FABRICATION OF NIOBIUM RF CAVITIES

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INTRODUCTION

Experimental studies of the nature and magnitude of ac losses in superconducting niobium were started by the Union Carbide Corporation, Linde Division in 1963. Most of this work was concentrated on niobium produced by the electroplating process developed within Union Carbide by Mellors and Senderoff.[1] Electrical resistivity measurements demonstrated that residual resistivity ratios greater than 20 000, a factor of nearly 10 greater than previously reported for niobium, could be obtained by vacuum outgassing this electroplated niobium.[2] In addition, vacuum outgassed electroplated niobium samples were prepared which showed the most complete magnetic reversibility and the lowest ac losses at magnetic fields up to $\sim$ 1400 G and frequencies up to 10 000 Hz ever observed in niobium.[3]

As the rf field amplitude is increased in a superconducting rf cavity the peak magnetic field at the cavity wall is also increased. Therefore, as the magnetic field at which the superconductor can be operated increases, the maximum energy gradient attainable also increases. Thus in choosing a superconductor for use in an rf cavity, in addition to those factors which influence the energy loss, consideration must be given to the maximum magnetic field at which it will be possible to operate the superconductor. In the case of a type II superconductor the maximum allowable magnetic field will be the thermodynamic critical field, H_c, while in the case of a type II superconductor it will be the lower critical field, H_{c1}. The lower critical field, H_{c1}, for ultra-high purity niobium is greater than either that of any other known type II superconductor or the thermodynamic critical field, H_c, of any type I superconductor. Thus the highest energy gradients theoretically attainable in a superconducting rf cavity would be in one fabricated of niobium. For this reason niobium is the preferred material for the fabrication of superconducting rf cavities. In addition, the performance of a niobium cavity is not as susceptible to deterioration with time due to oxidation as are lead cavities.

DISCUSSION

High-purity niobium appears to be the ideal superconductor for use in rf cavities designed for use in linear accelerators and beam separators. In this section some of the problems that have been found to date in fabricating superconducting niobium rf cavities with high Q's are discussed. In addition, a unique new method presently being developed by Union Carbide for fabricating superconducting niobium rf cavities is described.

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1. G.W. Mellors and S. Senderoff, J. Electrochem. Soc. 112, 266 (1965).
2. R.W. Meyerhoff, to be presented at and published in the Proc. of the Electro-Chemical Society Symposium on Preparation and Purification of Ultra-Pure Metals, Montreal, Canada, 1968.
3. W.T. Beall and R.W. Meyerhoff, to be submitted to J. Appl. Phys.

In principle, all that is required for a superconducting niobium rf cavity is a niobium structure having the desired shape with niobium walls of the order of a few thousand angstroms thick. However, since many of the rf cavities proposed have dimensions of the order of 30 cm or more, such a structure made of niobium only a few thousand angstroms thick would not be self-supporting. Thus, in order to fabricate a superconducting niobium rf cavity there are four alternatives:

1) The cavity could be machined from a massive section of niobium with walls sufficiently thick to support the cavity when it is evacuated.

2) Deposit the niobium in some manner on a suitable substrate using a thin deposit of niobium as the superconductor with the substrate supplying the mechanical support.

3) Deposit niobium on a substrate, which will subsequently be removed, to a thickness sufficient that the niobium will support itself after the substrate is removed.

4) Deposit a thin layer of niobium on a substrate which will subsequently be removed and deposit a layer of suitable supporting material onto the niobium before removing the substrate.

The first of the alternatives seems to be impractical for a number of reasons, not the least of which is the prohibitive cost of the niobium required. In addition to the high cost inherent in machining an rf cavity from a solid piece of niobium this method makes it difficult if not impossible in many cases to make a series of complex cavities without one or more joints. For example, cavities such as those shown in Fig. 1 would have to be made in two or more sections since it is not feasible to machine such internal shapes in a solid piece and produce a high quality surface finish.

