Mechanical Design and Manufacture of Microwave Structures*

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Summary—**The paper gives an account of the various aspects of the design and manufacture of microwave structures. The presentation of design information such as dimensions and tolerances is first discussed. Machining and other fabrication processes are then examined. Several methods of metal casting and associated techniques are described and the electrodeposition of waveguide components studied. Such final stages as inspection procedure, protective finishing and packaging are considered. The survey concludes with a bibliography.**

ENGINEERING FEATURES

Design Information

RECENT developments in microwave engineering have, to a large extent, been devoted to improved methods of design, manufacture and inspection. The essential parts of microwave structures are the surfaces which carry RF currents and the volumes in or around which the electric and magnetic fields exist. These parts are invariably internal and since they are required to be accurate in dimensions and smooth in surface their manufacture has presented special problems. There are currently a large number of manufacturing processes [68], [99], and several of these have been found [8] satisfactory for microwave structures. In the choice of a suitable method, the technical considerations to be taken into account include complexity and accessibility of replaceable components, reliability, reproducibility, possible multiplicity of techniques, size, and weight.

The bulk and weight of microwave assemblies can be reduced by employing compact types of transmission systems, *e.g.*, strip-line, dielectric-filled, and ridged waveguides. An alternative method consists in the use of topological rearrangement so as to form a compact configuration of components. This can be obtained by the elimination, as far as possible, of couplings, corners, twists, and conversion adaptors, to give an integrated assembly requiring less drawing and office work, and possessing greater robustness and simplicity of manufacture.

Miniaturization and simplification are achieved in the micromaze construction of Lewin [62]. An example is shown in Fig. 1(a). An integrated planar assembly was obtained by milling slots in a base- and cover-plate, into which partitions were inserted, thereby creating several waveguide channels side by side. Such built-in elements as hybrids, directional couplers, and filters, employed multipost construction [22]. The planar integrated assemblies described by Jamieson [52], [53] are suitable for structures containing hybrid rings and directional couplers. They permit several methods of manufacture and are economical for quantities of order of 100 off. An example is shown in Fig. 1(b).

Microwave structures are relatively expensive to manufacture and thus economy of the over-all production process is important. The cost of manufacture can be kept low by methods of mass production, because the special tool costs are spread over a number of items. This implies a degree of standardization of the product while consistency and good technique are obtained from specialization.

The ultimate inspection and testing of the article have an influence on the design. A high production yield, or diminished manufacturing cost can be achieved by relaxation of tolerances as much as possible. On the other hand, if the tolerances specified for individual parts are too lax, then the cost of rejection due to testing of and selection for the final complete assembly becomes high. Thus, it is evident that there is an optimum set of design tolerances. This optimum will, of course, be a function of the method of manufacture, procedure of testing, number of items produced, and other parameters.

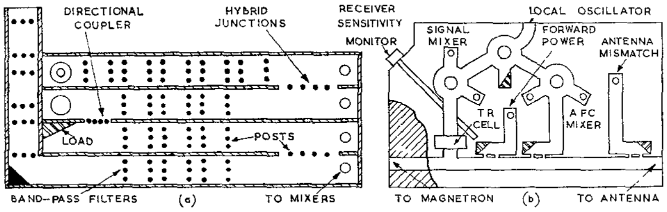

Fig. 1—Planar construction of microwave assemblies; (a) microwave repeater for 4 kmc using $2\times\frac{2}{3}$-inch waveguide, (b) typical RF head for 9.5 kmc using 0.9×0.4-inch waveguide.

Dimensions and Tolerances

To insure that the ultimate electrical performance of a microwave structure is satisfactory, it is necessary that drawings and specifications should state the exact manufacturing requirements in engineering terms. If the drawing merely outlines the conditions of mechanical interchangeability, then only minimum necessary data, often called control information, need be included. For example, in the bolted-type coupling shown in Fig. 2, the control information would include the diameters, the positions and lengths of the clamping holes, the squareness of the mating face, and the calling up of particular mechanical gauges. If, on the other hand, the drawing is intended for manufacturing purposes, addi-

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* Manuscript received by the PGMTT, March 30, 1959.

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tional information would, in this instance, include material, secondary dimensions and tolerances, provision of chamfers, and surface finish.

The nominal dimensions in any given design are usually obtained by theoretical calculation and by electrical measurements on a prototype model. The guide wavelength and characteristic impedance of a waveguide depend on its cross section; since microwave structures are often resonant or contain critically spaced admittances, the dimensions of the internal volumes must be closely controlled. In practice, the tolerances required are 1/2000 to 1/10,000 of the free-space wavelength and thus range from 0.001 to 0.00001 inch over the microwave region according to the type of instrument or component. The small radius in the corners of rectangular waveguide modifies slightly the characteristic impedance. If this change is restricted to one part in 1000, then the permissible radii range from 0.002 to 0.050 inch depending upon the guide size.

The effect of a change in a nominal dimension on the electrical performance is not easy to obtain from practical data, and it is necessary to break down a structure into simple elements such as irises, transformers, posts, and teejunctions. The behavior of these can then be examined individually with regard to tolerances and the structure built up again, making due allowance for cancellation effects.

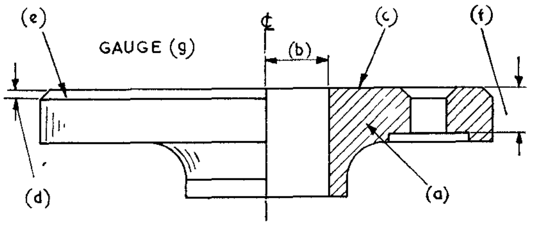


Fig. 2—Typical parameters requested on a drawing; (a) material, (b) toleranced dimensions, (c) surface texture, (d) flatness and squareness, (e) chamfers on mating face, (f) spot facing, and (g) use of inspection gauges.

As an example, Fig. 3 gives the tolerance on the width of an asymmetrical inductive obstacle of zero thickness plotted as a function of this width, both dimensions being expressed in terms of the cross section of the waveguide. The curves are constructed on the assumption that the obstacle is used as a matching device, the performance parameter being a/λ_g times the imaginary part of the reflection coefficient. Tolerances of the same order have been shown, in unpublished work by W. B. W. Alison, to exist for other types of elements and obstacles of both zero and finite thickness.

Tolerances tend to be especially close in structures such as rotating joints and polarizers where more than one mode may be propagated. For example, slight ellipticity in a nominally circular waveguide may cause a relative phase shift of two mutually perpendicular plane TE_{11} modes [80]. This means that both a circularly polarized and a plane polarized wave would be rendered elliptical by an imperfect waveguide. The phase errors have been examined in unpublished work by G. J. Rich and T. B. A. Senior. They may be calculated from the curve of Fig. 4 by taking the value of K and inserting it into

$$\phi = K(a - b)/a \qquad (1)$$

where ϕ is the phase slip in terms of the nominal guide-wavelength and a and b are, respectively, the major and minor axes. For example, at a frequency of 9.375 kmc and a tube of diameter 0.875 inch, one meter in length, phase slips of 1.6° and 90° would be obtained for differences of diameter of 0.0001 and 0.005 inch, respectively.

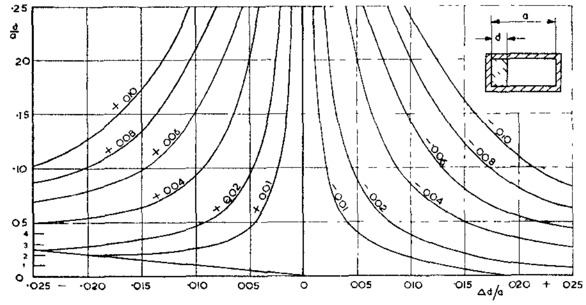


Fig. 3—Effect of dimensional tolerance on electrical performance. The figures on the curves are a/λ_g times the imaginary part of the reflection coefficient.

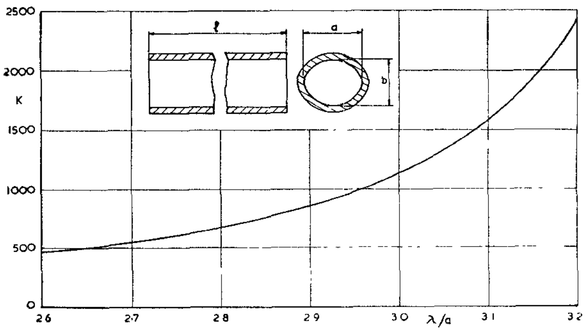


Fig. 4—Computation of phase errors in deformed circular guide.

A microwave structure will normally contain a number of toleranced dimensions and, if allowance were made for the worst case of all tolerances being unfavorable, then they would have to be unnecessarily close. Statistical relations between VSWR and attenuation and the magnitude and spacing of discontinuities in microwave structures were derived by Moore [67] and Mullen and Pritchard [71]. Their analyses assumed that the complex voltage reflection coefficients are small and additive so that

$$\hat{\rho} = \sum_{i=1}^{N} \rho_i e^{2j\theta_i}. \qquad (2)$$

It was further assumed that the line lengths between discontinuities are independent of each other, that all values of θ between 0 and 2π are equally probable and that the total number of discontinuities is large, say, $N>8$. It was shown that the over-all reflection coefficient has the Rayleigh distribution

$$W(\rho) = (\rho/\rho_m{}^2)e^{-\rho^2}/2\rho_m{}^2 \tag{3}$$

where ρ_m is the most probable value of ρ.

If ρ_0 is the rms value of the ρ's, then

$$\rho_m = (N/2)^{1/2}\rho_0. \tag{4}$$

The probability $P(\rho)$ that the reflection factor is less than ρ is given by

$$\begin{aligned} P(\rho) &= \int_0^\rho W(\rho)d\rho \\ &= 1 - e^{-\rho^2/2\rho_m{}^2}. \end{aligned} \tag{5}$$

This result may also be expressed in terms of S, the VSWR, as follows:

$$P(S) = 1 - \exp\left\{-\frac{1}{2}\left(\frac{S-1}{S+1}\right)^2\left(\frac{S_m+1}{S_m-1}\right)^2\right\}. \tag{6}$$

This value of $P(S)$ is plotted in Fig. 5(a) against S, with S_m as parameter. These curves can be used to compute the probability that, among a large number of possible designs with the same set of discontinuities, the VSWR of a particular design will be less than S.

Further results can be obtained if ρ' is defined as that reflection coefficient which there is only a 10 per cent probability of exceeding. Using (5),

$$\rho' = 1.52N^{1/2}\rho_0 \tag{7}$$

and the corresponding S' is plotted in Fig. 5(b) against S_0 for representative values of N. These curves permit a designer to predict, given a number of discontinuities and their typical values, a result for the over-all VSWR.

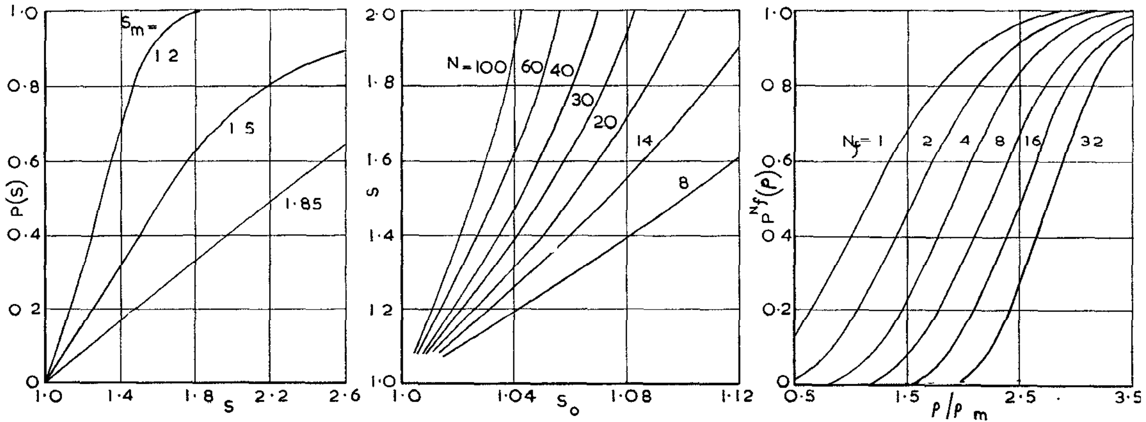
The effect of variation of frequency was considered as a sampling problem. When the frequency has changed sufficiently for the average electrical length between discontinuities to change by π, the individual reflection coefficients have changed their phases enough so that their sum can be considered as a new random variable. On this basis N_f, the number of independent frequency points spaced by Δf, is given by

$$N_f = f_b/\Delta f = 2f_b l/f\lambda \tag{8}$$

where f_b, l, f, and λ are, respectively, the bandwidth, line length, frequency, and wavelength. The joint probability that, at the N_f frequency points, there will be N_f cases when the reflection coefficient is less than ρ, is simply $P^{N_f}(\rho)$. The value of $P^{N_f}(\rho)$ is plotted in Fig. 5(c), using the normalized abscissa ρ/ρ_m with N_f a parameter.

