h \) surface heat transfer coefficient
\( T_1 \) temperature of the wall
\( T_2 \) usually the bulk fluid temperature.

The surface heat transfer coefficient \( h \) is usually found in the literature hidden in the dimensionless Nusselt number which for flow of water of thermal conductivity \( k \) in round tubes of diameter \( D \) is \( N_{Nu} = h D / k \).

The value of \( h \) is influenced considerably by the velocity profile of the fluid close to the solid boundary; this in turn depends on whether the flow is laminar or turbulent. The flow regime is determined by the Reynolds number \( N_{Re} \). For forced flow of water in round tubes and \( N_{Re} < 2300 \) laminar flow exists over the entire cross-section, whereas for \( N_{Re} > 10000 \) a well-established turbulent flow can be assumed. In order to obtain good cooling one normally chooses a turbulent flow for which the following empirical relationship has proved successful:

\[ N_{Nu} = 0.023 N_{Pr}^{0.4} N_{Re}^{0.8} \]

where \( N_{Nu} \) Nusselt number
\( N_{Pr} \) Prandtl number
\( N_{Re} \) Reynolds number.

In this particular formulation all physical properties are evaluated at the bulk temperature.

During turbulent flow, despite its name, a very thin surface layer is created at the wall of the pipe in which the flow is laminar and in which the velocity increases rapidly. Outside this layer the flow is turbulent with only small velocity gradients. Since high-velocity gradients correspond to high-temperature gradients, the surface temperature is considerably higher than the bulk temperature. This must of course be the case for any efficient transfer of heat.

\[ T_2 \] usually the bulk fluid temperature.

\[ N_{Nu} = h D / k \].

\[ N_{Nu} = 0.023 N_{Pr}^{0.4} N_{Re}^{0.8} \]

\( N_{Nu} \) Nusselt number
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