The second method in which one would fabricate an rf cavity by depositing a thin layer of niobium onto a substrate is more economical. In this case the mechanical support would be provided by the substrate. At first sight the simplest and most direct way of preparing this type of niobium rf cavity would be to use a high thermal conductivity material such as copper as a substrate and then deposit a thin layer of niobium on the inside of this substrate by some technique such as electroplating or vapor deposition. There are, however, two principal problems with this approach. First, rf cavities having complex shapes, such as those shown in Fig. 1, would have to be fabricated in two or more sections because of the difficulty in both machining such shapes and in depositing a niobium film on the inner surface of such shapes.

Second, in order to obtain the required performance in a superconducting rf cavity an extremely smooth superconducting surface is required. At this time the techniques given above do not produce an adequately smooth surface. It is possible to obtain a reasonably good surface by these techniques, if the original deposited niobium surface is then mechanically, chemically or electrically polished. However, this would be very difficult, if not impossible, in most cases because of the complex shapes of rf cavities.

Because of the economic and/or mechanical problems associated with the first two methods discussed above a new technique for manufacturing superconducting niobium rf cavities based on the third and fourth methods listed above is being developed. The steps used in fabricating an rf cavity by this method are illustrated in Figs. 2 and 3 and are described in detail below.

<u>Step 1.</u> The first step is the fabrication of a copper substrate designed to conform to the shape of the inside of the rf cavity. That is to say, the copper substrate has the same dimensions as will the

empty space within the finished rf cavity. After machining, the copper substrate is first mechanically polished and then electropolished. In the finished cavity the active niobium surface will be that surface which was originally in contact with the copper substrate and will therefore have a surface finish which is virtually identical to the original surface finish of the substrate.

Step 2A. A coating of niobium having the desired thickness is deposited onto the copper substrate by means of the fused salt plating process developed by Mellors and Senderoff.[1] Since this process is described in detail elsewhere[1] only a brief description is given below. An electrolyte consisting of 26.2 wt% LiF, 10.5 wt% NaF, 47.0 wt% KF and 16.3 wt% K_2NbF_7 is used. During plating this electrolyte is maintained at $\sim 775^{\circ}C$. Commercial grade niobium is used for the anode and OFHC copper for the cathode substrate although many other materials such as iron, stainless steel, etc. are also suitable as cathodes. Normally niobium is electroplated at a current density of 5-125 mA/cm^2 which corresponds to a deposition rate of 5.08 - 127.0 μ/h. A typical analysis of the electroplated niobium is as follows: carbon, < 1 ppm; oxygen, 40 ppm; hydrogen, 1 ppm; nitrogen, < 1 ppm; iron, nickel and chromium, 20 ppm each; tantalum, < 8 ppm; tungsten, 2 ppm. The first niobium plated from a new electrolyte will contain < 2 ppm tantalum; however, since this is considerably less than the several hundred ppm tantalum in the commercial purity niobium anodes used, the tantalum content in the electrolyte will increase with time with a concomitant small increase in the tantalum content in the electroplated niobium.

Step 2B. If the niobium deposited in step 2A is not thick enough to be self-supporting, a porous layer of tungsten is then deposited over the electroplated niobium. (While the tungsten can be deposited by plasma plating, powder metallurgy techniques or chemical vapor deposition, plasma plating has been used in the initial cavities prepared by this method.) The tungsten coating serves to support the niobium during the subsequent vacuum outgassing and to provide the mechanical support necessary in the finished rf cavity. In addition, the porosity of the tungsten should enable the helium in the liquid helium bath surrounding the cavity to circulate through it giving rise to an extremely high effective thermal conductivity between the niobium inner cavity wall and the surrounding liquid helium bath.

Step 3. Most of the machining of the plated cavity (machining of o.d. to final size, flanges, mounting holes, etc.) is done prior to the removal of the substrate. Those portions of the substrate used to hold the cavity during plating are also removed in this step.

Step 4. The copper substrate is removed from the electroplated niobium or niobium-porous tungsten composite structure. In the prototype cavities fabricated to date the copper substrate has been removed by dissolving it in dilute nitric acid. The copper substrate could also be removed electrolytically or by melting the copper and pouring most of it out using either nitric acid or an electrolytic method to remove the small quantity of copper left behind by the latter method.