In the specification of microwave structures, an upper limit should be given to the roughness [36] of the internal surfaces. The various grades of surface texture have been standardized [122] and are expressed, either as the rms or center-line-average height of the irregularities, in the range of 1–1000 microinches. For the short lengths of transmission line normally encountered in the average microwave equipment or when operation is at relatively low frequencies, a fine surface texture is not necessary. It becomes more important in the case of high Q-factor resonant cavities and in equipment for millimeter wavelengths. For general purposes [109] the surface roughness should not exceed about one half the electrical skin depth and thus, according to the frequency and material employed, values from 2–63 microinches are usually specified.

It is generally the primary texture, or roughness resulting from the action of the tool, which is of concern. The effect of secondary texture such as long-period waviness, resulting from imperfections in the performance of the tool, is small provided that, as is usual, the depths of the irregularities are much less than a wavelength and are within the specified dimensional tolerances. In those operations which produce a surface texture having a directional quality or lay, the method of manufacture should be such that this is parallel to the current flow where the latter is unidirectional.



(a) (b) (c)

Fig. 5—Statistical distribution of reflection coefficients; (a) cumulative probability of VSWR, (b) VSWR exceeded in only 10 per cent of cases, (c) cumulative probability that the reflection coefficient is less than ρ in a frequency band f_b.

MACHINING AND ALLIED PROCESSES

Precision Machining

The manufacture of microwave structures, which demand dimensional accuracy and good surface finish, has always relied to a large extent upon precision machining involving skilled labor and high-grade machine tools. Some economy is achieved by the use of copying methods involving jigs or templates; these may take the actual form of the work or may exercise control remotely by mechanical or electronic means. Such tools are special to the particular item produced and their use is justified only for large quantities.

One of the simplest copy tools is a drilling jig for machining accurately-positioned holes. The use of fixtures enables broaching to be employed for the manufacture of microwave components. By commencing with an undersize circular hole, the use of a series of broaches enables parallel-sided sections of a variety of shapes to be obtained with high accuracy and good surface finish. If the teeth are omitted from one or more faces of the broach, then channels can be formed in mating pieces of metal. A machined face with, say, choke and gasket grooves can be turned by the use of a form tool; a similar technique can also be used for milling. Another tool method is copy milling in which the cutters are controlled, by means of a pantograph mechanism, from a master pattern.

Large quantities involving elaborate machining might justify the use of such automation techniques as electronic machine control. In these systems, operations like drilling, turning, or milling are controlled by numerical information supplied by magnetic or paper tape, punched cards, or hand setting on control knobs. This involves an extra process—that of translating the spatial information from the drawing or design into numerical control signals—which, once done, will enable the electronic control system to carry out the various processes with the maximum speed at which the machine tool is capable of operating. While the accuracy of the measuring and positioning devices may be as good as 0.0001 inch, the over-all accuracy of setting depends on other factors as well and may be about 0.0005 inch. The control methods employed fall into two main groups.

In discrete position control, the work piece is brought up to the operating tool in a series of fixed positions. For example, the work table of the machine has to be moved in two dimensions under the control of numerical information on the x and y coordinates of, say, the hole to be drilled. When the required point is under the drilling tool, the worktable is brought to rest by a form of servomechanism operated by an error signal generated by the difference between the control setting and the position of the worktable.

The method of continuous position control in which the work moves continuously past the tool is more complicated. The general principle for, say, milling a piece part to a certain contour is that the numerical input information provides sets of coordinates of marker points defining the contour while a computer interpolates the intervening points in suitable curves. In one design, the output of the computer consists of sets of pulses which specify completely the contour to be machined in terms of increments of distance from a given reference plane.

As an example of the process times involved, some data are given [51] for different methods of milling a planar integrated waveguide assembly. Precise milling operations, with a Kearney-and-Trecker machine, on rolled aluminum sheet required a time of 35 hours, and the use of precast blocks to eliminate the initial rough milling did not appear to be justified economically. The use of a Gorton copy-mill reduced the time to ten hours, while a Tracemaster machine, using hydraulic control and a power feed, reduced the machining time to five hours. Best results were obtained with an electronic-control power-driven milling machine which carried out the operations in a time of two hours. In all cases, the design accuracy of ±0.001 inch was maintained.

Pressing and Hobbing

Pressing: Several methods of manufacture are based on the shaping of metal. Waveguide tubing of rectangular, circular and ridged cross section is invariably made by a drawing process [100] from a cylindrical billet. A variety of materials can be worked, and a bonded silver-sheath can, for example, be included inside a stainless-steel waveguide to give good conductivity and high mechanical strength. This method of manufacture is employed for sections ranging from 0.080 by 0.040 inch up to 11.50 by 5.75 inches. A small radius is required on the internal and external corners to give a reasonable life to the drawing dies.

Microwave components can be made from thin metal sheet by pressing it into U-shaped sections which are then soldered or riveted together to form the required shape. Contact shims can be made by stamping processes. Hot stamping of brass and other nonferrous metals is often employed. Typical examples are coupling flanges for waveguides of sections 0.50 by 0.25 inch to 6.50 by 3.25 inches.

Extrusion is a hot process carried out at a temperature near the plastic range of the metal. It has been used for the production of aluminum waveguide tubing. In impact extrusion, the component is formed under high pressure and may be used with metals such as magnesium. A pellet or small ingot is placed on the lower half of a hardened press tool which has the inner form of the component. The upper half of the tool takes the shape of the exterior. As the press closes, both the pellet and tool being preheated, the metal is displaced to fill the cavity and thus forms the component.

Hobbing: In the process known as hobbing, a hardened steel tool, termed a hob and machined and ground to a male replica of the required internal section, is pressed slowly into a metal blank and then withdrawn. The dimensions and form of the master are faithfully reproduced and no additional machining is required. Adequate support against bursting is required around the cavity and, to avoid providing excess material which subsequently has to be removed, it is usual practice to place the blank in a close-fitting bolster or nest made of nickel-chrome or other suitable steel. A typical arrangement is shown in Fig. 6. The press containing the hob should have a double-acting plunger and possess adequate capacity; a 200-ton bridge-press with pneumatic control has been found satisfactory for the hobbing of microwave structures. The length of the blank usually exceeds that of the cavity required in the finished component so that there is no need to force the hob right through the blank.

Microphotographs of etched sections of hobbed blanks have shown that this process involves considerable plastic flow of the material in both radial and axial directions [114]. This flow places limitations on the shapes of cavities that can be hobbed, but, even so, the method can be employed for a variety of sections ranging from the simple to the quite complicated. Only symmetrical structures can be hobbed and, to avoid the risk of tool breakage, the length of the cavity should preferably not exceed eight times the larger cross-sectional dimension.

Although iron and steel can be hobbed, the plastic flow of the material tends to favor the selection of nonferrous metals such as aluminum, brass and copper. Aluminum of 99 per cent purity, such as materials to BSS 1476EIC or 2L34, may be hobbed cold using a mineral-oil lubrication. Copper and brass, in view of their rapid work hardening, require heating to about 800°C before hobbing. This is preferably carried out in an electric muffle furnace, from which the blank is then transferred rapidly to its bolster. After hobbing, a period of 30 seconds is allowed to elapse, after which the blank, with hob in position, is quenched in water. The hob is then extracted cold, a process which gives minimum shrinkage, accurate dimensions, and good surface finish. Suitable materials are oxygen-free copper, and brass to BSS 251 which contains 61 per cent copper and $1/1\frac{1}{2}$ per cent tin; brass containing lead tends to crack and is thus not suitable.

Unless the dimensions are very small, the wear on hobs during use is negligible and they are thus ground to the size of the finished cavity, making a small shrinkage allowance in the case of hot hobbing. A small chamfer of about 0.001 inch is necessary on all sharp exterior angles to prevent cracks and splintering due to stress concentration. The hob is usually provided with a large head fitted with a flat face or collar to take the force applied by the press.

The steel used for the hob must be capable of deep hardening without distortion and must be of a dense, tough structure capable of withstanding compression loads up to 200 tons/inch^2. It must not "pick up" the softer metal of the blank and must permit smooth and easy withdrawal of the hob. In hot hobbing the material must be such that its temper is not drawn. A material found suitable for cold hobbing is 18 per cent tungsten high-speed steel; the other constituents being 0.75 per cent carbon, 4.5 per cent chromium, and 1.2 per cent vanadium. After heat treatment in two stages at 400–500°C, it is hardened at 1300°C, quenched in oil and tempered. The hardness figure required is about C62 Rockwell, with an ultimate tensile strength of 135 tons/inch^2. This material may also be used for hot hobbing, where maximum strength is desired, but an alternative for normal hobs, which retains its characteristics for a considerable period under hot working conditions, is an 8.5 per cent tungsten hot-die steel: the other constituents are 0.26 per cent carbon, 3.0 per cent chromium, 0.25 per cent vanadium, 0.5 per cent molybdenum, and 2.5 per cent nickel. After heat treatment at 800–850°C it is hardened at 1050–1100°C, quenched in oil and tempered to a hardness of C47 Rockwell and a tensile strength of 100 tons/inch^2.

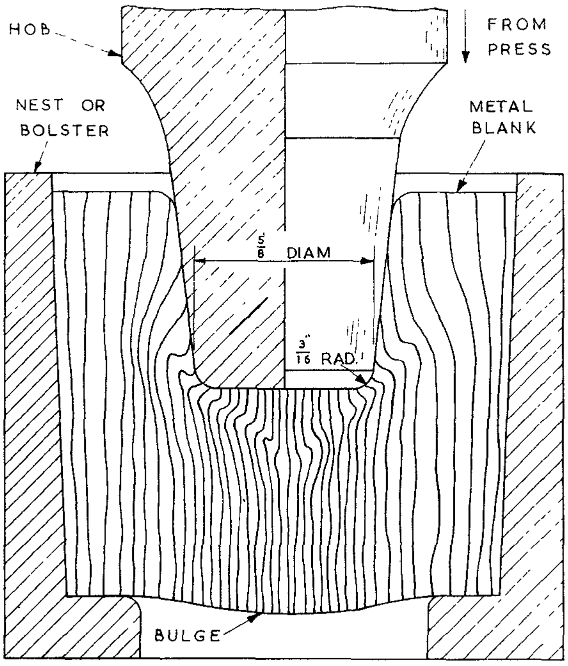


Fig. 6—Hobbing a metal blank. The general arrangement also shows the lines of flow in the metal.

Hobbing has found considerable application in the production of hollow structures with parallel, stepped, or tapered sides. The requirement of insertion and withdrawal of the tool does, however, mean that re-entrant shapes cannot be formed. The outside surfaces of the blank are machined to remove surplus metal and correct for the distortion which takes place during hobbing. The accuracy obtainable depends upon the complexity, but 0.001 inch is easily obtained with 0.0002 inch as a lower limit, and the repeatability of the dimensions is usually within 0.0001 inch. The surface finish depends upon the material of the blank but may be as good as four microinches, while the bulk metal is nonporous and will withstand vacuum or high pressure.

