Infra-Red Propagation Through Various Waveguide Inner Surface Geometries

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Abstract

The inner surface geometry of any given RF waveguide plays a major role in the amount of thermal radiation that is transferred through its length. Calculations predict that thermal radiation transmitted to the cold end of a waveguide can be greatly reduced via increased surface diffusivity and decreased reflectivity. Presented are the results of an infrared examination of the thermal radiation propagated through a ninety degree waveguide elbow with various inner surface geometries when a heat load is applied to one end. This is followed by results of surface studies of smooth, sandblasted, and acid etched copper using microscopy and IR reflectivity.

1 Introduction

This infrared radiation propagation experiment pertains to the heat load delivered to an SRF helium vessel by way of the RF waveguide to the cavity. Based on ray tracing simulation, a surface dull to IR has a much greater effect on attenuating IR than a macroscopically grooved (1/16") inner surface, such as that used on the Mark II cryostats. It was shown that macroscopic grooves disperse rays so that ultimately half the incident rays are reflected and half are transmitted, thus reducing transmitted power at most by a factor of 2. Further, the macroscopic grooves have proven troublesome to RF power propagation, whereby the enhanced electric field at the sharp ridges cause electron emission which feeds multipactor discharges and violent field emission. A dull surface is characterized by what are often the related properties of reflectivity (= 1 - absorption) and whether the surface has specular or diffuse reflection. Presented here are the results of IR propagation measurements performed on a 90° waveguide elbow E-bend with various inner surface geometries. This is followed by results of surface studies of smooth, sandblasted, and acid etched copper using microscopy and IR reflectivity.


(a)

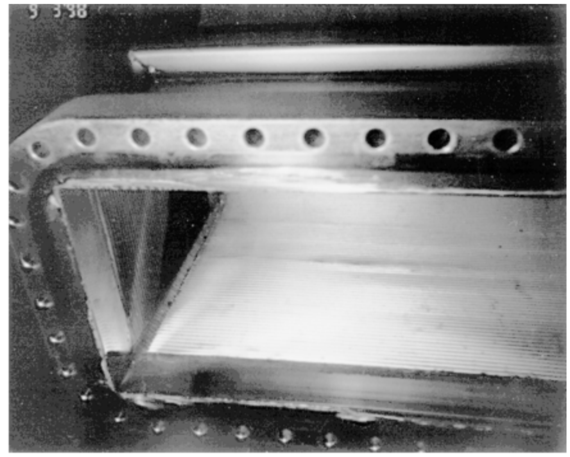

(b)

Figure 1. Two views of the grooved inner surface of the test waveguide elbow.