Step 5. The rf cavity, either all niobium or niobium backed with porous tungsten is vacuum outgassed and annealed at a temperature of

$\sim 2200^{o}C$ at a pressure of $\sim 10^{-8}$ torr. This step will also give rise to both some sintering of the porous tungsten increasing its mechanical strength and improving the quality of the tungsten-niobium bond.

Step 6. The last step consists of final trimming of the rf cavity, vacuum testing of the finished cavity and any other inspection operations necessary to insure that the finished product meets specifications.

SUMMARY

In the previous section a new technique for fabricating ultra-high-purity niobium rf cavities was described. It appears that this technique will eliminate the problems associated with the production of rf niobium cavities discussed earlier. The major features of this new fabrication method are discussed below.

1) This fabrication method provides a way by which a multiplicity of integrally connected rf cavities of complex shape can be fabricated in a single section free of joints.

2) By suitable initial finishing of the surface of the copper substrate an rf cavity can be fabricated which does not require any additional polishing to obtain an adequate surface finish on the niobium.

3) When a very high thermal conductivity is required porous tungsten can be used to provide mechanical support for the niobium.

To date, only a few rf cavities have been prepared by this fabrication method. These cavities, both the niobium and niobium backed by porous tungsten variety, have all been X-band cavities designed to be operated at 11.2 GHz. The best results obtained to date were on a TE_{011} mode cavity vacuum outgassed at $2000^{o}C$ for 3 h for which $Q \approx 2 \times 10^{9}$ and $H_{ac} \approx 350$ G.[4] A TM_{010} mode cavity tested as plated with no additional polishing or heat treating gave $Q \approx 3 \times 10^{7}$ and $H_{ac} \approx 110$ G.[4] A TE_{011} mode cavity tested as plated gave $Q \approx 1 \times 10^{8}$.[4]

A few typical cavities fabricated by this method are illustrated in Figs. 4 and 5. Future work is planned to further improve the values of Q and H_{ac}. Some of the results obtained thus far indicate that by improving the quality of the surface finish on the copper substrate prior to electropolishing niobium higher values of Q and H_{ac} can be obtained for both the as-plated and the vacuum outgassed cavities. In fact for some applications, especially at frequencies lower than X-band, it may be possible to prepare cavities with useful Q's without the need of any heat treatment subsequent to the electroplating.