A hob and an 18-vane magnetron anode made from it are shown in Fig. 7(a). In order to obtain a square shoulder, the hob is reduced in section and brazed into its holder. The hob shown in Fig. 7(b) was employed for producing an item containing two blind semicircular choke-grooves, 0.125 inch wide by 0.375 inch deep and 0.687 inch in radius, positioned in relation to the rectangular aperture of 0.90 by 0.40 inch within ±0.001 inch [118]. A simple taper between rectangular waveguides can be made by means of the hob in Fig. 7(c), while the H-section aperture in Fig. 7(d) is an example of a component which could not otherwise be made.

Spark Machining

The spark-machining or erosion process was developed [63], [82], [111] mainly for producing holes in hard steels, but it has also proved useful in forming small apertures of complicated shape in microwave structures. The general arrangement is shown in Fig. 8, from which it will be seen that the process relies basically on an electrical discharge or spark taking place between an electrode and the workpiece. The discharges occur in rapid succession and the erosive action is greatly intensified by submerging both tool and workpiece in a suitable dielectric such as paraffin or light oil. Apart from cooling, the incompressibility of the liquid restricts energy release to a much smaller space, resulting in a considerable increase in energy density.

The cutting action starts when the gap between the tool electrode and the workpiece is narrowed down to the breakdown voltage. At the point of highest field strength, a spark will pass, pitting the workpiece and, to a smaller extent, the tool. The next spark will similarly discharge at another point where the field strength happens to be highest, and this process will be repeated, the spark always following the locus of the highest field strength.

The energy of the spark is derived from a bank of capacitors which is charged through a resistance from a high-voltage dc supply; the discharge takes place at the optimum voltage. The spark frequency is limited to about 10 kc by de-ionization effects in the gap. The total capacitance of the capacitors determines the intensity of the spark. This intensity affects the speed of cutting and the surface finish—the larger the spark the faster the rate of cutting but the rougher or more pitted the surface. There are a number of machines specially designed for this process. The U.K. examples of the "Sparcatron" made by Impregnated Diamond Products, the "Erodomatic" of Wickman, and the "G.K.N." of Welsh Metal Industries are typical.

In practice, there is a clearance of only 0.003 inch between the electrode and workpiece, and thus quite intricate forms can be produced. The choice of electrode material depends on the metal being machined and is important in view of the considerable wear which takes place. Normally the electrode wears or erodes at about one sixth the speed of the workpiece, and thus the hole is initially slightly tapered. This is eliminated when the electrode has passed through the work, for the unused portion opens up the hole to the correct size. Dimensional accuracy of the order of ±0.002 inch/inch with a surface finish of 20–30 microinches can usually be achieved. In the illustration, the small transverse and longitudinal slots in a directional coupler are being spark machined; several are being done at one operation to save time. Spark machining has also proved satisfactory for linear antenna arrays with slots cut in the broad face and anode blocks of millimeter-wave magnetrons.

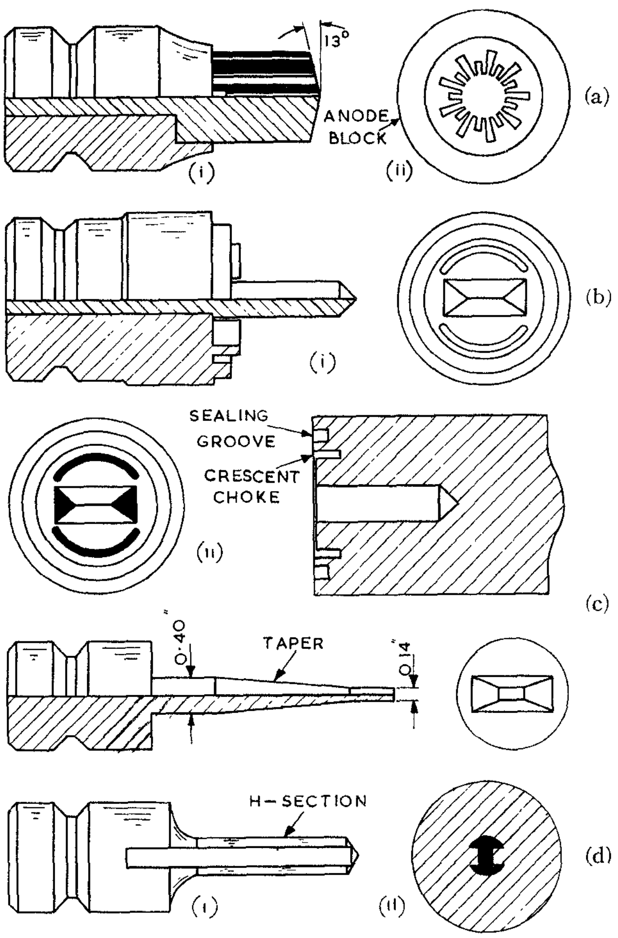


Fig. 7—Typical hobs and finished parts. The hobs are shown in (c) and in (i) of (a), (b), and (d); while the articles so formed are shown in (ii) of (a), (b), and (d).

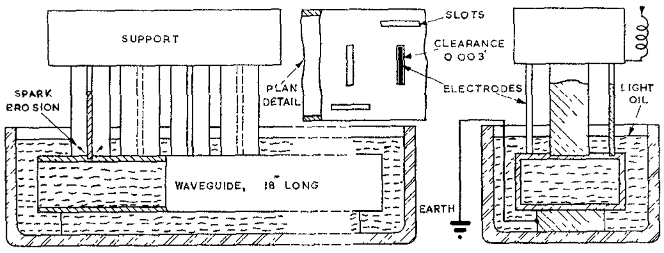


Fig. 8—Manufacture by spark machining. Example shown is a multiple-slot directional-coupler in 0.9- by 0.4-inch ID, 0.05-inch wall, waveguide. The operation is half completed.

METHODS OF FABRICATION

Soldering and Brazing

Waveguides in very small sizes, lightly-stressed components-supported inside equipment, and accurate test gear are usually designed for assembly by soft soldering, since the low temperatures involved minimize distortion [65]. Where mechanical strength and fatigue resistance are required, the parts are usually assembled by brazing [11]–[13]; this is a process in which the metals are joined without raising them to their melting point, by the use of a filler alloy of lower melting temperature which is drawn along the joint by capillary action [5]. Copper brazing [98] as well as the medium-temperature Easiflo processes may be employed. For complicated assemblies and production quantities, some suitable methods are furnace brazing, surface heating and induction heating, where temperature and operational times can be closely controlled [24].

Light alloys of aluminum and magnesium are often employed in the construction of microwave components [1], [84]. Such structures may be held together with epoxide resins [35] such as Araldite [70], provided some mechanical pinning is incorporated to give alignment and strength. The soldering and brazing of, for example, aluminum presents difficulties due to the film of oxide which rapidly forms on the surface. This oxide is refractory and requires active fluxes at high temperature for removal.

In one method of assembly, the contact areas are electroplated with copper and, after tinning, joined with soft solder. The oxide film can be removed at low temperatures by various forms of vibratory soldering irons [73], [96], thus enabling tinning and subsequent soft soldering to take place. Such joints, because of the combination of metals present, are liable to corrode; but one example, after being coated with Araldite and cured at 130°C for 7 hours, successfully withstood humidity and salt-spray tests [107].

A number of special aluminium soft solders have been employed for microwave components [6], [112]. Zinc-based alloys have an operating temperature of 450°C to 500°C, but their penetration in lap joints tends to be variable. Another alloy contains 67 per cent cadmium and 33 per cent zinc, but its melting range of 265°C to 310°C puts its operating temperature above the satisfactory range for ultrasonic iron and organic flux application, and it therefore has to be applied to the aluminum surfaces by scratching methods. There are one or two tin-rich solders, *e.g.*, 76 per cent tin, 20 per cent zinc, 4 per cent aluminum, which have given satisfactory corrosion results but, in general, these results become increasingly suspect with solders rich in tin, cadmium, and lead; *i.e.*, the lower melting-range solders. One product, with a working temperature of 200°C, showed signs of corrosion after humidity tests.

Stronger and more reliable joints can be made with processes which employ pure aluminum, such as argon-arc welding [66]. The parts may then be given protection against corrosion [107], [121] by anodizing. A similar advantage exists with brazing processes [57], [91], [102]. The fillter rods used are of an aluminum-silicon alloy with a melting temperature some 50°C below that of the metals to be joined. The parts should be degreased and scratch-brushed to reduce the thickness of oxide. A suitable flux, preferably as a distilled-water suspension, is applied to the surfaces to be joined and also to the filler rod. The joints should preferably be of the lap type, and gaps should be of 0.005–0.015 inch and preferably tapered to assist the capillary flow of the filler. Flame brazing requires skill, but has been employed, for example, in the assembly of coupling flanges on waveguide tubing.

In dip-brazing, the component parts, which must be made of nearly pure aluminum and be suitably supported, are immersed in a bath at brazing temperature. Where jigs or fixtures are used, Wernz recommends that they be designed specifically for dip-brazing, since experience proves that hooked springs with locking bars, springs with key-hole slots, and similar holding devices are the most satisfactory [97]. The fixture body must be adequately braced to avoid warping during heating or cooling and, if necessary, provided with supporting legs. Fixtures should be made of materials such as Inconel, Nimonic, nickel and some stainless steels.

In salt-bath or flux-dip brazing, the joints are filled with a material rich in aluminum [17], [92]. The whole assembly is then immersed in a mixture of salts which acts as a flux and also raises the temperature to a value in excess of the melting point of the filler but below that of the aluminum. In such dip-brazing processes distortion is eliminated and cleaner and more uniform joints are obtained.

In another bath process, the joints are painted with flux and the assembly is immersed in a special alloy containing silicon in solution [104]. The aluminum oxide film is removed under the action of the hot flux, and the metal along the joints takes in silicon from the solution, forming an alloy with a eutectic melting-temperature below that of the bath. The joint is thus made with a molten metallic deposit. The aluminum still continues to absorb silicon and, as the alloy changes in composition, so its melting point eventually rises above the bath temperature, thus enabling the parts to be removed.

A technique of self-jigging of waveguide components, providing lighter and more flexible designs, involves the use of brazing-alloy-clad aluminum sheet [108]. This sheet is punched to the required size and shape and assembled by an interlocking tag-and-slot construction. Tolerances on 0.90 by 0.40 inch waveguide parts can be maintained, after dip-brazing, to within 0.002 inch. Using this technique it has been possible to produce a complicated assembly weighing only one pound. A similar system produced by die casting weighed eight pounds.

Bending and Twisting

In the bending of both circular and rectangular waveguide, care must be taken to avoid distortion. The bent waveguide is thrown partly into compression and partly into tension about a dividing line termed the neutral axis. The part of the tube in tension must stretch, so that it becomes thinner in wall section, and the part in compression must shorten, so that the wall becomes thicker. These changes tend to zero at a short distance along the straight portion and beyond the tangent line of the bend.

Before bending the tubing, it is desirable to bright-anneal it at, for example, 500°C in the case of brass and copper. One simple bending method, requiring manual skill, consists in filling the guide with materials such as hard waxes or fusible alloys like Cerrobend. A draw-bending method is then employed, the tube being gripped by form-and-clamping dies while being allowed to slip between the pressure-and-wiper dies. The tube is constrained by top and bottom plates and its outside surface is lubricated with mixtures containing, say, castor oil, graphite, white lead, or waxes. All surfaces which come into contact with the waveguide should be hardened, ground, and polished, to minimize friction and wear.

Better accuracy is obtainable with the mechanized process [118] shown in Fig. 9. The particular example is an E-plane bend of 3-inch radius in 0.90 by 0.40 inch guide. The tubing is formed in a tool which contains, between two side plates, an upper punch and a lower die. During bending, the punch is pressed slowly downward by a fly-press, while being guided by locating surfaces in the die. The waveguide is supported internally by mild steel strips [120] placed normal to the radius of curvature. A suitable material is Chesterman's 0.020-inch thick tape, which is just wide enough to enter the guide. Before they are loaded, the tapes are given a film coating of lubricating oil, and it is usually necessary to pull the last tape through with a motor driven attachment, a device also used for the final extraction after bending.

