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FABRICATION AND TESTING OF RF STRUCTURES

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Abstract

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FABRICATION AND TESTING OF RF STRUCTURES

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Modern RF structures make great demands on both materials and fabrication techniques. In addition to high required precision, they need to be compatible with ultra high vacuum, high power RF and the presence of particle beams. We introduce materials compatible with these demands and summarize their relevant characteristics. Methods of forming and joining follow, again with emphasis on those suited for the fabrication of accelerating structures, and we point out their limitations. We mention different tests which will be designed into the fabrication process, and describe in some detail the testing of the RF properties of accelerating structures. The following overview is non-exhaustive and limited to normal-conducting structures; many of the examples relate to a possible next-generation linear collider.

1 Introduction – selection criteria

The criteria for selecting special materials and fabrication techniques naturally follow from the desired use of the RF structure in an accelerator. Typically, the choices have to be compatible with peak and average power levels, high electric field levels, low ohmic losses, ultra-high vacuum and the radioactive environment. Other criteria for the choice of materials are the mechanical stiffness, the toxicity of the materials (Be), their corrosion resistance and more generally their durability and reliability. Heat conductivity is important if ohmic power losses are to be dealt with. The machinability of the materials and the joining techniques to be applied are also important to consider.

The mechanical tolerances are typically dominated by the choice of the radio frequency and by beam dynamics considerations, along with compatibility with the joining techniques. The tolerances required for the RF structure's final performance will be the main criteria in selecting the fabrication method.

2 Materials

We will limit the discussion here to some of the materials predominantly used in conventional RF structures for accelerators, both travelling and standing wave. Superconducting RF structures, the fabrication techniques for which have made

tremendous progress over the last decades, are not included in this article and are treated separately.

Metals used in room-temperature RF structures are mainly copper, for its high conductivity, and stainless steel for beam tubes, vacuum manifolds and – when copper plated – also for RF structures. For insulators and RF windows, ceramics are used, mostly sapphire or alumina (Al_2O_3), but also beryllium oxide, silicon nitride or others. Ceramics used as damping materials are typically silicon carbide (SiC) or different types of ferrites.

Often surface coatings on both metals and ceramics are used, such as Ti or titanium nitride, which reduce the secondary electron emission and thus can prevent multipactor.

2.1 Metals

Even though we will concentrate on copper and stainless steel, in Table 1 they are compared with some other metals, with regard to some of their electrical and mechanical properties. Many of the quantities given here depend strongly on the temper and the purity of the metal or alloy and thus are only indicative.

The electrical conductivity given in Table 1 is at room temperature (300 K). The yield strength indicates the stress at the upper limit of the elastic range, i.e. where the linear range of the elongation-stress curve ends; at the R_p 0.2 % point, the elongation is 0.2 % beyond purely elastic. The (ultimate) tensile strength indicates the maximum stress obtained under tension before the material tears.

Table 1: Some characteristics of metals

	el. cond.	density	yield strength (R_p 0.2 %)	tensile strength	Brinell hardness	melting temperature
	MS m^{-1}	g/cm^3	MPa	MPa		$^{\circ}\text{C}$
Ag	62.6	10.5	30	130...160	15...36	960.5
Cu soft	59	8.94	100...150	200 ... 250	40 ... 50	1083
Cu hard	55		300...450	400 ... 490	80 ... 120	
Cu-OFS	58	8.92	70...360	220...450	50...100	1083
CuZr	53.8	8.89	42...500	200...530		980
Cu- Al_2O_3	49.3	8.8	410...560	480...580		1080
Au	45.4	19.29		100...300	13...75	1063
Al	38	2.7	25...200	70...250	15 ... 70	658
Mo	20.8	10.2	400	700...1200	150	2630
W	18.2	19.3	1500	400...4000	250	3380
Pd	9.8	11.97		200...400	40...100	1552
Nb	6.6	8.57		500	120	2477
SS 316LN	1.1	7.9	300	600	180	1350

Other properties, not indicated in Table 1, but nevertheless important when selecting a metallic material for RF structures, are the thermal conductivity, the elasticity module, the fatigue stress, the machinability, the ability to braze or weld it, the vacuum outgassing rate, the work function and the secondary emission yield, the magnetic permeability, and finally also the cost.