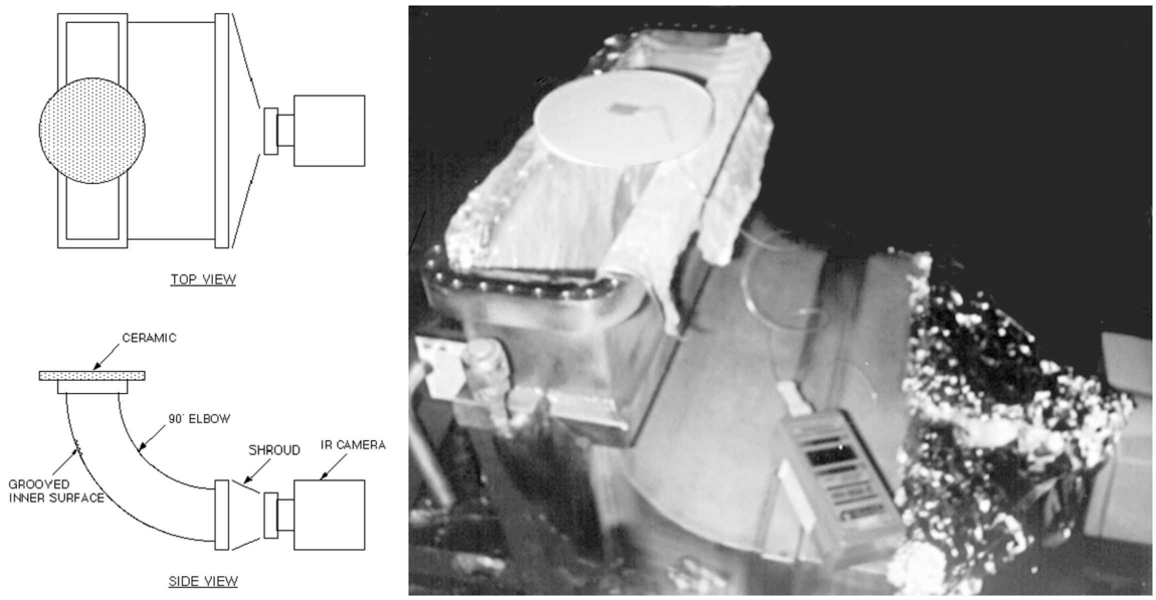
2 Waveguide Apparatus

Three different surface geometries were tested: IR specularly smooth, IR dull via sandblasting, and simultaneously macroscopically grooved and IR dull. The machined surface of the waveguide elbow used for the experiment had a macroscopically grooved inner surface of right angle sawtooth geometry with 1/16" depth, as shown in Fig. 1. An IR specular surface was obtained by laying aluminum foil along the inner surface of the waveguide. For the IR dull case, the aluminum foil was sandblasted prior to lining the inner surface of the waveguide, the amount of sandblasting being modest as limited by destruction of the foil.

Illustrated in Fig. 2 is a schematic layout of the test assembly as well as a photograph. A ceramic disc (alumina) at a temperature of 80°C was placed against one aperture of the elbow and an 8-12 μm IR camera with an aluminum foil shroud viewed the other aperture to measure the thermal radiation propagating through the elbow. The radiated power density of the ceramic is given by the familiar black body law

$$U = \varepsilon \sigma T^4 \ , \tag{1}$$

where ε is the material emissivity ($\varepsilon \cong 1$ for alumina), $\sigma = 5.67 \times 10^{-8}\ \mathrm{W/m^2 \cdot K^4}$ is the Stefan-Boltzman constant, and T is the temperature in Kelvin. The majority of the power spectrum is in the IR. Since all tests were conducted at a room temperature of 295 K, the background radiation level was nominally $429\ \mathrm{W/m^2}$. The radiation density due to the



(a) **(b)**

Figure 2. Waveguide elbow IR test assembly schematic and photograph showing the thermocouple monitoring ceramic temperature.

353 K (80˚C) ceramic disk was 880 W/m^2, so the *above-background* radiation density due to the hot ceramic disk was

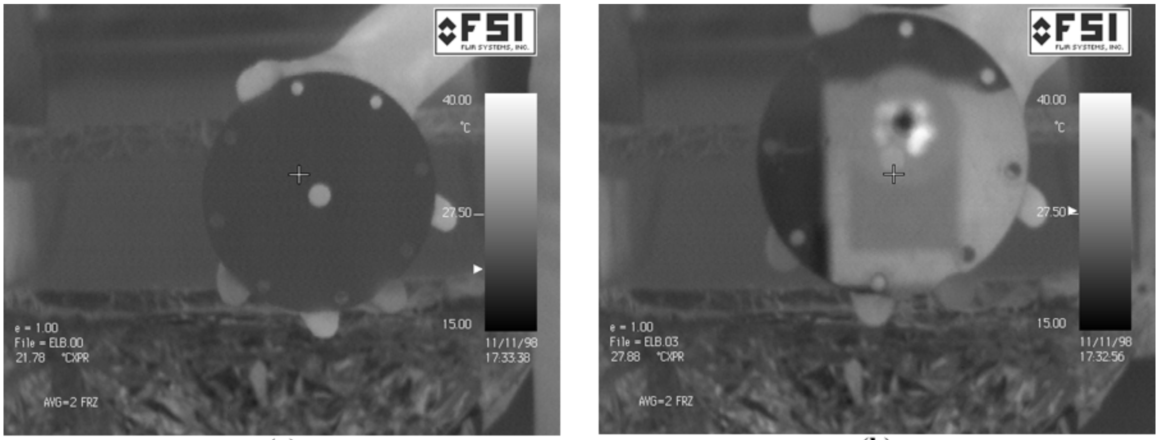
$$U_{above} = \varepsilon\sigma(353^4 - 295^4) = 451 \text{ W/m}^2 \ . \tag{2}$$

A portion of the 15 cm diameter ceramic was occluded by the 4" high waveguide aperture, thus the exposed ceramic area was 0.01398 m^2, and the 353 K disk radiated an above-background power of 6.3 W.