For even greater accuracy of section, the waveguide is degreased, annealed again and cleaned, the internal bore then being sized by having rollers pushed through it. In practice, a set of 10–20 rollers of varying diameter is employed, the smallest being 0.010–0.020 inch less than the final tube size. Each roller, as it is inserted, swages the metal of the walls and irons out any small irregularities. The rollers may be pushed through by the fly-press or, as illustrated, by a screw attachment to the bending tool.

An articulated drawing mandrel was used by Fuchs for producing bends in rectangular waveguide. This employed a draw-bending technique in conjunction with a hydraulic bender operating on an automatic cycle [34]. As the tube is bent by rotation of the form-and-clamping dies, the articulated links follow the curved form and provide internal support. To avoid wrinkling, the faces of the wiper and form dies are offset by the amount of the increase in wall thickness. By this means, a production rate of 100 bends per hour can be achieved.

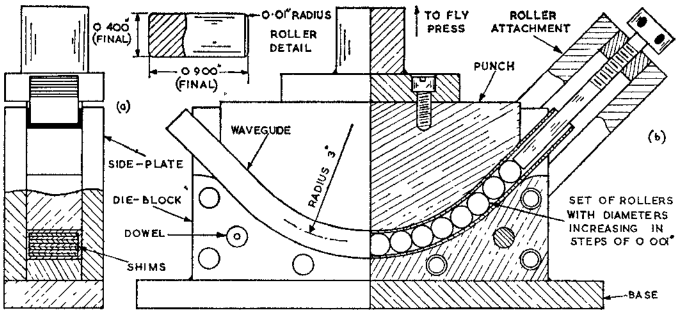


Fig. 9—Press tool for bending waveguides; (a) waveguide tube, with shims in position, during bending, (b) insertion of rollers for final sizing.

In small radius bending, the outer wall is severely stretched and fracture may occur. To reduce this tension, force can be applied to the end of the guide to cause compression. This "boosting" has the effect of shifting the neutral axis towards the outside of the bend. To prevent the tube from leaving the form die, in sharp or zero radius bends, support is given by a chain-like member. This method is also suitable for compound bends and for mitre-shaped tuned corners of various angles.

Rectangular waveguide may be twisted axially by a suitable fixture, distortion being minimized by the use of wax or fusible alloys as a filler. Steel tapes cannot be employed, but accurate sections have been obtained by 0.020-inch thick shims inserted transversely in the guide; after the twisting, these are simply pushed out. Step twists are considered as a small component and may thus be fabricated in any of the usual ways. This also applies to waveguide corners or elbows, whose method of manufacture depends upon the particular design and the quantities involved.

PRECISION CASTING

Permanent-Pattern Processes

Conventional metal casting, in which a sand mold is made with a permanent pattern, is only employed for the larger microwave structures or when some finish-machining can be tolerated. In most cases, the various improved methods known as precision casting are preferred [33]. In one of these, centrifugal casting, the molten metal is poured into a cup or hole in the center of a revolving table and forced through channels into the molds by force [4]. Better quality castings are thus obtained because air pockets and occlusions are not formed.

In another modification, a shell-mold of fine sand and resin may, after removal of the pattern, be backed to form a smooth-surfaced refractory into which the metal can be poured. Such molds are compact and light, being simply placed on the foundry floor for casting. The risk of slight distortion in the baking process is avoided in the casting method in which the sand is mixed with a chemical so that the mixture sets hard in the presence of carbon dioxide.

Several precision-casting processes are based on the use of ethyl silicate, a colloidal ester of silica and ethyl alcohol [83]. In the presence of a small proportion of water or other reagent, this compound goes through a gelling process, finally condensing to a solid. It is usual to add to this reactive liquid sufficient powdered-refractory filler to form a smooth, easily-poured slurry. In the Shaw process, the slurry is poured over a pattern, preferably of metal, arranged to give the desired parting lines [123], [124]. After a short period, the mixture gels to a tough, rubber-like consistency and stripping is carried out. Complete elastic recovery occurs, so that there is no loss of accuracy, and the gelling process is then allowed to continue until completion. The structure of the mold material is such that there is no appreciable shrinkage during solidification while it is also very permeable. It is inert at temperatures up to 1800°C and is thus suitable for materials with high casting temperatures, especially as it is resistant to thermal shock. Another silicate process employs high-grade refractory fillers such as sillimanite, zirconite or molochite and allows the mold to set dry in position [106]. After removal from the pattern, it is then heated to give a finely-divided amorphous-silica bond with good mechanical properties.

To obtain castings with satisfactory internal surfaces, special attention must be given to the core material. In the Parlanti process the metal is cast around a stainless steel mandrel or core which, of course, can be used a number of times. In another process, plaster cores are used [106]. They are prepared from a standard plaster mixed with a refractory and a special hardening agent. After vibration to remove air bubbles the slurry is poured into highly polished core-boxes made of aluminum bronze.

The dimensions of the core-box allow for shrinkage in the subsequent operations. The cores set in about 20 minutes and are then removed to a stoving oven where they are slowly dried by gentle heating to remove free and combined water. The outside of the casting may be formed by any of the usual methods; and in the casting of corners in the 2.84 by 1.34 inch waveguide illustrated in Fig. 10, ordinary sand molding in boxes was employed.

Plaster cores possess high mechanical strength and have good crushing-resistance and venting properties. Furthermore, when they are wetted, the cores disintegrate freely into a soft mush which is readily flushed away, thus causing little damage to the internal surfaces of the casting. Plaster-core casting is suitable for alloys of copper, aluminum and magnesium; castings containing sections thinner than 3/64 inch are difficult to feed and porosity results, while only core shapes which can be withdrawn from the boxes are practical. The surface finish of the casting depends upon the plaster but is usually about 30–40 microinches. In aluminum alloys LM6 and LM8, typical tolerances are about ±0.003 inch/inch with a minimum of ±0.001 inch and a maximum of ±0.010 inch.

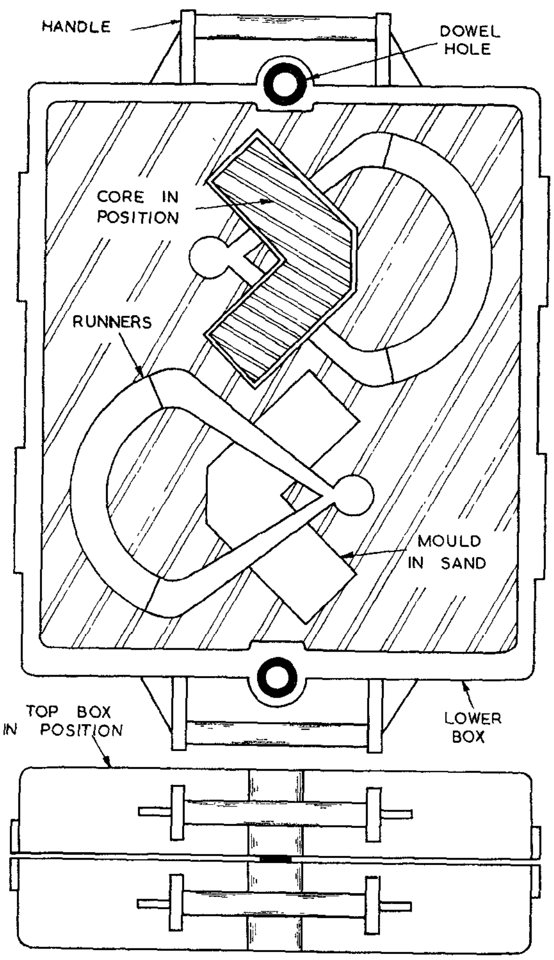


Fig. 10—Sand casting with plaster cores. The sand mold, with one plaster core shown in position, is for producing two waveguide corners at a time in 60/40 brass.

Disposable Pattern Casting

Lost Wax: Precision casting methods may involve the use of disposable patterns. Such investment casting, as it is sometimes termed, essentially consists in making a pattern of the component to be cast, coating it with a suitable fine-grained refractory material and thus investing it to form a mold [16], [26], [116]. After disposal of the pattern, a cavity is left into which the casting metal is poured. The mold is then broken up to leave the finished article. The process is especially suitable for hollow parts and thus has been much used for microwave structures.

In the lost-wax casting process, the pattern material is simply a suitable wax [27], [29], [93]. This should preferably have a high melting point with narrow softening and melting zones. Production of exact wax models is essential and, although dies can be made of inexpensive materials such as rubber, plastics, low-melting point alloys and plaster, for long runs and highest accuracy steel dies are advisable.

When liquid wax is injected into metal dies, difficulty arises in the avoidance of "sinks" and "draws" caused by contraction when the material is passing from the liquid to the solid state. It is important that the wax take up faithfully the fine detail of the die, and for small patterns this can be insured by injecting the wax at the lowest possible temperature, under pressures of 1500 to 2000 pounds/inch.^{2} Turnbull describes a method for large patterns which consists of injecting the wax at a temperature of 20°C above its solidification point and at a pressure of 100 pounds/inch^2, and, 30 seconds after injection, removing the wax injector and applying compressed air at 100 pounds/inch^2 [94]. More complicated patterns can be made by vacuum wax-injection, as shown in Fig. 11(a). After the die is placed in position, the system is evacuated and wax is introduced under pressure through a slide tube on the top plate. Excellent surface finish is obtainable, but the operating cycle times are longer than with simpler methods.

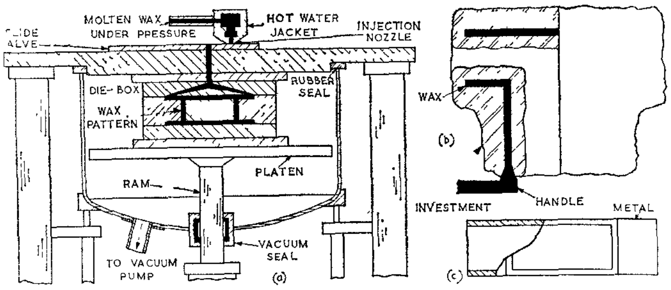


Fig. 11—Lost-wax investment casting; (a) vacuum wax-injection machine, (b) wax pattern with refractory investment, (c) finished cast article—an *H* plane, T junction.

Suitable investment materials include silica or similar refractory oxides suspended in an organic silicate, although others are employed for very-high-melting-point metals. The wax pattern is dipped in the slurry and, after it has been allowed to dry, another dipping is given. This process is repeated until the required thickness—normally $\frac{1}{4}$ to $\frac{1}{2}$ inch, depending upon the size of the casting—is obtained. The appearance is then as shown in Fig. 11(b). Removal of the wax by oven treatment tends to crack the investment shell, and it is preferable to employ a solvent vapor bath containing, for example, trichlorethylene. The wax is then available for reclaiming. The investment is then fired at about 1000°C for two hours to give a hard, strong mold of maximum porosity.

The casting metal is now poured into the mold and such conventional foundry techniques as pressure, centrifugal and suction casting may be employed. In some cases, the shell investments are packed in Nimonic boxes with a refractory mixture to give mechanical support. Aluminum, gunmetal, copper, magnesium and iron alloys can be cast in such molds without any interaction occurring. After cooling the mould is carefully broken away to leave the finished casting as in Fig. 11(c). The accuracy obtainable with the lost-wax casting of microwave structures is about ±0.003 inch/inch and surface textures are in the range 60–80 microinches.

Lost Mercury: In the Mercast investment process [72], [117] the disposable pattern is made of frozen mercury and is cast in steel dies made to a negative of the finished casting. The die is machined to tolerances better than ±0.001 inch, and allowance is made for the volumetric expansion of 3.47 per cent on melting. This low expansion of the pattern material means that thin shells, down to 1/16 inch, are usable and large and complex castings can be made. Frozen mercury is resistant to creep, so that mold dimensions are faithfully and consistently reproduced.