The outgassing rate indicates the vacuum level in mbar per surface (in cm^2) that can be obtained with a given pumping speed (in l/s), and is given in units of $\text{mbar l s}^{-1} \text{cm}^{-2}$. The level that should be obtained is on the order of $10^{-11} \text{ mbar l s}^{-1} \text{cm}^{-2}$. Bake-out can improve the outgassing rate by roughly one order of magnitude.

The work function is important for the maximum tolerable surface electric field without breakdown (sparking), since it enters in the equation for field emission of electrons, along with the surface shape, roughness and purity. However, the work function for practically all metals is in the range of 4 to 5 eV; impurities tend to decrease this value, this is done intentionally e.g. for cathode surfaces.

The secondary emission yield (SEY) is important when considering multipactor. Electron multipactor (multiple impact) describes a resonant emission of electrons on electron impact, which can lead to an exponentially growing electron current inside the structure at certain power levels, if the SEY is larger than one. The SEY is a function of the angle and energy of impacting electrons, but its maximum is a characteristic of the material. Furthermore it is important whether the material can be conditioned, i.e. whether the SEY can be reduced when exposed to high power RF.

2.1.1 Copper

Copper is the most frequently used metal for normal-conducting RF structures, thanks to its high electrical conductivity (59 MS/m, 94 % of the conductivity of Ag). The conductivity of copper and copper alloys is often given as “IACS” (international annealed copper scale) conductivity percentage, which is defined as 100 % IACS = 58 MS/m. (For those not used to SI units, $\text{MS} = 10^6 \Omega^{-1}$)

Copper can be machined to high precision and small surface roughness; it is compatible with ultra-high vacuum (UHV), is an excellent heat-conductor (385 W/m/K) and can be conditioned (treated with high power RF under vacuum) to high surface field levels, and it has a comparatively low secondary emission yield (max. around 1.3). Its main disadvantages are its lack of strength, and the fact that it becomes particularly soft after full annealing above 300 °C (HB 40 ... 50). Note that this temperature is normally considerably exceeded when a structure is brazed.

Copper regains strength and hardness with cold working, which also eliminates porosity and reduces the grain size, which is often required for leak tightness of thin walls. The conductivity of copper is reduced by forging by up to 2.5 %.

The skin-depth in copper is $6.6 \mu\text{m} \cdot \sqrt{\frac{100 \text{ MHz}}{f} \cdot \frac{58 \text{ MS/m}}{\sigma}}$, i.e. only a layer of a few skin-depths on the inside will carry RF currents.

The most frequently used type of copper for RF structures is oxygen free electronic grade (OFE) copper, formerly known as OFHC (high conductivity) copper, according to ISO 431 nominated Cu-OFE, or UNS grade C10100. It is of high purity (above 99.99 % Cu). The typical maximum content of oxygen is below 5 ppm, which allows welding and heat treatment. The electrical conductivity of Cu-OFE is >102 % IACS.

Copper alloys like Cu-OFS (UNS C10700), which contains 0.1 % silver to increase its creep resistance (to prevent buckling under atmospheric pressure with thin walls), or CuZr (UNS C15000) with 0.2 % zirconium to increase its hardness, are considered for special applications in RF structures. All copper alloys however have lower electrical conductivity than Cu-OFE.

Another copper alloy sometimes used in accelerating structures is Glidcop®, which contains Al₂O₃ and has improved strength and hardness, again at the expense of lower electrical conductivity (85 % ... 93 % IACS, depending on the alumina concentration). The alumina micro-particles dispersed in the copper are pinning the lattice dislocations to the dispersions (dispersion-hardening). UNS grades for Glidcop are C15710, C15720 and C15735.

Brazing (and soldering) alloys are based on copper, typically Cu-Sn, Cu-Ag, or Cu-Au alloys, some of which are mentioned below.

2.1.2 Stainless steel

Stainless, i.e. corrosion resistant steels consist of more than 10 % chromium. When exposed to air, this chromium forms a tough, adherent, invisible and self-healing chromium-oxide film at its surface which passivates it. More than 70 grades of stainless steel are standardized. Referring to their metallurgical structure, these are characterized as martensitic (AISI 410, 420, 440, ...), austenitic (304, 310, 316, 317, ...), ferritic (409, 430, ...) and superferritic (442, 446), duplex (2205) and precipitation-hardened steels. Only austenitic steels are non-magnetic.