4. J.P. Turneaure, Stanford University, private communication.

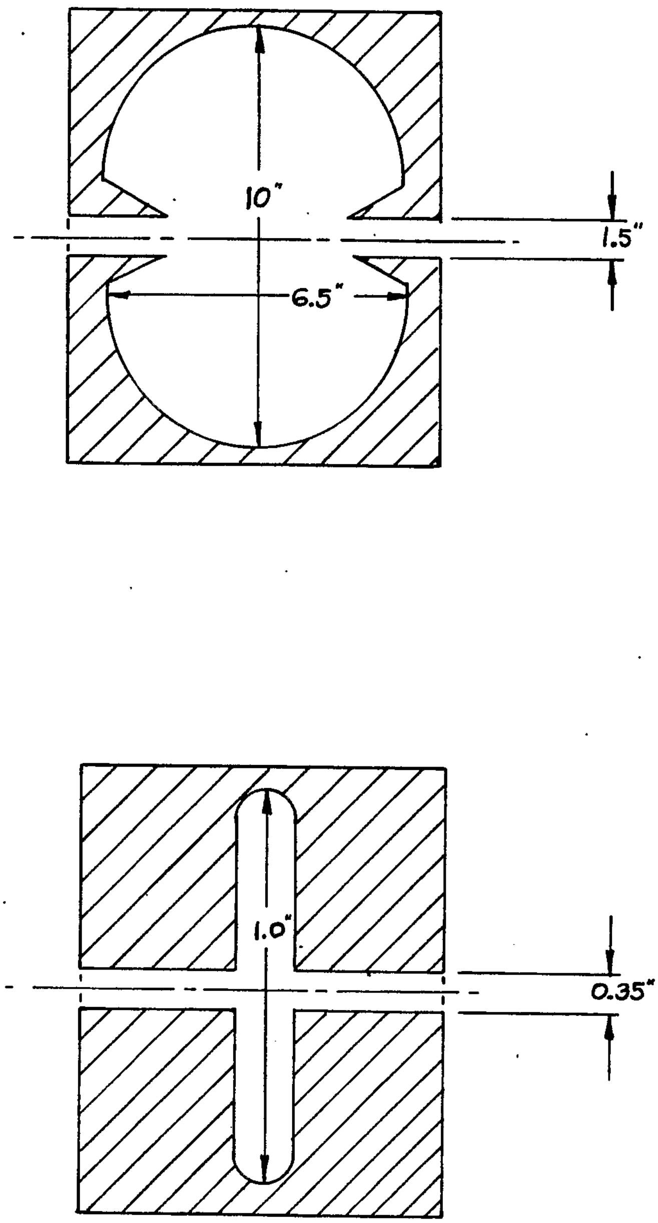

Fig. 1. Typical geometrically complex rf cavities.