3 Waveguide Measurements

3.1 Baseline IR Reflectivity of Surfaces

To establish references for diffuse and specularly reflecting surfaces in the IR, a stock copper plate that was not specular at visible wavelengths was sandblasted on one side, then viewed from both sides with the IR camera. As seen in Fig. 3a, the sandblasted side is quite diffuse in the IR, presenting a uniform room-temperature black-body image to the camera. As seen in Fig. 3b, the non-sandblasted side is quite specular in the IR, transmitting coherent images of distant objects, such as the IR camera that took the picture. Establishing these references is important to the experiment in that we ultimately desire



(a) **(b)**

Figure 3. a) Sandblasted side of a copper disc as seen by IR camera. b) The non-sandblasted side of the same copper disc specularly reflecting a thermal image of the IR camera.

surface conditions that have poor IR reflectivity, and we require the IR camera to be able to distinguish between them.

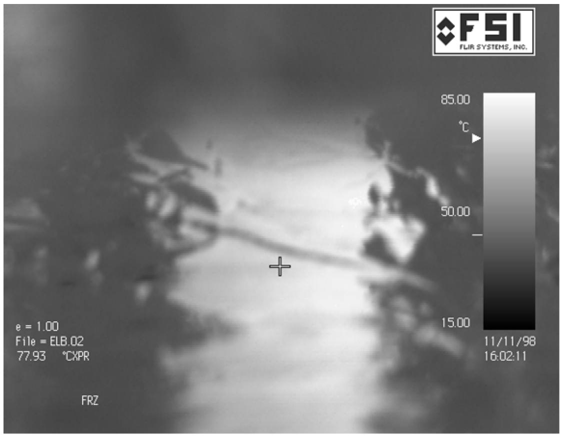
3.2 Radiative Load Delivered to the IR Camera for Three Waveguide Inner Surface Conditions

3.2.1 Smooth Waveguide

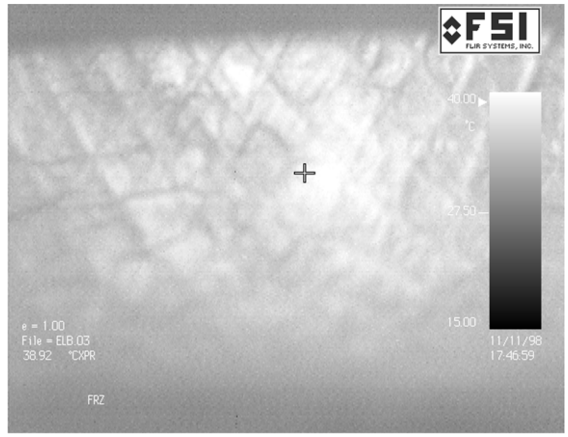
Shown in Fig. 4a is an image taken with the IR camera looking into the waveguide elbow aperture opposite of the hot ceramic disk (as shown in Fig. 2) when the elbow is lined with smooth aluminum foil. The IR radiation from the ceramic is well transmitted, with the temperature display indicating an output of 77.9˚C, very close to the ceramic temperature of 80˚C. Within the few ˚C resolution of the IR camera, nearly 100% of IR radiation is transmitted through the elbow for this specular-lining case.

3.2.2 Sandblasted Waveguide

Shown in Fig. 4b is an IR camera image looking into the waveguide elbow when lined with sandblasted aluminum foil and the 80˚C ceramic at the opposite aperture. In this case, there is considerable attenuation of transmitted radiation, the camera measuring a



(a)



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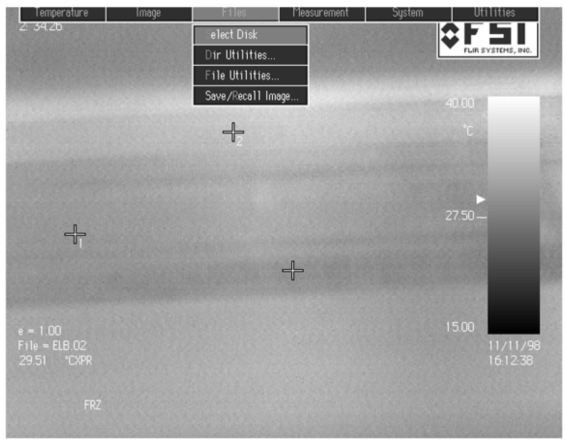