Because of its relatively low electrical conductivity (less than 2 % that of Cu), steel is not normally suited as a RF structure material that has to carry RF

current – the ohmic losses would be too high. It is however frequently used for ancillary systems, in particular vacuum beam pipes and flanges. When used as a cavity body, copper-plating the inner surfaces may be considered (see below).

For vacuum, cryogenic and accelerator structure applications, the type of stainless steel mainly used is AISI 316LN or DIN “X2CrNiMoN 17-13-3”. It consists of 17 % Cr, 13 % Ni, 3 % Mo, and below 0.03 % of C (the L stands for “low carbon content”). Vacuum firing at 950 °C removes impurities, notably water vapour, from both the surface and the bulk material. A nitrogen content of 0.2 % stabilizes the austenite and improves the yield strength (300 MPa). This stable austenite is non-magnetic, with a relative permeability of below 1.005 and a vanishing magnetic remanence. It can well be machined and welded.

2.1.3 Copper plating of stainless steel

The necessary strength for larger cavities without buckling under atmospheric pressure can be obtained by using a stainless steel body with galvanic deposition or cladding of a copper layer of a thickness of at least several skin-depths.

Galvanic deposition (electroplating) of copper on stainless steel is possible, but requires some care to assure adhesion. After degreasing and – if necessary – de-oxidizing, the surface is activated in sulphuric acid, rinsed, and activated in hydrochloric acid. Since copper does not adhere directly to steel, the next step is the galvanic deposition of a 2- μm nickel layer from a bath of nickel chloride, boric acid and hydrochloric acid. After rinsing, the bath for copper deposition consists of copper sulphate, sulphuric acid and salt. With a current density of about 4 A dm⁻², layers of some tens of microns can be easily obtained. Afterwards, rinsing and passivation in a bath containing chromic acid and sulphuric acid is necessary.

To assure a regular thickness of the copper layer even with an irregular shape of the RF structure to be plated, a special anode has to be fabricated, adapted to this shape. If this anode is made from platinum-coated titanium, it resists the chemicals and can be re-used.

During the electroplating process, gas forms at the anode. To prevent this gas from forming bubbles in areas that are to be copper-plated, the bath normally has to be agitated during the process. This also helps to assure that the ion concentration does not become locally depleted.

Figure 1: Inside view of a copper plated stainless steel cavity.

Figure 1 shows the inside view of a large stainless steel cavity (diameter 1.6 m) with a 40- μm layer of electroplated copper.

2.1.4 Other metals

Some cavities have been successfully made of aluminium, but aluminium tends to form an oxide layer on its surface, which has a high secondary emission yield and consequently is prone to multipactor.

For special requirements, e.g. to obtain very high accelerating gradients (on the order of 150 MV/m), as currently under study for the CLIC 30 GHz main linac structures, one might consider using metals with lower vacuum pressure and higher melting temperature, like Mo or W. First results with these materials are encouraging. Figure 2 shows machined tungsten irises for high gradient test cavities at 30 GHz [1].

Figure 2: Tungsten irises prepared for a test structure at 30 GHz.

Although not treated here, it should be mentioned that the preferred metal for superconducting accelerating structures is Nb. Either bulk niobium is used, or it can be sputtered on the inside of copper cavities, which may save cost. The most remarkable progress however in terms of maximum obtainable surface fields has been made using pure niobium, in particular over the last decade for the TESLA accelerating structures.

2.2 *Ceramics*

Ceramic materials are typically used in feed-throughs (windows) where low losses are required, or as damping materials.

Even though RF accelerating structures have to be under vacuum, some window for the RF power to be fed into them must be provided. RF windows sometimes have to transmit very high RF power. Even if the dielectric losses, characterized by the $\tan \delta$ (loss tangent) of the material, can be made very small, they are not negligible and cause the window to heat up. Since these windows are normally thin, cooling (edge cooling – i.e. the heat has to be transported through the thin window to its edge) can become a serious issue. At the same

time, the window has to withstand the atmospheric pressure, so the $\tan \delta$, the heat conductivity and the maximum tolerable bending stress are important characteristics of a window material.