In the actual process the pattern die is filled with acetone, which acts as a lubricant, and then liquid mercury is poured in at room temperature, displacing the acetone. The die is now immersed in a freezing mixture of acetone and solid CO_2, the temperature being in the range -65°C to -95°C. The mercury sets because it has a sharply-defined freezing point at about -39°C. In some cases the mercury is poured into the cold die. To provide a convenient means of handling the pattern, a thick wire rod is placed in the filling hole so that it freezes into the mercury.

The die is opened and the pattern removed; it looks like and is about as hard as lead. Frozen mercury has a high rate of self-diffusion, so that when two surfaces are pressed into contact they will weld together. This facility is termed "booking," and advantage is taken of it to produce complicated shapes with intricate cored passages; this is facilitated by using suitably positioned dowels on the mating dies.

The pattern is then coated with the investment material in the usual way and is allowed to dry at room temperature. The mercury runs out and is reclaimed for further use. After firing, the mold is ready for pouring. A typical die, which employs booking, is shown in Fig. 12; the final article is an *E*-plane bend with flanges.

The dimensional tolerances obtainable are about ±0.002 inch/inch [81]. For example, the cross-section dimensions and deviation of the axes in a component using 0.90 by 0.40 inch guide are about ±0.003 inch depending on the complexity of the casting. A tolerance of ±0.008 inch can be held on a 4-inch dimension. The minimum slot that can be incorporated in a casting is 0.040 inch for a maximum depth of 0.060 inch. The surface finish attained on aluminum-alloy waveguide castings is 30 to 40 microinches while corners can have radii as sharp as 0.020 inch.

The types of waveguide components which have been produced by this process include *E*- and *H*-plane bends, rotating-joint parts, hybrid rings, and similar components in copper-base and light alloys. Inserts such as irises and posts can be cast in position. An advantage of the Mercast process is that in many cases structural features can be incorporated in the waveguide, thus conferring savings in manufacturing space and cost. Castings in light alloy weighing 300 pounds have been produced.

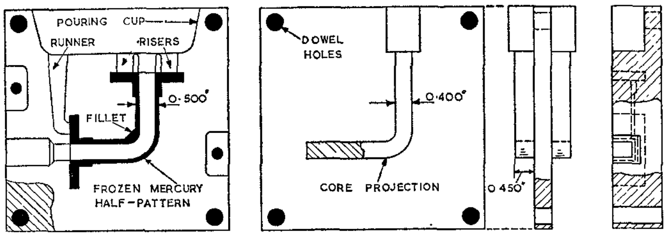


Fig. 12—Typical booking-die for Mercast process. The left- and right-hand die-halves are shown with the central plate. After the mercury is frozen, the plate is removed and the two die-halves booked together so that the two half-patterns become welded into one unit.

Permanent Dies

The casting of metal in permanent dies is a well-known technique [74] and has been employed for the manufacture of accurate waveguide parts. To facilitate extraction of the finished component, it is usually necessary to split it into two or more parts, the division of the waveguide being made, where possible, along the central E plane.

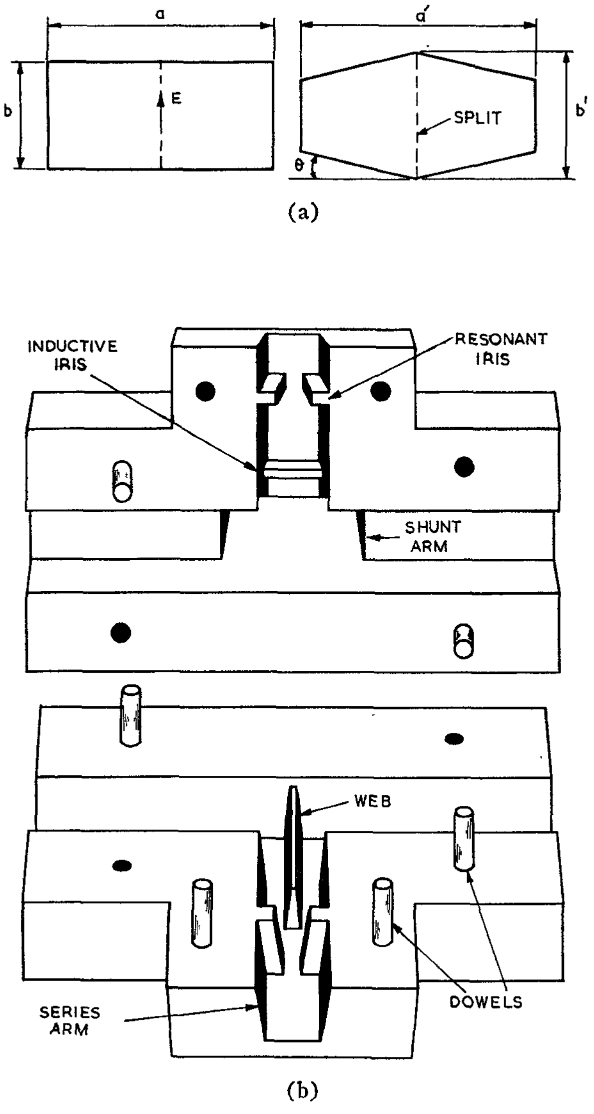
Although gravity-feed of the metal to the die has been used on a limited scale, better results are achieved with pressure die-casting. The tools must be very robust and may weigh as much as 10 cwts; they are also expensive and take several hours to reach operating temperature. Thus, this casting method is best suited to long production runs.

The easiest metals to die cast are low-melting-point zinc alloys such as Mazak, since they cast cleanly with a good surface finish. The electrical resistivity of these materials is not sufficient to eliminate their use for normal microwave components, but they tend to be brittle or have low shock resistance if there is the slightest trace of poisoning from other metals, such as cadmium. Any lack of purity of the zinc also leads to poor corrosion resistance and, although protection can be given by varnishing or chromating, such alloys have not found application in service equipment.

Materials such as brass can, with difficulty, be die cast, but the light alloys have been employed extensively for microwave components. To avoid distortion due to parting of the component from the tool during ejection, a considerable draw or taper must be provided. The larger the taper, the better the surface finish and the longer the life of the tool. While angles of $\frac{1}{2}°$ per side have been found just sufficient, there are advantages in employing a figure of 5°. The casting process is simplified and, if necessary, one of the sides may be made vertical.

Humphreys has designed such a hexagonal waveguide so that it mates with standard rectangular sizes, having the same impedance and cut-off frequency [48]. The geometry is shown in Fig. 13(a). If $\theta=5°$, $a=1.122$ inches, $b=0.497$ inch, then the dimensions of the equivalent hexagon are $a'=1.174$ inches, $b'=0.525$ inch. If $a=0.900$ inch, $b=0.400$ inch, then $a'=0.939$ inch, $b'=0.423$ inch. The effect of a small corner radius is negligible, and moreover it is likely to be present in both types of guide. The junction discontinuity gives a voltage reflection coefficient less than 0.005.

Satisfactory die castings have been made in L33 light alloy, containing 10–13 per cent silicon, with dimensional accuracies ±0.002 inch/inch, and surface finishes of 10 microinches. A hybrid Tee, designed for die casting, is shown in Fig. 13(b). Both inductive and resonant irises are tapered and the usual post replaced by a tapered web. The shunt arm was made to standard dimensions of 1.122 inches by 0.497 inch, since it was broached to size. It is not practicable to carry the 5° taper along its entire length. The performance of this Tee was equally as good as that made by machining techniques with rectangular sections.



(a)

(b)

Fig. 13—Components made by pressure die-casting; (a) equivalent hexagonal guide-section; (b) hybrid-T cast die in aluminium.

SINTERING AND SPRAY TECHNIQUES

Powder Metallurgy

Sintering or powder metallurgy is a process of molding powdered metals, such as alloys of copper, zinc and aluminum [115], [119]. The finely divided metal is screened and compressed, or briquetted, in a die under pressures of 25–50 tons/inch^2 to form a compact mass. The part is then removed and transferred to a sintering furnace in which it is heated nearly to the melting point, a process that fuses the powder into a hard metal comparable in strength to a casting [60]. The process is practicable for metals such as tungsten which have very high melting temperatures.

The methods employed for the manufacture of metal powders are being improved with the objects of reducing their cost, *e.g.*, by making them direct from metal ores, and of providing better quality in the finished product, especially in strength, density, and ductility. For example, a modern pure iron powder, compressed at 27 tons/inch^2, sintered in dry hydrogen for one hour at 1100°C and then recompressed and resintered under the same conditions gave a density of 6.5 g/cm^3, a tensile strength of 10.8 tons/inch^2 and an elongation of 14.5 per cent. Stainless-steel powder corresponding to A.I.S.I.318, after somewhat similar treatment, gave a tensile strength of 41 tons/inch^2 and an elongation of 36 per cent. Fine-particle sizes are necessary for good physical properties, and grinding is able to produce diameters as low as 60 μ. The sintering atmosphere has an influence on the final product, while infiltration techniques, in which the pores are filled with a metal of lower melting point by capillary action, improve the physical properties.

In powder metallurgy, the costs of the die and of setting up production are high, and thus the process tends to be of use for the manufacture of large quantities of identical parts. The final items are often porous and are not satisfactory where pressurization is required. The high pressures used in molding mean that thin wall sections should be avoided while shapes long compared with the transverse dimensions are not practicable. Dimentional tolerances are about 0.004 inch/inch, and this process has, for example, been employed for wafer-type crystal mounts, a tolerance of ±0.001 inch being maintained on a 0.280 by 0.140 inch aperture.

Metal Spraying

In the metal-spraying process of manufacture, the material is passed through a flame and blown, in a finely divided state, on to a retractable former until the required thickness of deposit is obtained [105]. The operation is carried out in a spraying booth which should have good air extraction. The available spray guns employ metal in either powder or wire form. A suitable gun is that made by Metallisation which takes $1\frac{1}{2}$-mm diameter wire and contains a high-pressure air turbine. The gun weighs $3\frac{1}{2}$ pounds and, to avoid fatigue to the operator, can be suspended from a support. Acetylene and oxygen are suitable for the flame jets.

The formers can be made of materials such as stainless steel. Before they are used, all traces of oil are removed by a degreasing liquid. To avoid bonding of the initial coat of sprayed metal, the former is coated, in a dust free atmosphere, to a thickness of 0.0003 inch with a synthetic lacquer which is then stoved for 15 minutes at 150°C. This lacquer is usually brightly colored to facilitate the visual observation of uniform thickness.

The metals that can be deposited include zinc, silver-cadmium alloy, silver-tin alloy, brass, copper, aluminum, tin, lead, nickel and its alloys, and steels, including stainless steel. Where silver-cadmium alloy, zinc or tin is employed for the initial deposit, this need only be about 0.010 inch in thickness. This can then be followed by brass, steel or other metal to any required thickness to give greater strength. It is essential that at no time must the temperature of the component rise to the melting temperature of the initial layer, and this is achieved by adjusting the rate of deposition or by air or water cooling of the former. The former can finally be removed by means of a press, and the lacquer dissolved with a suitable solvent.

The structure of the deposited metal tends to be porous, and the tensile strength is only 25 per cent of the wrought metal. Vacuum impregnation with a suitable resin can be used to increase the tensile strength up to the order of 60 per cent of the wrought metal and to render the component vacuum tight. The internal dimensions and finish tend to follow closely those of the original former.

The metal spraying process does not require skilled labor, and a typical taper waveguide of section 0.90 by 0.40 inch would take about twenty minutes. An *E*-plane 90° bend with a socket for waveguide connection can be deposited in 15 minutes, while a twist might take 30 minutes. A circular-section resonant cavity with either silver or gold internal finish has been produced in 0.4 per cent carbon steel, the internal-surface finish being 4 microinches and the bore diameter correct to within 0.0001 inch. Planar components such as hybrid rings and couplers can be made as thin shells, the backs of which are filled with an aluminum casting and an aluminum-powder loaded resin to achieve the required strength with economy of spraying time.