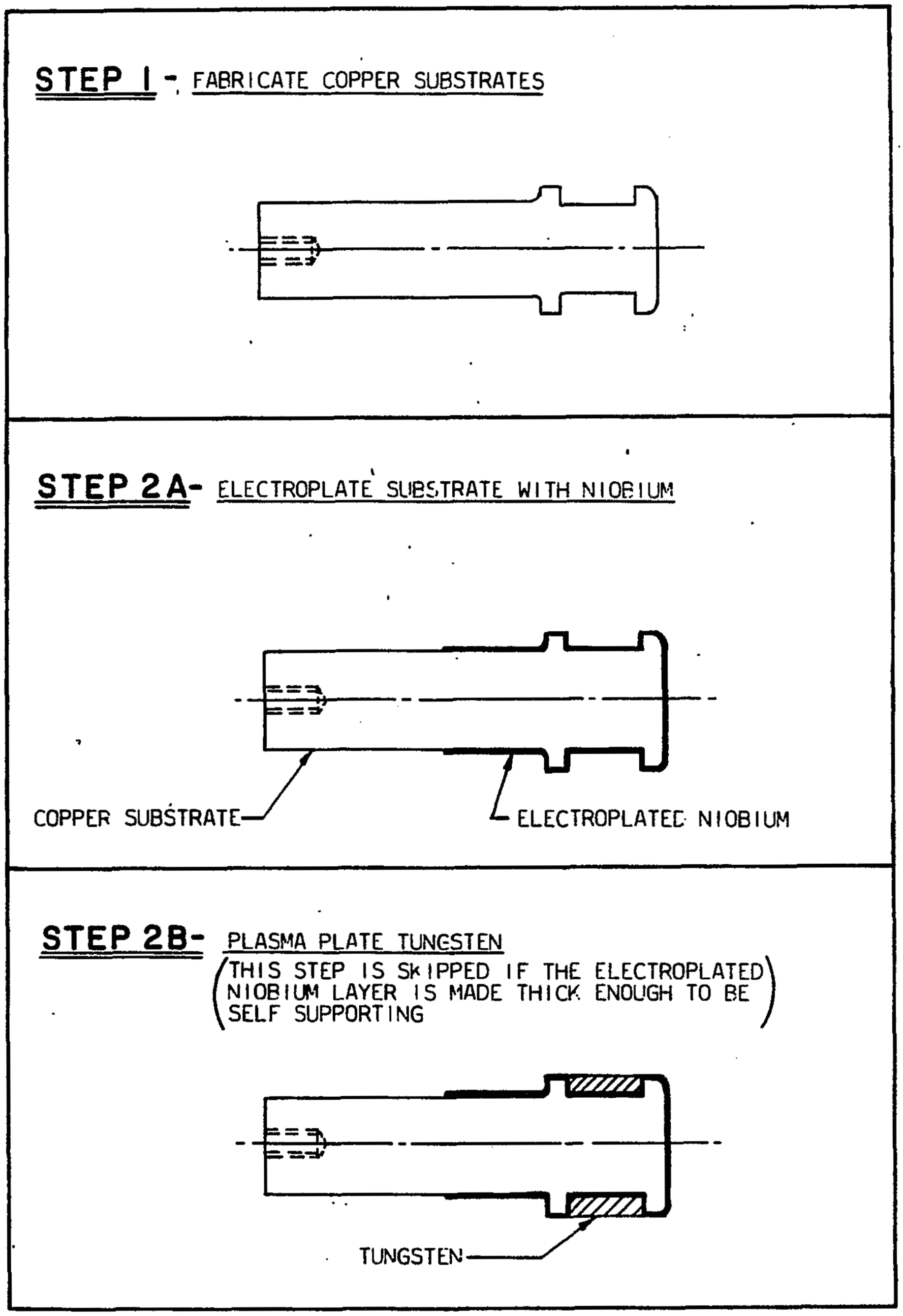

Fig. 2. Steps in the fabrication of rf cavities.

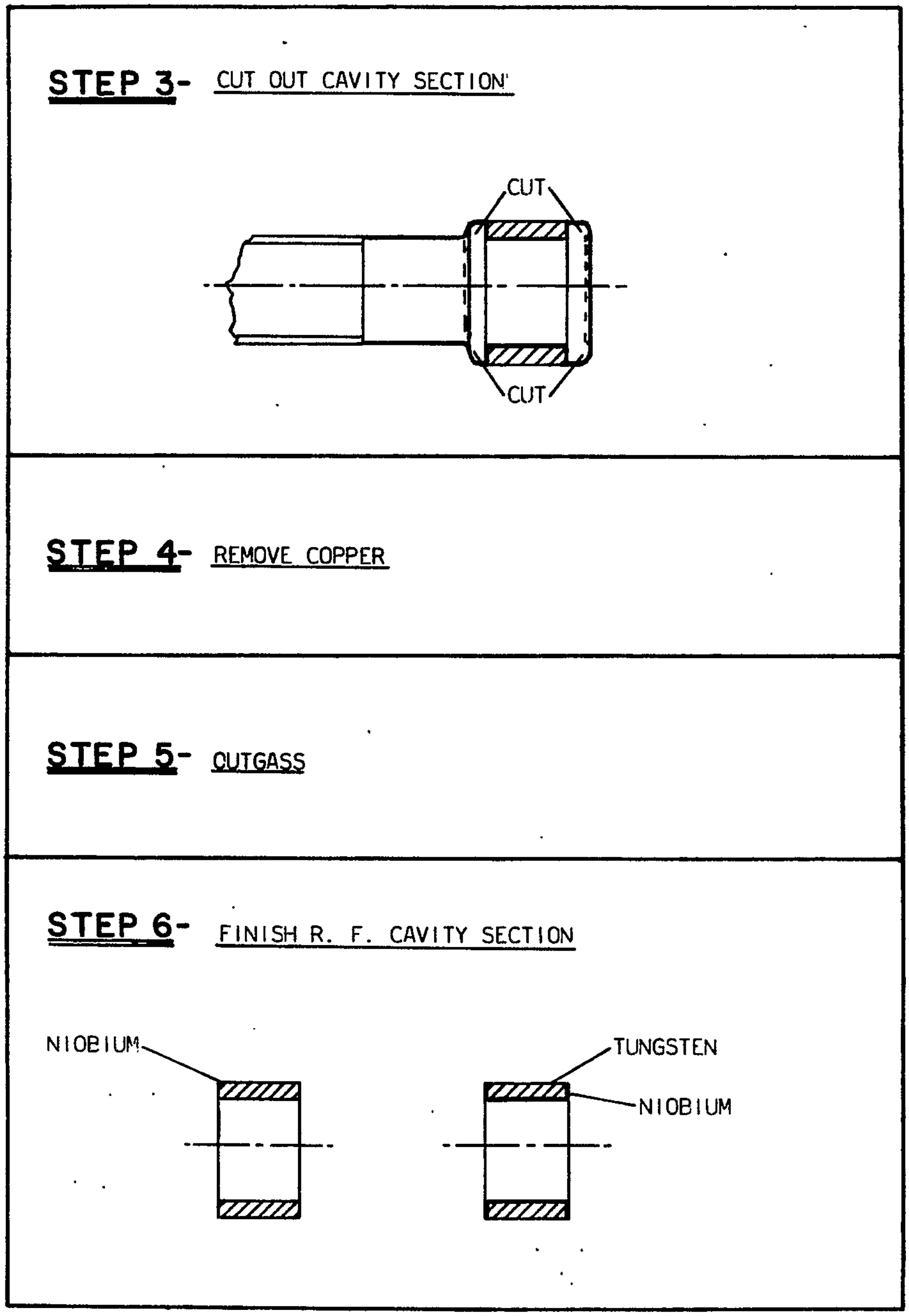

Fig. 3. Steps in the fabrication of rf cavities.