The most frequently used materials for RF windows are ceramics like alumina (Al_2O_3 , sapphire if mono-crystalline), but also beryllia (BeO), silicon nitride (Si_3N_4) or others. Table 2 summarizes some parameters at room temperature of materials used for RF windows. Much experience with these materials has been gained with high CW power gyrotrons for fusion plasma

Table 2: Some characteristics of ceramics

	ϵ'_r	$\tan \delta$	density	elasticity modulus	bending strength	thermal conductivity
		10^{-5}	g cm^{-3}	GPa	MPa	$\text{W m}^{-1} \text{K}^{-1}$
BeO	6.7	70	2.85	345	140	260
Al_2O_3	7.5...11.5	50	3.99	385	410	30...40
Si_3N_4	7.84	30	3.4	320	800	59
diamond	5.67	2	3.52	1050	500	2000
SiC	2...14	20000	3.2	420	400	100

heating.

The table also includes SiC, which is not used as window material but, because of its high dielectric loss, rather as RF absorbing material, e.g. to damp higher-order modes. Mono-crystalline SiC is a semi-conductor – it is used in modern transistors. The behaviour of poly-crystalline SiC however is dominated by its density and purity. Reproducible values for the dielectric constant and the loss tangent could be obtained with high temperature (2600 °C) sintered, dense, undoped SiC. At 10 GHz e.g., the dielectric constant of this material was measured to be approximately 13 with a loss tangent of 0.2.

For completeness it must be mentioned that carbon loaded aluminium nitride and different ferrite materials are also used as RF absorbing materials. However, the magnetic properties of ferrites may not be compatible with the nearby presence of the beam and the beam-guiding magnetic elements.

3 Forming techniques

3.1 Casting and moulding

Casting and moulding are not normally relevant for the fabrication of RF accelerating structures, even though the blanks are normally die-cast.

3.2 Deformation forming

The different techniques of deformation forming of metals are forging, deep drawing, extruding, bending and rolling. Because of the limited precision of these forming techniques, they can not normally be used to render the final shape of RF accelerating structures, but they are relevant because of the effect of work-hardening, homogenizing and reduction of grain-size. As seen from Table 1 above, in particular copper changes its properties substantially when cold-worked. It must be considered however that when the material is deformed in only one dimension, e.g. when rolling sheets, the grains tend to deform anisotropically, which may result in an anisotropic inner structure. Inclusions and shrink holes may thus become long and subsequently may form channels, which may lead to vacuum leaks. Consequently, for certain applications 3-dimensional forging is obligatory.

Table 3: Surface roughness obtained with different machining operations.

Surface finish	N8	N7	N6	N5	N4	N3	N2	N1
<i>Ra</i> (µm)	3.2	1.6	0.8	0.4	0.2	0.1	0.05	0.025
drilling
turning
diamond machining
milling
lapping
EDM
polishing

roughness obtained with standard workshop practice

roughness obtained with special care

3.3 Machining

Modern machine tools like lathes and milling machines with numerical control allow obtaining excellent surface qualities along with small tolerances. Table 3 indicates the typical surface roughness that can be obtained by some classical machining operations. The maximum tolerable surface roughness on the inside wall of RF accelerating structures is a function of frequency; as a rule of thumb Ra should not exceed a quarter of the skin-depth.

3.3.1 Turning

Turning is a well controlled, reliable, precise and comparatively cheap machining technique. Consequently, already during the design phase of an RF accelerating structure one should consider using round geometries where possible.

Figure 3 shows turned discs for a 30-GHz disc-loaded accelerating structure, which probably present the limit of what is technically feasible. The inner part (the actual cavity) and two circular ridges have optical surface finish ($Ra = 15$ nm); the absolute tolerances realized were in the 2- μ m range. The outer diameter is 33 mm, the iris diameter 4 mm.

Figure 3: turned discs for a 30-GHz disc-loaded accelerating structure.

3.3.2 Milling

Modern milling machines allow achieving tolerances and surface finish comparable to that produced by good lathes.

Surface shapes of considerable complexity are possible with special CNC milling machines, which allow simultaneous control of 5 axis movements of the tool (x, y, z and two angles). Accelerating structures optimized for both strong damping of wake-fields and extremely high surface fields are now being studied for next-generation linear colliders (JLC/NLC and CLIC). These structures have complex shapes which could be realized using 5-axis milling. However, this technique is still relatively expensive today.