ELECTROFORMING

Plating Techniques

Electroplating techniques have proved useful in the manufacture of microwave structures. The conventional method of photoetching enables a thin foil to be produced containing an intricate structure such as the ladder circuit of a backward-wave electron tube or the common wall of a multislot directional coupler. This foil may be made thicker by electroplating, although the fine definition of the process may be impaired if the deposit is too great. Photoetching may be carried out with a number of metals including molybdenum [44].

In electroforming or electrodeposition, a former, in the shape of the internal volume required, is electroplated to a thickness sufficient to provide adequate strength. The former is then removed to leave an electroformed blank. The material for the former may be of a permanent or expendable nature. The thickness of the deposit, which ranges from 0.04–0.40 inch, means that the electroforming process should have a high plating speed and good throwing power [59], while the deposited metal must be homogeneous, hard but machinable and free from defects.

Many metals can be electroformed [113]. Very hard deposits are obtained with nickel, chromium and nickel-cobalt alloy, but their throwing power tends to be poor. Light weight is provided by aluminum, but special electrolytes are required which must be operated in an atmosphere of dry inert gas. Deposition from fused mixtures of quarternary ammonium salts and an aluminum halide has been achieved [49], [79]. At an operating temperature of 30°C, current densities of $2A/dm^2$ and deposits 0.04 inch thick were obtained. Another electrolyte is based on a complex of sodium fluoride and aluminum tri-ethyl, with an operating temperature of between 80°C and 150°C [101]. Deposits 0.020 inch thick of very pure aluminum have been produced with hardness in the range of 24–33 Brinell. Heritage and Balmer [42], [43] have electroformed waveguide parts, with a bath composition [21] of 300-g aluminum chloride, 6-g lithium hydride and one liter of anhydrous diethyl ether. By employing a sealed vat to keep out moisture, satisfactory operation of the electrolyte was obtained for several months. The rate of deposition at $1A/dm^2$ was 0.0005 inch/hour, and coherent, ductile deposits up to 0.15 thick were obtained on simple cylindrical formers.

In microwave structures, the initial layers are either silver or copper to give maximum conductivity, the metal for the remainder being chosen for other reasons. Most electroforming is, however, carried out with copper, and various techniques have been described [20], [31], [37], [64], [87]. The conventional copper electroplating techniques [10] based on inorganic electrolytes give low throwing power, a metal hardness of B10–B55 Rockwell, and a rough deposit, but, because of their simplicity [3] and economy, they are commonly used.

Improved results [37], but with greater complication and expense, are obtained with the process developed by Jernstedt [54]–[56], which is based on an organic electrolyte containing cyanides of copper and other elements. This process involves periodic-reverse plating in which the article being electroformed is made alternately cathodic and anodic, the net current-time product being, of course, positive. The optimum periods depend upon the shape and size of the formed article but generally lie between 20–100 seconds cathodic and 10–40 seconds anodic, when the respective currents are nearly equal. The anodic cycle deplates any unsound metal and the more sacrificial cycles are required for complicated shapes. A plating speed of 0.006 inch/hour is obtainable with current densities around $8A/dm^2$ at a temperature of 85°C, or 0.002 inch/hour with lower current densities and temperatures down to 50°C. Even and symmetrical deposits are achieved if the former is slowly rotated in the bath, while the solution is agitated and continuously circulated through filters and a purifier containing activated charcoal. The metal deposited is ductile and machinable while photomicrographs have shown freedom from inclusions. The hardness depends upon operating conditions but is within the range of B50–B100 Rockwell.

With any plating process the deposit tends to be less in regions of low electric field as in internal angles. Fig. 14 shows the result of plating on a former with corners of different radii. It will be observed that, with the process described, a constant thickness layer is deposited until the center of the circle is reached, from which point a crack develops. Thus, some radius must always be provided to insure a continuous internal layer of metal. Considerations of mechanical strength require an artificially increased deposit, and suitable methods of achieving this are shown in Fig. 15.

Permanent Formers

Where the shape of the article permits, permanent formers can be employed. These should be made of high-tensile steel, treated by passivation, and coated with a separating medium such as tin or chromium plate. Other materials which have been employed include Invar, molybdenum, titanium, glass, quartz, hard plastics, and stainless steel. The latter material has proved very convenient since it can easily be ground to complicated shapes. For example, a former ½ inch in diameter and 3 inches long was made circular and parallel to within 0.00002 inch with a surface roughness of 4 microinches. After plating to a thickness of ⅜ inch, the cavity diameter was within 0.00002 inch of that of the former, the ovality being 0.00005 inch and the roughness 5 microinches. These precise measurements show that electroforming is a very accurate method of manufacture for microwave structures.

Formers of cylindrical section are easily ground in the form of blades which are then brazed into stainless-steel heads, as shown in Fig. 16(a), while more complicated shapes are machined and ground in one piece, as in Fig. 16(b). Polythene stops are fitted during plating, and Fig. 17 shows a typical former after electrodeposition. The former or mandrel may be extracted by a simple machine after immersion of the assembly in hot water.

Components involving coupling apertures and slots can be electroformed with the aid of additional pieces, as shown in Fig. 18. These pieces should be of plastic to prevent shielding in the corners. Complicated components need multiple-mandrel assemblies, with support and alignment provided by jigs made of aluminum or stainless steel. Fig. 19 shows an assembly for electroforming a hybrid Tee, with a guide of 0.28 by 0.14 inch,

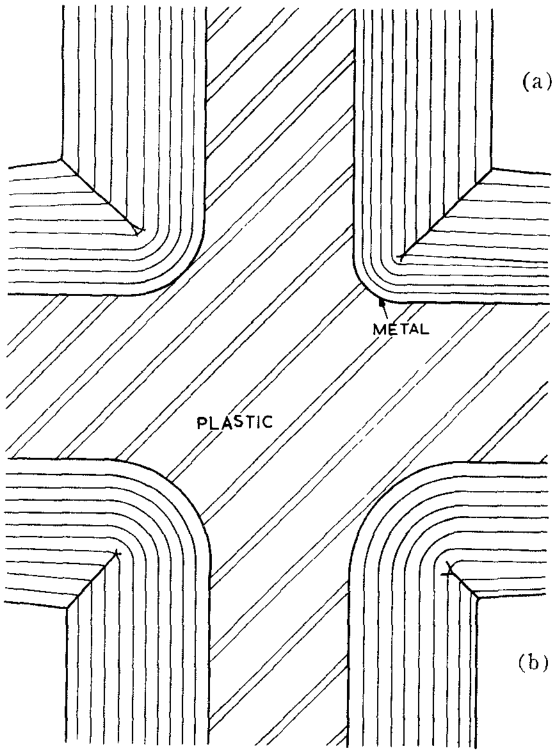
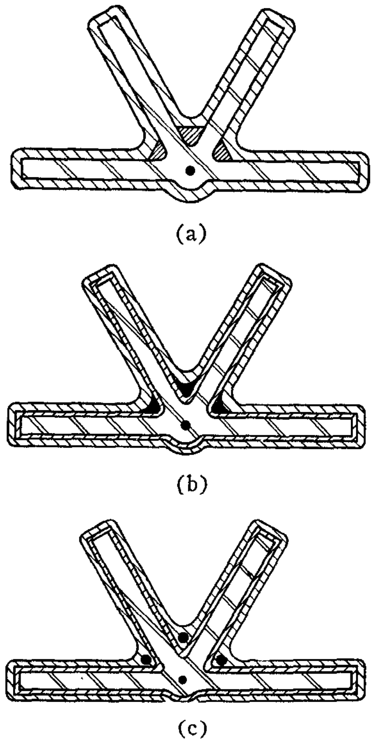


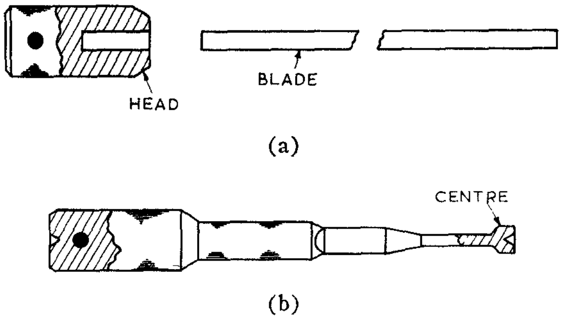
Fig. 14—Electrodesposition in corners of different radii; radii are (a) 0.040 inch, (b) 0.060 inch, (c) 0.100 inch, and (d) 0.120 inch.


(a)

(b)

(c)

Fig. 15—Methods of increasing thickness of deposit in corners; (a) shaped metal inserts, (b) packing by solder, silver powder, amalgams or sprayed metal, (c) drilling out and plugging.



(a)

(b)

Fig. 16—Manufacture of permanent formers; (a) rectangular mandrel made separately and brazed into its head, (b) complex former with various sections made in one piece. The centre at the free end is removed in a final operation.

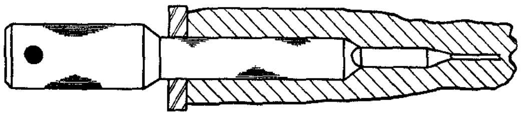
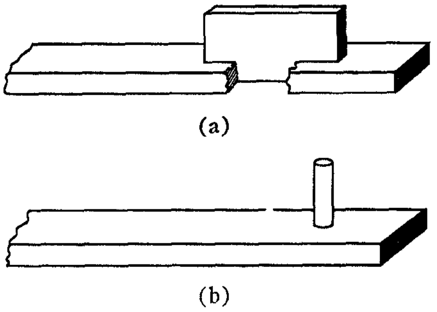


Fig. 17—Permanent former with electroformed piece still in position. The polythene stop provides a square face. This former has an extra cylindrical portion to serve as a guide during extraction and as a support for the electroformed piece in subsequent machining.


(a)

(b)

Fig. 18—Formers for the electrodeposition of components with coupling apertures. The strip in (a) and peg in (b) are made of plastic to prevent shielding in the corners thus formed.

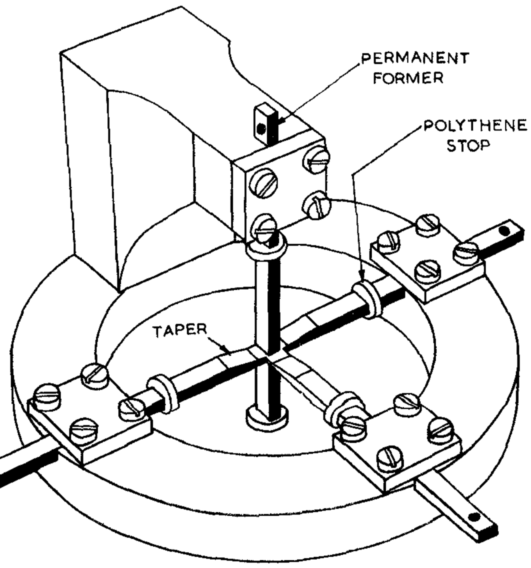


Fig. 19—Assembly jig with formers for producing a hybrid T.

while examples for other components are shown in Fig. 20. It will be noticed that inserts to provide corners or coupling apertures are used freely.

Disposable Formers

Disposable formers impose no restriction on the shape of the article to be electroformed. Suitable materials for these formers include aluminum which can be subsequently dissolved in dilute hydrochloric acid, hard waxes and fusible alloys which can be removed by melting, and plastics which can be removed by organic solvents. Plastic formers may easily be injection-molded and are thus suitable for quantity production. Methacrylate resins, such as Diakon, have a molding shrinkage as low as 1 per cent and small water absorption. By using automatic molding machines, in which the temperature of the die, the injection and cooling times, and other conditions are held constant with pressures of 15 tons/inch^2, dimensional accuracies of 0.0005 inch can be achieved [37]. Some examples of plastic moldings are shown in Fig. 21, where the guide section is 0.28 by 0.14 inch.

