Measurements at 8.6 GHz on TM mode superconducting niobium cavities have been carried out at SLAC in an attempt to establish definitive conditions for reproducibly attaining high peak electric and magnetic fields and high residual Q. Four cavities, processed by techniques which insure the presence of an oxide layer on the niobium surface before final high temperature outgassing, have given peak magnetic fields exceeding 1000 G and corresponding peak electric fields in excess of 56 MV/m. From this and related experience it is speculated that, in order to achieve high peak fields, carbon present on the niobium surface must be removed through the formation of volatile compounds with oxygen or fluorine during high temperature processing. Data are also presented on the effect on rf properties of exposure at room temperature to various gases. Measurements on anodized cavities are briefly discussed.

Introduction

A large number of measurements have been made at SLAC on superconducting X-band cavities in an effort to gain an increased understanding of the factors which limit the residual Q and the peak rf electric and magnetic fields at superconducting surfaces. A frequency on the order of 10 GHz is convenient because of the small cavity size and consequent economy of fabrication and ease in processing and handling. Recent work at SLAC has been performed on TM mode cavities, since the electric and magnetic fields in such cavities correspond closely to the fields to be expected in a single cell of standing wave superconducting accelerator structure.

Ideally, the conditions at the superconducting surface should be characterized by LEED, Auger and other appropriate techniques simultaneously with the measurement of rf properties. In principle this could be accomplished by using a rod-shaped sample which, after being processed and subjected to surface characterization studies, is lowered into place within the same vacuum envelope to become the center conductor of a TE011 mode coaxial cavity for rf measurement. Because of the difficulties associated with the construction of an apparatus of this complexity, we have turned to the TM mode cavity as the simplest unit in which rf properties can be measured, and for which there is reasonable control over the environment seen by the cavity surface during the various stages of processing and handling. Nevertheless it is still difficult to carry out surface characterization studies on samples which are meaningfully correlated with conditions on the inaccessible cavity interior. On the basis of limited microwave and Auger measurements made on cavity sections following processing and rf testing, relying also on intuition, trial and error and simple phenomenological models, we have tried to develop procedures for the reproducible construction of cavities with low residual loss and high limiting fields.

Fabrication and Processing Procedures

Most of the effort has been devoted to cavities which have been processed at high temperature and assembled in nitrogen without exposure to air. Only a few anodized cavities have been measured, partly because this technique is being vigorously investigated at other laboratories, and partly because the rf properties of clean niobium surfaces are felt to be relevant even if the surface is later anodized. Likewise, electropolishing has not been actively pursued at SLAC, in part because of the difficulty of applying the process to the convoluted interior surface of accelerator structures, and in part because good success has been attained in X-band cavities by chemical polishing alone. Further, we have not been able to detect any significant difference in results obtained using the refrigerated solution (60% of 98% H2PO4, 40% of 85% H3PO4) and a solution (1 part 85% H3PO4, 1 part 70% HNO3, 1 part 48% HF) as opposed to a buffered room temperature chemical polishing solution (1 part 85% H2PO4, 1 part 70% HNO3, 1 part 48% HF).

The cavities reported upon here have been fabricated from reactor grade, electron beam melted niobium.4 The most successful cavities have been electron beam welded after final machining using an air heater as described in Fig. 1. We have not had good success at SLAC using outside full penetration welds. After welding, the cavities are typically chemically polished to remove about 10 microns of niobium, high temperature outgassed at about 2000°C for around ten hours, chemically polished a second time, and then again high temperature fired. After the second outgassing cycle, the furnace is let down to pure dry nitrogen and the rf window and valve assembled to the cavity in a glove box attached to the furnace, hopefully without the slightest exposure to air. After assembly, the cavity is pumped without baking until the pressure is on the order of 10^-10 torr, at which time the attached all-metal valve is closed and the radiation shown in Fig. 1 is pinched off. Good results have been obtained using both an induction furnace and a resistively heated furnace. The most important variable, in fact, seems to be the purity of the nitrogen gas used in the let down and assembly procedure. No correlation between rf results and firing temperature, over the range 1900-2100°C, has been observed.