Figure 4 illustrates the possibilities of 5-axis milling with the help of a

Figure 4: Scale 1 mock-up of a 476-MHz cavity (PEP II) demonstrating 5-axis milling of cooling-water grooves.

simpler example, where grooves forming cooling water channels are machined into a mock-up of a PEP II cavity.

3.3.3 Diamond machining

For very high frequencies, for example for the accelerating structures considered for the next-generation linear colliders, tolerances in the μm range and optical

surface finish (of some tens of nanometres) are required. This can be obtained using mono-crystalline diamond cutting tools and possibly special lathes, like the cells shown above in Figure 3. Diamond tools are also available for milling where similar tolerances and surface finish have been obtained.

3.3.4 Cutting fluids

Cutting fluids need special attention since they may leave impurities at the metal surface, which limit the later performance and are difficult to clean off. While conventional cutting fluids may be used during rough machining, care has to be taken that only cutting fluids free of oil and sulphur are used for the final machining of surfaces that will later be exposed to vacuum, and consequently have to be extremely clean. Alcohol has been used successfully as a cutting fluid for this delicate last fine machining step.

3.3.5 Grinding

Grinding is used primarily to machine ceramics. Because of their hardness, ceramics cannot be cut like metals. Grinding allows obtaining similar precision and surface finish as milling.

3.3.6 Electric Discharge Machining

Electric discharge machining (EDM) is also known as spark erosion. There are basically two different types of EDM, as shown in Figure 5, die sinking and wire cutting.

Both the tungsten machining electrode and the workpiece are immersed in a dielectric liquid, normally water. An electrode under high voltage is made to approach the workpiece. A spark forms where the field concentration is highest, i.e. where the distance between electrode and workpiece is smallest; the workpiece is heated locally to around 10 000 °C and disintegrates here, whereas the electrode only wears off slightly. The eroded material is flushed away with the dielectric and the electrode can advance.

All conducting materials can be machined by electric discharge machining (EDM), including metals, carbides and graphites. Tolerances below 0.01 mm can be obtained with surface finish down to $Ra = 0.1 \mu\text{m}$. During EDM, no forces are exerted on the workpiece, so no stresses are induced, and the edges are free of burrs. Thin slots (0.3 mm, limited by the minimum wire thickness) can be machined.

Figure 5: Two different geometries suited for EDM: Left: die sinking, right: wire cutting.

3.3.7 Electro-polishing

Electro-polishing may be described as the inversion of the electroplating process described above. When the ion current through the electrolyte is inverted, the surface is attacked, and – because of field enhancement – more at protruding tips and less at hollows. This results in an overall smoothing of the surface and rounding of outer edges and corners. Electro-polishing is one of the processes for obtaining high surface fields in superconducting niobium cavities.

4 Joining techniques

When two workpieces of the same metallic material are heated locally above the melting temperature of the metal, this is welding. On the other hand, when a filler metal or alloy is used with a lower melting temperature than that of the two pieces to be joined (which can be different materials), this is brazing.

4.1 TIG welding

TIG (tungsten inert gas) welding is characterized by the use of an inert gas (Ar) flow to shield the heated area around the joint from the oxidizing atmosphere, and a non-consuming tungsten electrode from which an arc forms to the workpiece to heat it locally. TIG welding is a well established technique that can

produce good joints. However, thick components can be considerably deformed during the welding. Another disadvantage is that dissimilar metals or ceramics cannot be welded.

4.2 EBW

Electron-beam welding uses a finely (sub mm) focussed electron beam to vaporize (rather than melt) the workpiece near the joint to be. When joining copper pieces by EBW, the advantage compared to brazing is that only a small volume of copper is heated (annealed), while the bulk material will maintain its hardness. However, the workpieces have to be under vacuum. Joints between different metals are possible with EBW.

4.3 Brazing

Vacuum brazing is the preferred brazing technique. During the brazing process, the temperature will be such that the brazing alloy becomes liquid, and so the pieces and the brazing joint itself have to be designed such that a) the melted filler material moistens the joint surface well, in a controlled and regular fashion, that b) the pieces to be joined do not “float” out of their position while the brazing alloy is liquid, and that c) the liquid brazing alloy will not penetrate into the cavity and form drops inside, which would detune the cavity. In order to obtain a good braze, the surface should not be too smooth – a surface roughness Ra of 0.8 is considered appropriate.