The surfaces of the plastic are given a conducting coat by evaporation of a metal in high vacuum or, more usually, by chemical silvering [41]. In the latter process, the former is degreased and then activated by immersion in an acid solution of stannous chloride. The actual silvering involves the reduction of a silver complex by a suitable reagent such as cane sugar, formaldehyde—Rochelle salt and hydrazine sulphate. This process can be carried out by dipping or, more conveniently, by a special gun from the nozzle of which two jets of the constituent solutions emerge to form, on coalescence, a thin adherent film of silver.

In the electroforming process, metal inserts of silver, or silver plate, may be employed which are held in position by simple clips. The shapes of these inserts should be such that sharp corners are avoided and a post, for example, should be shaped as shown in Fig. 22(c) to insure sound bonding and deposition. Flanges which are grown in position should be provided with tapers.

Fabrication of Electroformed Pieces

Although the complete microwave structure can sometimes be electroformed, it is more usual to carry out some additional machining and assembly operations. In such cases, the article should be supported on the locating internal surfaces by a mandrel of hardened steel, machined and ground to the required shape and provided with means for centering and driving.

The assembly of electroformed pieces is preferably carried out by soft-soldering to avoid distortion. The need for a soldered joint may be avoided by electrodeposition. For example, a hybrid ring has been made by machining the channels in a block of copper, temporally filling these with wax or plastic, and then electroforming the fourth side.

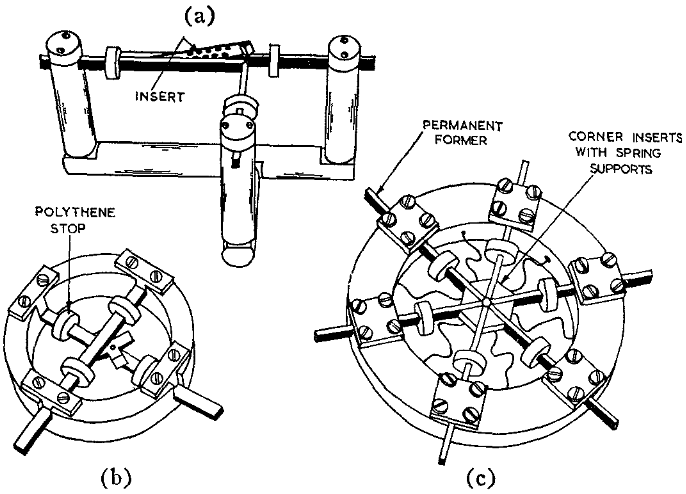


Fig. 20—Miscellaneous assembly jigs; (a) multiple-hole directional coupler, (b) cross-over directional coupler, (c) hybrid ring, two of the arms being finally plugged.

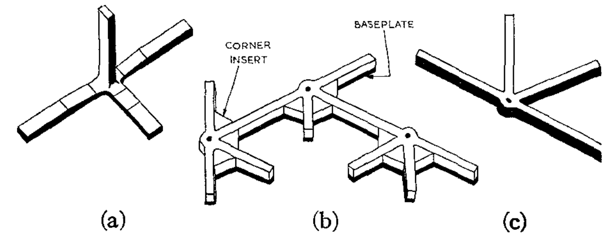


Fig. 21—Disposable formers made in plastic, waveguide size, 0.28 ×0.14 inch. The radii on the various corners are provided to assist electrodeposition. (a) Hybrid T, (b) multiple-ring, (c) single ring.

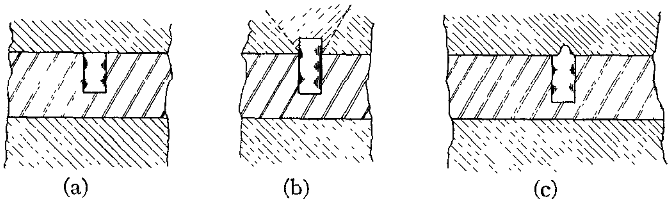


Fig. 22—Electroforming inserts in position using disposable formers. (a) The flush-fitting pin gives sound deposition but poor keying. (b) The protruding pin gives poor deposition but good keying. (c) The shaped protruding pin gives sound deposition and good keying.

Straight waveguides, electroformed to a large diameter, have been machined to form bearings for sliding parts such as post tuners. Locations for side arms in Tee junctions, cross-over connections and directional couplers may be similarly provided, eliminating the complication of strengthening supports. Electroforming is very suitable for the manufacture of taper transitions from one size or type of waveguide to another. Bends, corners and twists are examples of other components which can readily be made by these techniques [7].

The original former can be shaped so that, without any elaborate machining, the electroformed piece can provide proper housing and alignment [38] for such things as micrometer heads. This process has made relatively easy the manufacture of movable short-circuits, wavemeters and stub-tuners in which plungers, actuated by micrometer heads, are moved along lengths of waveguide. Electroforming has been proven the only satisfactory process of making very small waveguides with sections down to 0.034 by 0.017 inch.

Increased strength can be given to an electroformed structure by metal spraying, using, for example, aluminum or brass, and supporting it in a jig or encapsulation in one of the resins employed in potted circuits [25]. Several components could be so encased to form a subassembly which would withstand mechanical shocks and adverse climatic conditions. Morrison [69] has electroformed the triple hybrid ring shown in Fig. 21(c) to a thickness of 0.040 inch by using periodic-reverse silver plating. The subsequent assembly was secured with Araldite in a stainless steel jig. Measurements on the component gave a loss of about 0.5 db and a discrimination between the arms not worse than 40 db over a 3 per cent bandwidth. Such results compare well with the prototype made by machining.

INSPECTION AND MEASUREMENT

Inspection Methods

Inspection of and measurements on microwave structures are an important aspect of their manufacture. A satisfactory method of inspection must take into account the statistics of production. For example, if there are many toleranced dimensions on a component then one of these may be out by as much as 50 per cent of the tolerance without appreciably affecting the electrical performance. As a result, components will be rejected when, in fact, they are quite satisfactory. This is due, of course, to the remainder of the dimensions being well within tolerance and to the fact that the electrical performance is a function of all the critical dimensions involved. If the dimensional errors have a symmetrical distribution, then some waste can be avoided if the design gives the probable tolerances based on standard deviation.

The inspection of microwave structures has been shown in unpublished work by L. V. Byrne to fall into three principal methods: explicit mechanical inspection, implicit mechanical inspection, and electrical inspection. Which one or combination of these three general methods can be used depends upon the type of component, its shape and method of manufacture. Mechanical inspection in its broad sense includes visual inspection for such things as surface defects and faulty manufacture. Such inspection, although very important, is a subjective assessment depending on the skill and experience of the inspector and it is customary in microwave engineering to depend more on the actual measurements.

Explicit mechanical inspection means the direct inspection of the component by measurement of its size, shape, positions, and surface finish. If the inspection of a purely mechanical component such as a drawn waveguide tube is considered, the problems of measurement of size and shape can be readily appreciated. Waveguide couplings are of different types and size, but the basic functional requirement is common and necessitates the verification that features such as fixing holes, waveguide apertures and chokes are within tolerance.

Implicit mechanical inspection means inspection of the former, mandrel or tool from which the part is produced or assembled. Here again the measurement of size, shape, positions, and surface finish are involved. Such implicit inspection is common in microwave manufacture since the measurement of the significant internal dimension is virtually impossible in such components as bends, twists, double tapers, millimeter-wavelength parts and items of complicated shape such as hybrid Tees and rings. In one method of coupling-flange assembly, the two accurately sized and positioned locating holes are drilled after fitting to the waveguide by means of a jig. In such a case, inspection is directed towards checking the jig and insuring that it is properly used.

Electrical inspection involves the measurement of one or more specified electrical characteristics of the component the results of which usually provide the criterion of acceptance. Most routine tests involve measurement of the VSWR at defined points in the specified frequency band and attenuation at a specified, *e.g.*, mid-band, frequency. The great advantage of electrical inspection is that it gives a positive indication of the functional performance of a component, whereas mechanical inspection by itself, although always necessary in some degree, cannot prove with certainty that a component will fulfill its functional requirements.

The fact that measurements of individual dimensions do not alone insure a satisfactory component is especially true when more than, say, ten variables are involved. Brown has shown that, in these cases, microwave structures must be assembled on an electrical test bench by choosing one part as a central unit and adding others one at a time [14]. In this selective assembly, items which do not cooperate in the phase and amplitude of their reflections and produce a poor over-all performance are rejected until a place is found for them in later assemblies. This process is continued until the combination of tolerances or errors in the complete assembly is such that the test is passed. This process is facilitated if the VSWR meter is provided with some kind of visual display.

Mechanical Dimensions

There are two kinds of dimensional errors: random or accidental errors, and systematic errors. Random errors result from the inability of man and machine to achieve perfect reproducibility of objects made in quantity. These errors can be reduced to almost any desired degree if one is willing to take the time and pay the costs, but they can never be completely eliminated.

Random errors are distributed symmetrically about the "correct" dimension which is to be achieved. Systematic errors are caused by such things as mistakes in design and incorrect calibration of machine tools or measuring equipment. This type of error usually leads to an asymmetrical distribution with respect to the "correct" dimension. In either case, a determination of the actual dimension and its departure from the design value is required. This may be carried out by metrological or gauge methods.

Metrological methods involve the actual measurement of the mechanical dimensions by means of a suitable machine. This is an expensive process which is only employed when extremely high accuracy is required and in the prototype, type-approval or production-sample testing stage of a component in order to verify that such features as wall thickness, rectangularity, radii of inside and outside corners, displacement of rectangles, and internal dimensions are within their permitted tolerance. Typical machines can measure external and internal dimensions to within 0.00002 inch and angles to within 5 seconds of arc. This method may be simplified where larger quantities are involved by a comparator process, the item under test being replaced by a standard.

The usual method of checking mechanical dimensions of microwave structures is by some form of gauging. For example, the dimensions of a waveguide tube would be checked internally by "Go" and "Not-Go" plug gauges and externally by "Go" and "Not-Go" gap gauges. The explicit measurement of internal dimensions of long lengths can be achieved with pneumatic gauges of the Solex type. These consist of a loose-fitting plug fitted with one or more air outlets. The actual internal dimensions determine the amount of clearance and hence of the air pressure in the supply line. Such gauges are very convenient for medium sized waveguides. In order to check that the relative positions of these various features are within tolerance, a more complicated microwave component such as a coupling flange containing a rectangular aperture, fixing holes and a choke would necessitate a receiver or interchangeability gauge. A fixed-type receiver gauge is designed to accept a component in the maximum-metal condition, simultaneously making an allowance for the maximum positional tolerances. This means that all features must be individually checked to insure that they are within limits before the component is offered to the receiver gauge.

Surface Texture

The complete inspection of microwave structures must involve some means of measuring or comparing surface texture. In many instances this measurement can be carried out directly, but where the surface is inaccessible, as on the insides of chokes and very small waveguides, a nondestructive test is possible by making plastic replicas and then measuring their surfaces. In order to show the range of finishes which have to be measured, Table I gives values for a number of typical manufacturing operations.