Cavities with several different geometries have been tested, although most of the measurements reported upon here have been made with cavities as shown in Fig. 1. For this cavity geometry, the product of unloaded Q and surface resistance is 213 and the ratio of peak electric and magnetic fields is 0.06 (MV/m)/G.

Experimental Results: Gas Exposure Tests

The results of exposure of clean niobium cavities to various gases at room temperature will be briefly reported here. Additional measurements are planned, and a more complete account will be published later. In these experiments, the cavities, after they have been fired and tested as usual, are let down to the gas in question at a pressure of about 1/4 atmosphere for about 1 hour. The gas is then pumped from the cavity until the residual pressure is below 10^-10 torr (without baking), the valve attached to the cavity is closed, and the cavity is retested. The results to date are summarized in Table I. In this table, each series gives the results of successive exposures for a given cavity. The Q jumping factor is the ratio of Q at low power (measured at about 1.5 K) after the application of high rf power, to the low power Q before the initial application of high power.

It is seen that the effect of various common gases on the rf properties of the surface can be profound, even though the metallurgy of the surface layer within the penetration depth must remain essentially unchanged. The results point out the importance of cleanliness in cavity assembly after high temperature firing. The importance of the kind and amount of residual gases remaining in the cavity, and the desirability of isolating a cavity from the room temperature vacuum system by means of a low temperature rf window. Recent results at HEPL show that magnetic field breakdown generally occurs at that location in the cavity which is the first to cool and to form a site for trapping residual gases. This again points out the importance of cleanliness and residual gas composition. We can conclude that it is highly desirable to have an appendage attached to the cavity which is cooled during
transfer before the main cavity, and which can act as a cryopump to trap out the residual gas content well away from surfaces seen by the rf. This appears to be the situation for the cavity assembly as shown in Fig. 1.

In recent measurements at Siemens, 4 increased magnetic breakdown fields have been obtained by introducing helium gas at a low residual pressure (below the glow discharge region) during the application of power. Presumably, continuous helium ion bombardment "scrubs" the surface and moves any adsorbed residual gas into regions of the cavity where the rf fields are low.

**Experimental Results: The Role of Surface Carbon**

At one point in the cavity measurement program at SLAC, the results were extremely discouraging. Every effort was made to improve cleanliness at each step of cavity processing and assembly, but in spite of all such efforts cavities continued to be limited by breakdown fields in the 200–500 G range. There seemed, in fact, to be a negative correlation between cleanliness and breakdown field. In analyzing the steps that led to the production of the few relatively good cavities measured by the rf fields are low.

The presence of carbon on a fired niobium cavity surface has been seen in electron microprobe studies 8 at SLAC. The carbon tends to occur as granules with dimensions on the order of 10 microns, frequently located at crystal boundaries. Similar carbon inclusions have been seen 2 at Cornell on samples studied with a scanning electron microscope. These carbon clumps can presumably become regions of enhanced local heating leading to magnetic field breakdown at fields well below the critical field expected for a homogenous surface.

Three techniques have been used at SLAC to facilitate surface carbon removal. The simplest is a double final firing in which the furnace is let down to oxygen for several hours between firings. A second technique is to anodize the cavity before final firing. Finally, two cavities have been processed for an hour or so in the induction furnace in an oxygen atmosphere at a pressure of 7 × 10⁻⁸ torr and a temperature of 1000°C. After this step, the oxygen was then pumped out and the temperature raised to 2050°C for several hours to outgas dissolved oxygen from the metal. In these two tests the residual Q's were 1.8 × 10⁹ and 6 × 10⁹, and the respective rf magnetic breakdown fields were 830 G and 613 G. The high power behavior of one of the cavities (XTM 12-3) is shown in Fig. 2. The second cavity with the lower breakdown field and residual Q had a very unusual, sharp resonance peak in the curve of surface resistance vs. field level.