When designing a joint fitting, a gap of about 0.02 to 0.05 mm should be provided to optimize the moistening. Figure 6 gives an idea of how a brazing stack of cells (cups) of an iris-loaded accelerating structure and the brazing joints could be designed. The grooves for the wires of brazing alloy are located about 5 mm from the edges, which allows the filler material to moisten a sufficiently large area around the groove, which assures vacuum tightness. Sharp corners are required at the inside to stop the liquid braze and thus prevent it from penetrating into the cavity. The sketch also suggests a method to centre the cups with external fittings.

Different brazing alloys behave differently when becoming liquid, and it requires experience and exact temperature control to attain the desired result. The most frequently used brazing alloys for vacuum brazing are

Figure 6: Sketch of a section through a brazing stack of an iris loaded structure, indicating the design of the brazing joint.

- Type I: Ag 72 %, Cu 28 %; B-Ag72Cu-780 (cf. ISO 3677); purity higher than 99.99 %,
- Type II: Ag 68.4 %, Cu 26.6 %, Pd 5 %; B-Ag68CuPd-807/810 (cf. ISO 3677); purity higher than 99.99 %,
- Type III: Ag 58.5 %, Cu 31.5 %, Pd 10 %; B-Ag58CuPd-824/852 (cf. ISO 3677); purity higher than 99.99 %.

The type I brazing alloy is a eutectic alloy with a melting temperature of 780 °C, the others have higher melting temperatures – the numbers given in their names indicate the fusing range in °C. More complex assemblies can be made using these different brazing alloys in consecutive brazing cycles at different temperature levels without re-melting a former brazing joint.

A typical brazing cycle is sketched in Figure 7. The slope during the heating and the duration of the flat top just below the melting temperature of the brazing

Figure 7: A typical brazing cycle, indicating temperature versus time

alloy are programmed as a function of the size and complexity of the assembly and will assure that the heating of the assembly is homogeneous.

Other brazing alloys are available for higher fusion temperatures (containing Au, with melting temperatures ranging from 910 to 1030 °C) and for lower fusion temperatures (containing In or Sn). However, not all filler materials are compatible with UHV; in particular they must not contain Zn or Cd.

So-called “active brazing alloys” (containing Ti) exist, which allow brazing to ceramics without prior metallization.

Brazing under vacuum requires a special furnace that can provide a vacuum better than 10^{-5} mbar at a working temperature of 1000 °C. In order to obtain uniform heating of large workpieces, the furnace must be equipped with a number of independent heating zones (typically molybdenum panels), controlled via a sufficient number of thermocouples connected to the workpiece. The temperature control (using a sufficient number of thermocouples on the workpiece) must allow temperature homogeneity and absolute precision in operation of a few degrees.

Another important feature of a vacuum brazing furnace is its closing mechanism: it must open and close without any shock or vibration, otherwise the

parts in the stacked assembly risk changing their relative positions before brazing.

When brazing workpieces of different materials, it must not be neglected that in vacuum the only heat exchange into and out of the workpieces is by radiation. Consequently, the workpieces will heat up and cool down at different rates, which may lead to temperature differences and differential stresses. The situation can be improved by slow heating as indicated in Figure 7 above. When brazing stainless steel flanges to a copper structure, e.g., it also helps to copper-plate the flanges prior to brazing.

As an example, Figure 8 shows an S-band accelerator structure during stacking in the vacuum brazing furnace (CTF3 drive beam accelerator). The waveguide-to-coax transitions at the coupler cell are for final RF tests and are to

Figure 8: Cells of an S-band accelerator structure being stacked inside a vacuum brazing furnace.

be removed before brazing.

A simpler furnace can be used when brazing under a controlled hydrogen atmosphere, a method that is also used to braze accelerator structures. However, the hydrogen tends to remain in grain boundaries near the surface, which subsequently requires bake-out to attain good vacuum.

4.4 Diffusion bonding

A diffusion bond is created between extremely smooth surfaces (optical finish) under high pressure ($> 10 \text{ N/mm}^2$) and temperature ($> 350 \text{ }^\circ\text{C}$). As opposed to brazing, no melting takes place, but the filler material (e.g. Ag) diffuses into the workpiece.