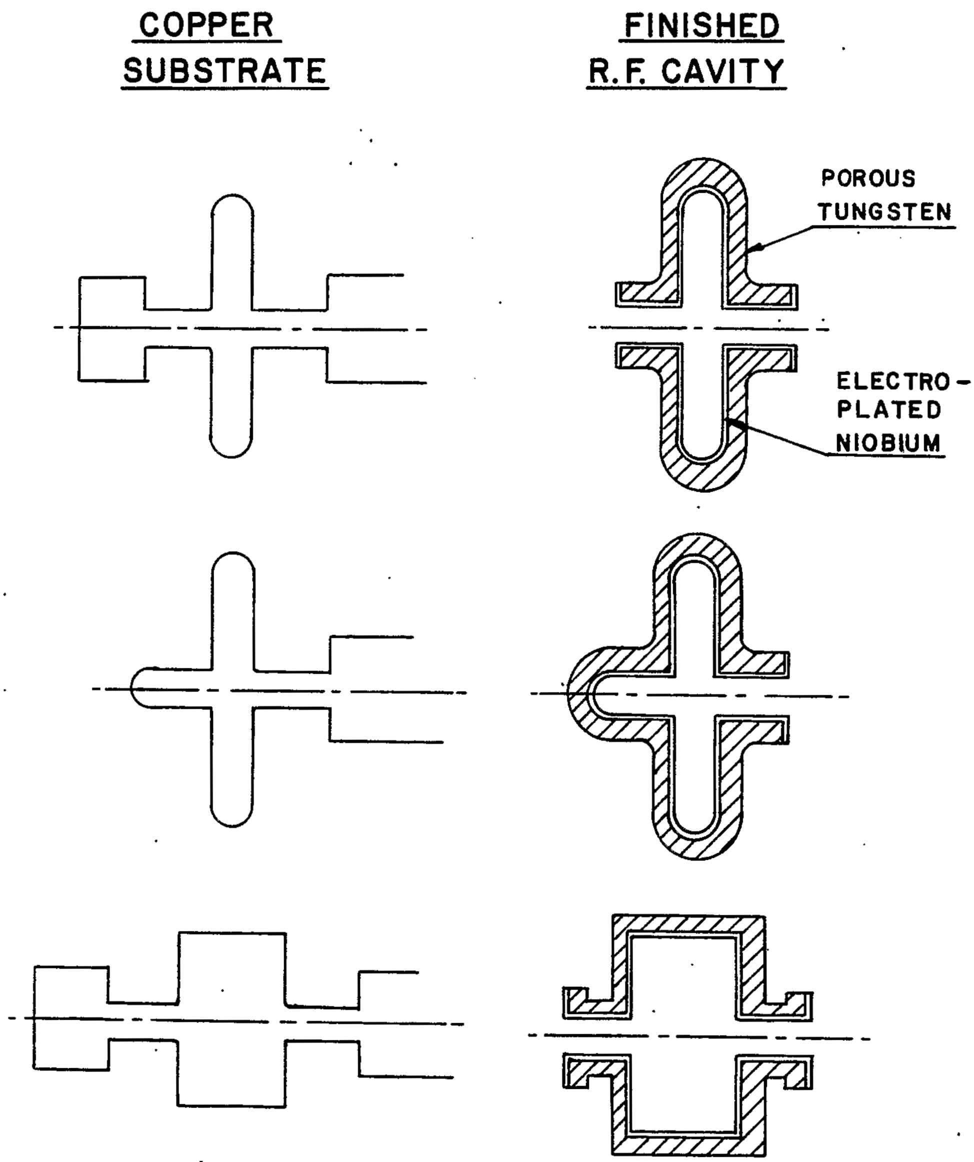

Fig. 4. Examples of easily fabricated geometrically complex rf cavities.