TABLE I

SURFACE TEXTURE FOR VARIOUS METHODS OF MANUFACTURE

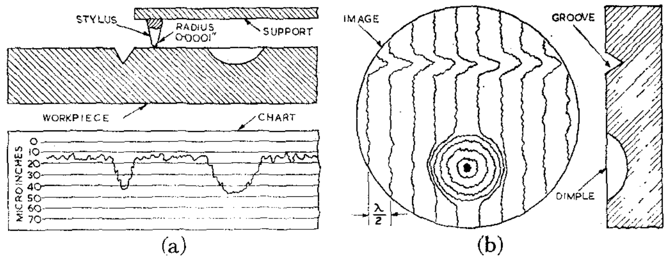
Method of Machining or Fabrication	Microinches
Turning, preliminary finish	63 to 125
Turning, ordinary finish	32 to 63
Turning, fine, ferrous metals	8 to 32
Turning, fine, nonferrous metals	4 to 16
Turning, diamond, nonferrous metals	2 to 8
Boring, ordinary	16 to 32
Boring, fine, ferrous metals	8 to 16
Boring, fine, nonferrous metals	4 to 8
Boring, diamond, nonferrous metals	2 to 4
Planing, ordinary	16 to 63
Planing, fine	8 to 16
Extrusion or drawing, mirror finish	8 to 32
Hobbing	8 to 32
Milling, ordinary	32 to 63
Milling, fine	8 to 32
Reaming, ordinary	16 to 32
Reaming, fine	4 to 16
Broaching, ordinary	16 to 32
Broaching, fine	4 to 16
Scraping	8 to 32
Burnishing	2 to 8
Grinding, ordinary	16 to 32
Grinding, fine	8 to 16
Grinding, super fine	2 to 8
Honing	1 to 8
Lapping	1 to 4
Superfinishing	1 to 4
Polishing	1 to 2
Casting, investment	63 to 125
Casting, polished dies	4 to 32
Powder metallurgy	63 to 125

Most of the listed methods can be put into one of three classes. The first has little or no lay and includes grinding, lapping, honing, superfinishing, and polishing, as well as casting and powder metallurgy methods. The second class is performed with sharp-pointed tools and has a lay in the direction of the movement of the work with respect to the tool, irrespective of which is fixed and whether the motion is in a straight line or in an arc. Operations in this class include turning, boring, flycutting, and planing; similar textures are given by extrusion, drawing and hobbing. In the third class, the tool is broad and the lay tends to be parallel to the width of the tool and at right angles to the relative movement of the work. This class includes roller-milling, broaching, reaming, scraping and burnishing.

An ideal machine for the measurement of surface texture of microwave structures would record the increase in the linear dimensions of the surface. Although this can be achieved by the photography of sectioned items, there appears to be no direct-measuring instrument [2]. In practice, surface finish is assessed in three main ways.

The first is visual and tactile, making use of experience. This is a completely subjective assessment and is liable to large error and much disagreement. The second method employs a measuring instrument and is the most accurate. It is a true comparator inasmuch as it can be calibrated against known standards such as gratings ruled on glass. The normal practice [78], [122] in the United Kingdom is to traverse a stylus, the radius of whose tip does not exceed 0.0001 inch, over a short sampling length of the surface. The deviations of the stylus are recorded, after amplification, on a moving chart or displayed on an integrating meter. Such a measuring machine gives the center-line-average (cla) height of the irregularities. In the U.S.A., it is more usual to amplify the electrical output of a pick-up traversed over the surface. This gives the rms roughness value, which, for most types of surfaces is 1.11 times the cla figure and this factor can, in practice, be ignored. The principle of this stylus method and a typical record on a paper chart are shown in Fig. 23(a).

Very fine surface textures can also be measured by instruments based on optical interference [86], [88], [89]. As shown in the arrangement of Fig. 23(b), the lack of parallelism of fringes between the surface under test and that of an optically flat glass plate is a measure of the roughness. In one example, the optical system of the microscope is arranged so that the reference surface does not make contact with the specimen [103]. A slight tilt is given to produce the fringes, the difference in level of the specimen between any two of which is one half the wavelength of light chosen for illumination. With green light, an estimate of surface irregularity of 0.1 of a fringe is equivalent to 1 microinch. Such stylus and optical machines [90] are expensive and are hence usually installed in laboratories or standards rooms remote from the workshop.



(a) (b)

Fig. 23—Measuring surface texture by instruments; (a) mechanical stylus, (b) optical interference. The scale of the texture is exaggerated.

The third method is to employ comparator plates of known surface texture which are compared with the workpiece by appearance and/or sense of touch. It is thus desirable that the plates should include all three classes of finish. The textures shown in the particular example [36] of Fig. 24 are considered appropriate to the manufacture of microwave structures. In the preparation of these scales, the appropriate finishes were put on the ends of stainless steel plugs which were then mounted in an engraved circular copper disk. From this master, a negative copy was made by electrodeposition in nickel and thence positive copies were made in copper. The plates were then backed to give rigidity and given a chromium flash on the face for permanence. Such plates are inexpensive, portable and convenient to use. Errors arise in the texture values because of imperfections in the master and small changes which occur in the reproduction process; while errors in use arise because of possible different materials employed in, and variations of surface texture of, the standard and specimen. Provided care is taken in the visual and tactile estimation, the over-all accuracy is to within one-half of a scale step, which is considered reasonable in such a simple device.

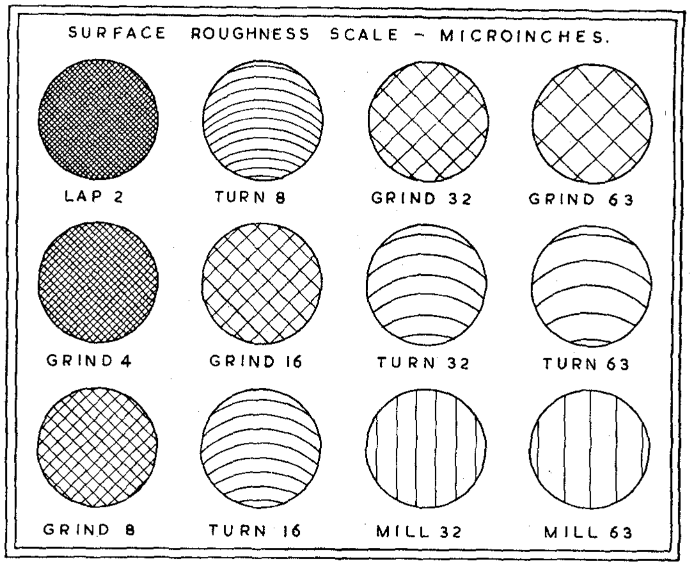


Fig. 24—Surface-texture comparator. The comparator is electrotype-copied in copper, the working surface being flashed with chromium. Over-all size is $4\frac{1}{2} \times 3\frac{1}{2}$ inches, thickness $\frac{1}{16}$ inch.

PROTECTION AND PACKAGING

Internal Finishes

The performance of microwave component depends upon the condition [18] and finish of the internal surfaces which are mainly governed by the method of manufacture. The requirement of dimensional accuracy usually excludes any polishing or buffing operations, although these can give very smooth surfaces. Such operations are, in any case, not recommended for microwave surfaces since they tend to form an amorphous low conductivity Beilby layer [9], which may have a thickness up to one microinch.

For some metals, electropolishing provides a good surface finish. The principle is that of selective dissolution under the influence of current, whereby the surface is made progressively smoother and more brilliant. The actual mechanism appears to depend upon the presence of a viscous film of the products of interaction between the metal and the electrolyte [28], [75]. The film-electrolyte junction does not follow the metal surface irregularities so that the film thickness is not constant. This results in a varying current-density and preferential dissolution.

Chemical polishing produces a levelling effect on metals when a thin film of oxide or basic salt is present on the surface during the process [76], [85]. The surface is smoothed because slower diffusion of metal ions from microdepressions than from microelevations causes the film over the elevations to be dissolved at a greater speed by anions in the polishing solution. The metals which can be chemically polished are copper, brass, bronze, nickel-silver, nickel, zinc, aluminum, iron, steel and most aluminum alloys. To obtain the desired result the total thickness of metal removed must be between 0.001 and 0.0015 inch.

Smooth surfaces are also obtained by bright electroplating which is achieved in silver baths by the addition of sulphur in the form, for example, of turkey-red oil and in copper baths by colloidal material such as gelatine. Electroplating, especially with gold and rhodium, is often employed to give increased protection against corrosion. This flash coating must be much thinner than the skin depth if increased loss is to be avoided.

The internal surfaces of microwave structures can also be protected by nonmetallic finishes. Varnishes that have been used include phenol formaldehyde, cellulose mitrate, varnish DTD Specification X17, seaplane varnish and beeswax dissolved in benzene. In the case of light alloys, anodizing gives good protection with negligible increase of attenuation. In general, it is recommended that the sealing facilities of standard waveguide couplings and fittings be employed, in conjunction with proper desiccator-breathing systems, to maintain the microwave system free from dirt, moisture, and corrosive atmosphere. The open ends of the transmission system should be sealed with polythene tape, windows or covers. More complex assemblies can be fitted inside boxes provided with means for sealing against moisture and variations in external pressure.

External Finishes

A large variety of external finishes are available including paints, varnishes, and resins, while corrosion inhibitors may also have applications [15], [77]. Electrolytic plating should employ a metal giving to the surrounding structures a potential difference not greater than 0.5 volt for ordinary purposes and 0.25 volt when exposure to the weather and salt-spray conditions is likely [110]. Nickel, cadmium, and tin have been found satisfactory under most conditions. For small laboratory instruments, plating with 10^{-4} inch of silver and 2×10^{-6} inch of rhodium [95] gives a hard-wearing and attractive finish which has good resistance to humid conditions. If wearing qualities are not required, gold is also a satisfactory finish.

A method of electrofinishing which is very suitable for microwave components is the Dalic brush-plating process in which metals are deposited from electrolytes held in absorbent pads attached to portable electrodes [45]–[47]. The pad is made the anode of an electrical circuit; the workpiece forms the cathode. The method has the great advantage that the article need not be immersed in an electrolyte and the deposit can be limited to a defined area giving good mechanical properties, high adhesion, and low porosity. The properties of the solution are important and are found only in aqueous solutions of complexed organic salts of the metals concerned. An extensive range of twenty or more metals can be deposited in this manner. The rates of deposition vary from 0.150 inch/hour for copper to 0.004 inch/hour for rhodium. The current densities are of the order of 500 A/dm^2.

The variable thickness of commercial electroplating on intricate shapes is not satisfactory for closely fitting parts such as locating bolts, sleeves and slides, and it is preferable that these should be made from corrosion-resistant alloys such as stainless steel, Tungum, nickel-silver and silver-bronze. Screw threads, especially those in stainless steel and light alloys, should be coated before assembly with graphite or molybdenum disulphide compounds to reduce liability of pick-up after prolonged use. In the standard range of waveguides, couplings and components for service and other arduous use the designs and materials have been chosen to withstand the full relevant specifications [39]. In certain circumstances protection against nuclear radiation may be required [61].

Packaging and Marking

Special care should be taken so that such precision items as microwave components and instruments, which are sometimes delicate, are packed so as to afford protection from damage and distortion during storage, transit, and handling. The open ends of waveguide tubing may be sealed with plastic inserts. In one test, a 24-inch piece of 0.90 by 0.40 inch guide, containing a small amount of silica-gel desiccant and sealed with an approved type of molded-polythene plug, was subjected to cycling between +25°C and +35°C in an atmosphere of 95 per cent relative humidity. After 14 days there was only slight loss of brilliance of the internal surface and an increase in weight of the desiccant, due to moisture absorption, of only 0.4 gm.

Waveguide tubing for service stores is normally packed so that each length is in a separate cleated case from which the guide is removed only when required for use. Small items such as electroformed pieces, dowel bolts and nuts should be enclosed in sealed polythene bags and packed in strong cartons. Coupling flanges, adaptors, bends and twists may, according to their size, be packed in cartons or wooden boxes, the mating faces of any fitted flanges being protected by molded plastic or similar covers.

Measuring instruments are usually supplied by the manufacturer in fitted wooden or plastic cases to which they should be returned when not in use. Equipment destined for use and storage overseas requires more elaborate packing. Such climatic or tropical packing protects the contents from the deteriorating effects of high humidity and extremes of temperature, and also of mold growth and insects.

Identification marking must be carried out so that no damage to the electrical, mechanical, and sealing properties of the equipment occurs. Light stencil markings or transfers are permissible in positions fulfilling no electrical or essential mechanical function, while transit, packing or instrument cases should be marked or labelled.

ACKNOWLEDGMENT

The author is indebted to the Engineering Unit, Royal Radar Establishment, to his colleagues on the Radio Components Res. and Dev. Waveguide Committee for useful discussion and assistance on this subject, and to J. R. Balmer for reading the manuscript.

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