For the fabrication of CLIC 30-GHz accelerating structures a hybrid method was developed that combines direct diffusion bonding of copper (without filler material) with conventional brazing, which is illustrated in Figure 9. Since extremely flat and clean surfaces are required, the discs are diamond-turned with the required precision, and feature 1-mm-wide annular surfaces at the edges of the discs for the diffusion bond, as shown in Figure 3 above. Between these rings

Figure 9: Diffusion bond and brazing technique used for CLIC 30-GHz accelerator structures.

is an area with surface roughness and spacing suitable for normal vacuum brazing – this area will be filled with brazing alloy. A cavity Q of near 100 % of the theoretical values could be obtained by using this technique. At the same time, the diffusion bonds prevent braze from leaking into the structure.

5 Testing

Different types of tests are to be integrated into the fabrication process. Only these tests allow assuring the performance of the final accelerating structure and allow corrective action at early stages of the fabrication. Since many of these tests are industry standard, we will concentrate in the following on those specific to RF accelerating structures, i.e. tests of the RF properties, which allow us to predict the eventual performance.

5.1 Material testing

As mentioned above, many material properties are important and require a tight specification. On reception of the materials, some standard tests need to be performed. Some of these are, in particular for metals: chemical analysis,

Figure 10: Cell of the 3-GHz Drive Beam Accelerator of CERN's CLIC test facility 3 during automated dimensional control.

structural tests (inclusion content, grain size), ultrasonic tests, penetration test and other standard mechanical tests (elasticity, yield stress and tensile strength, elongation at break, hardness). Also some electrical properties like conductivity or magnetic permeability may require testing. For ceramics, measurement of the loss tangent at the operation frequency may be necessary.

5.2 Dimensional control

Dimensional controls will be necessary throughout the fabrication process. In particular the inner dimensions of the final structure are critical. For a standard travelling-wave accelerating structure e.g., the sensitivity of the frequency on an inner radius is approximately given by $\delta f/f \approx \delta r/r$, which for a typical S-band (3-GHz) structure e.g. translates to 100 kHz/ μm .

Figure 10 shows a cell of an S-band accelerator cell during a computerized dimensional test with conventional measuring tools. For ultra-high precision, non-touching sensors may be required. As an example for laser-interferometric control of surface flatness, Figure 11 shows the output from a flatness control of a RDDS (rounded damped detuned structure) cell for the NLC study [2].

5.3 Helium leak detection test

The vacuum level that can be obtained in later operation is determined by the outgassing rate of the materials used and the pumping speed applied. A prerequisite however is the leak tightness, which can be controlled by the helium leak test. Even small vacuum leaks should not be tolerated and must be repaired,

Figure 11: Interferometric measurement of surface flatness of an X-band accelerator cell (SLAC RDDS).

since in later operation they tend to grow.

The procedure for the helium leak detection test is the following: The device under test is connected via a turbo-molecular pumping station to a calibrated helium leak detector and immersed for 10 minutes in an atmosphere of helium (10^5 Pa = 1 bar He partial pressure). The helium leak rate signal is recorded during the entire immersion period. The detection limit of the calibrated helium leak detector must be checked immediately before the test. The leak detector is moved around the outside of the assembly under test. Leak rates down to 10^{-11} Pa · m³/s can be detected in this way.

During the manufacture of an accelerating structure it is advisable to perform leak tests of subassemblies.

5.4 RF properties

The most important properties to be tested for accelerating structures are of course those of relevant RF parameters. It is obvious that for a complicated assembly it is appropriate to test those properties at an early stage of the assembly process, such that corrections can still be made. For example, in a brazed multi-cell linac accelerating structure, one would be advised to control the correctness of the individual cells before the actual brazing.

Other RF relevant tests can be performed only after finishing the whole assembly: to test whether the accelerating structure can support the nominal input power and develop the nominal accelerating gradient, for example, requires conditioning of the structure, i.e. it has to be trained to attain those power levels. These power levels can normally be obtained only after conditioning.

An unconditioned surface tends to multipact, as we have mentioned above. Conditioning is a process of cleaning and smoothing the inner surfaces of the structure with the RF power, and driving the surface into controlled localized breakdown, and in particular it also modifies those inner surfaces such that the SEY is reduced. For copper surfaces, the maximum SEY occurs typically at a few hundred eV, and is reduced during conditioning from about 1.6 to below 1.3. Conditioning can last from a few hours to a few days, depending on the duty cycle and the geometry of the accelerating structure. It requires patience and good control of the power and the controlled breakdown activities in the cavity, e.g. by careful monitoring of the vacuum gauges.