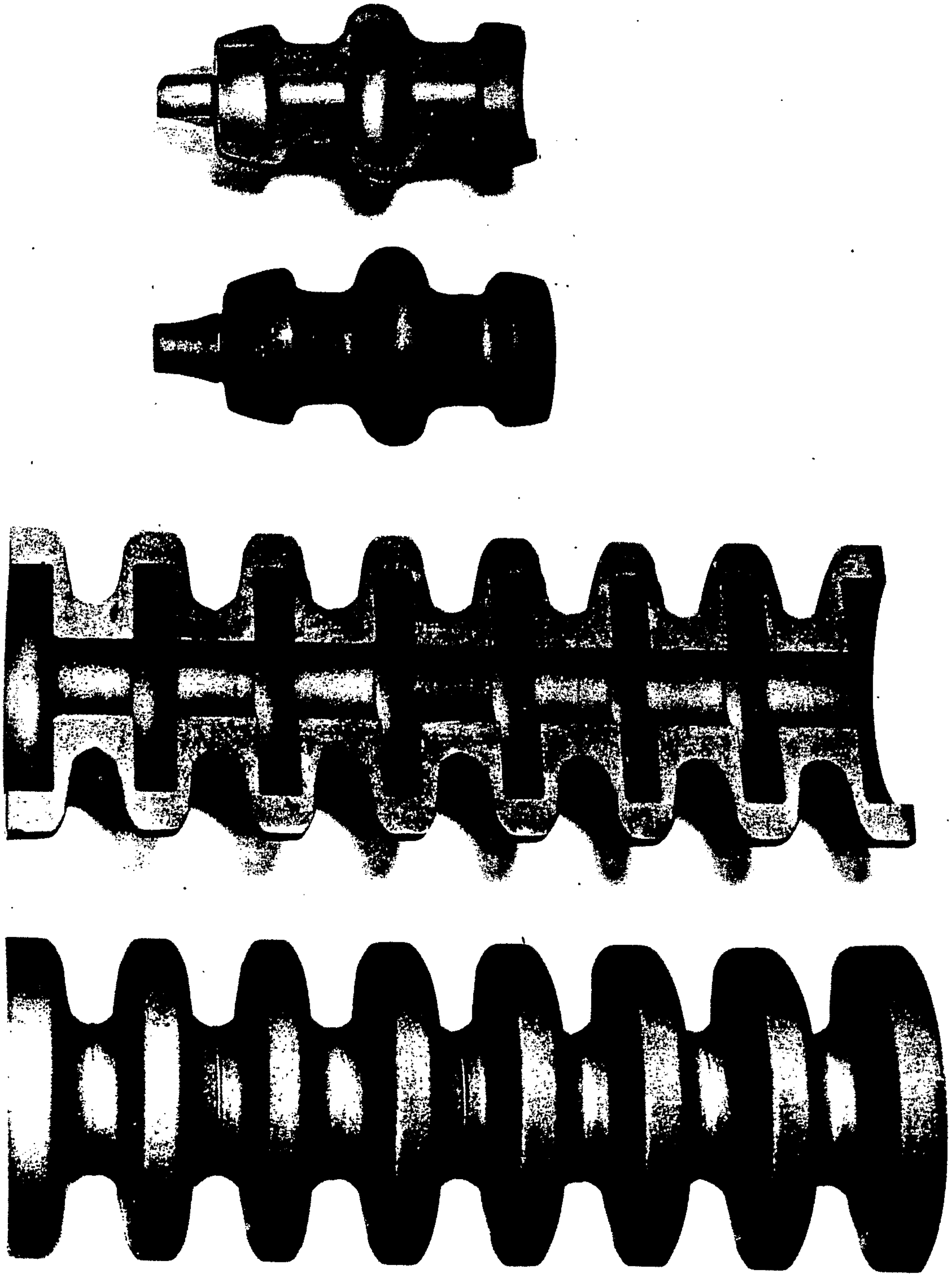

Fig. 5. Examples of easily fabricated geometrically complex rf cavities.