The results of Giordano et al., 8 indicate that a high solute oxygen concentration has an adverse effect on both residual Q and breakdown field.

**Experimental Results: Anodizing**

Several tests have been made on anodized X-band cavities, with mixed results. A TM₀₁₁ mode cavity was anodized at 50 V and stripped six successive times in an effort to expedite the removal of surface carbon. Several tests have been made on anodized X-band cavities, with mixed results. A TM₀₁₁ mode cavity was anodized at 50 V and stripped six successive times in an effort to expedite the removal of surface carbon. Several tests have been made on anodized X-band cavities, with mixed results. A TM₀₁₁ mode cavity was anodized at 50 V and stripped six successive times in an effort to expedite the removal of surface carbon.
High Field Results

Data on the processing techniques together with rf results for five high field cavities are given in Table II. It is seen that all three techniques for processing with oxygen have given good results. The behavior of the surface resistance of these cavities as a function of field level is shown in Fig. 2. In general, the surface resistance is seen to decrease at moderate field levels, rising again at the highest fields. This general behavior is similar to that observed by Kneisel et al. for anodized TM010 mode cavities at S-band. A rise at high field levels in the effective surface resistance would normally be expected as the result of simple thermal heating, although in two of the cases shown in Fig. 2 a considerably steeper rise was observed, associated with field emission loading. For cavity XTM 10-7, a Fowler-Nordheim plot was made using the observed radiation level outside the dewar, following a relation due to Schopper et al., which takes into account absorption by the cavity and dewar walls. The dose rate divided by \( E_m \) is plotted on a semi-log scale as a function of \( E_m \), where \( E_m \) is the maximum electric field in the cavity in MV/m. The enhancement factor is equal to \( 2.2 \times 10^4 \) divided by the slope of the resulting straight line.

For XTM 10-7 an enhancement factor of 50 was calculated in this manner.

The variation in effective surface resistance as a function of field level for one of the cavities (XTM 6-13) is shown in Fig. 2 for several different temperatures. The behavior is unusual in that the breakdown field clearly does not vary as \( (1 - (T/T_C))^2 \). During initial processing, this cavity first showed classical magnetic field breakdown at the 700 G field level. After a period of processing, this breakdown field suddenly increased to the 980 G level shown for 1.7°C K. A relatively slight increase in temperature to 2.06°C K caused the breakdown field to drop to 660 G. We can speculate that a small region on the cavity surface went normal at about 700 G. At the lower temperature thermal conduction was just adequate to remove the heat generated at the defect so that thermal runaway did not occur at that field level. An increase in temperature to 2.06°C K changed the thermal balance sufficiently to allow thermal runaway, causing the breakdown field to drop abruptly back to the 700 G level.

Concluding Remarks

During the period reported upon here, about a dozen tests were made in an attempt to obtain good cavities using one of the three methods of processing with oxygen, and in which there was not at the same time an obvious source of known degradation such as an inadvertent exposure to air. The breakdown fields for these tests ranged from 313 G to 1660 G, and the residual Q's from 0.5 to \( 5 \times 10^6 \) (median values for the breakdown field and residual Q were 630 G and \( 3 \times 10^6 \)). Thus it appears that the presence of sufficient oxygen during high temperature processing may be a necessary condition for obtaining good rf properties, but it is obviously not a sufficient condition. Particularly toward the end of the measurement period, contamination of the nitrogen used for let-down and assembly was suspected as a factor in a series of poor results. The gas exposure tests have led to a better understanding of these results, and have pointed the way to the necessary steps for improvement.

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References

6. Carried out with the cooperation of the Center for Materials Research, Stanford University.
7. R. Sundelin, Laboratory of Nuclear Studies, Cornell University, private communication.
FIG. 1--TM mode X-band cavity assembly.

FIG. 2--Effective surface resistance as a function of peak rf magnetic field for several high field cavities.

FIG. 3--Effective surface resistance of XTM 6-15 as a function of peak rf magnetic field at several temperatures.