5.4.1 Single cell frequency measurement

As an example of a single frequency test we consider a travelling-wave accelerating structure with a phase advance of 120° per cell (or a cell length of $\lambda/3$ in the case of an electron accelerator). Since for a single cell one cannot easily reproduce a boundary condition equivalent to a phase advance of 120° , one could either measure the resonant modes of a unit of 3 cells, which can be short-circuited at both ends, or one could think of a special, well characterized device in which a single cell is mounted, thus allowing measurement of the 0-mode and the π -mode of this assembly, and calculate the resulting $2\pi/3$ -mode.

The validity of computing the $2\pi/3$ -mode from the 0- and π -mode must of course be checked (for example with a field simulation program), but for a typical structure of this type, where the next higher-order mode (HOM) is relatively far away, the dispersion curve of the first pass-band can be modelled to a high accuracy by the simple formula

$$2f^2 = f_0^2 + f_\pi^2 + (f_0^2 - f_\pi^2)\cos(\varphi),$$

where f is the frequency for phase advance φ , and f_0 and f_π are the measured resonance frequencies of the 0- and π -mode, respectively. Figure 12 shows the dispersion characteristic of an S-band accelerating structure, designed for operation at a phase advance of 120° , which for this case is indistinguishable

Figure 12: Dispersion diagram of a $2\pi/3$ structure indicating 0- and π -mode.

from the approximate formula above.

The single-cell measurement described here thus allows checking the RF property of a cell for the travelling-wave accelerating mode by the relatively simple measurement of the 0- and π -mode. However, since such a measurement – or any other frequency measurement of a vacuum cavity – is normally done in air under atmospheric pressure, the measured frequencies must be corrected for the dielectric constant of air and – in general – also for the ambient temperature which may be different from the temperature at which the structure will be operated. The dielectric constant of air at 20 °C and 60 % humidity is approximately 1.0006, which will lower the frequency by 0.3 ‰ from its vacuum value. The ambient temperature influences primarily the linear dimensions of the accelerating structure itself and changes the frequency according to $\delta f/f \approx -\alpha_l \cdot \delta T$; with the thermal expansion coefficient of Cu ($\alpha_l \approx 16.5 \cdot 10^{-6} \text{ K}^{-1}$) e.g., this results in -50 kHz/K for a 3-GHz structure.

5.4.2 Bead-pull measurement

The bead-pull measurement is based on the fact that a small object (the bead) perturbs the field at its position, and causes a reflection proportional to the electric field-energy at that position. This allows sensing the field distribution in the accelerating structure, when measuring the reflection coefficient at its input port while dragging the bead along its axis. A vector network analyser (NWA) is connected to the input port of the structure as shown in Figure 13 and operated at a fixed frequency, which should correspond to the operating frequency, corrected for the temperature and the atmosphere present inside the structure (see above). The network analyser is set to S_{11} measurement and to polar display, calibrated to indicate zero for the structure without perturbation.

When the bead is now moved through the structure, S_{11} will change its amplitude and phase as a function of the position of the bead – it will be large when the bead is at a position of large electric field (in the centre of each gap), and small in regions of small electric field (in the iris). At the same time, the phase of the reflection coefficient will vary as twice the phase advance of the field. While the perturbing bead is moving through the structure, the complex input reflection will thus describe a locus on the polar display of the NWA.

Figure 13: Schematic set-up for a bead-pull measurement to determine the phase advance in an iris-loaded structure

As an example, we will again consider an accelerating structure with a nominal phase advance of 120° per cell, but the method can be adapted to other phase advances following the same idea. Figure 14 shows the principle shape of this locus: it starts at zero for the bead outside the structure, rises with constant phase while the bead enters through the cut-off beam pipe into the coupler cell, and subsequently describes a regular pattern, advancing in phase by $2 \cdot 120^\circ$ when the bead advances by one cell. Thus the phase advance error and amplitude imbalance will clearly show.

Figure 14: Locus of the complex reflection coefficient while the bead is moving through the accelerating structure.

A possible way to correct for these errors is to prepare the individual cells for “dimple tuning,” i.e. to locally deform the cavity wall. A more detailed description of this method can be found in Ref. [3].

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