(c)

Figure 4. IR images at the opposing end of the thermally loaded waveguide elbow for a) the smooth inner surface condition, b) the diffuse sandblasted inner surface condition, and c) the grooved and diffuse inner surface condition.

maximum temperature of 39˚C. This corresponds to an above-background radiation density of

$$U_{above} = \varepsilon\sigma(312^4 - 295^4) = 108 \text{ W/m}^2 \ . \tag{3}$$

Dividing this by the above-background launched power density of 451 W/m^2 (eq (2)), the transmitted IR power through the elbow is 24% for this diffuse-lining case.

3.2.3 Grooved Waveguide

Shown in Fig. 4c is an IR camera image looking into the waveguide elbow with no lining, just its diffuse machined surface of macroscopic right angle sawtooth grooves, as shown in Fig. 1, and the 80˚C ceramic at the opposite aperture. In this case, there is even greater attenuation of transmitted radiation than the sandblasted surface, the camera measuring a maximum temperature of 30˚C. This corresponds to an above-background radiation density of

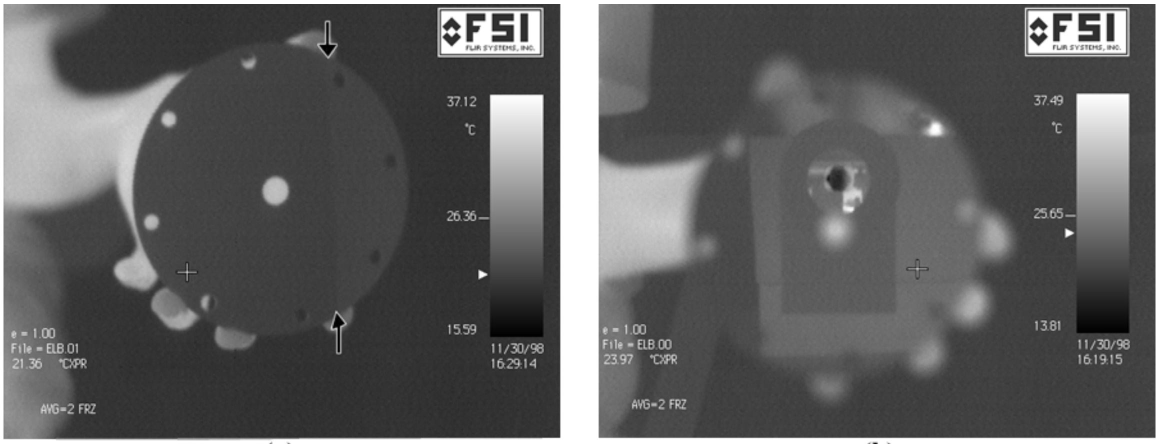
$$U_{above} = \varepsilon\sigma(303^4 - 295^4) = 49\ \mathrm{W/m^2}\ . \tag{4}$$

Dividing this by the above-background launched power density of $451\ \mathrm{W/m^2}$ (eq (2)), the transmitted IR power through the elbow is 11% for this diffuse and grooved case. This measurement of 11% transmission thus demonstrates the additional factor of 2 attenuation introduced by macroscopic grooves over the 24% transmission of the previous case, as discussed in the introduction.

4 Surface Study of Smooth, Sandblasted, and Acid Etched Copper

The experimental results presented above confirm ray-tracing simulations that indicate the IR diffuseness of a surface, with its inherent absorption, is of greater importance to reducing thermal radiation transmission than macroscopic geometries. The concern with the use of a sandblasted surface is the same that very likely plagues the sharply grooved waveguide surface used in the first E2 cryostat and the cause for this study: A vacuum waveguide surface with enhanced electric field at sharp protrusions will more readily emit electrons, which in turn feed multipactor discharges and violent field emission. This would certainly apply to a jagged surface resulting from sandblasting, and the multitude of such small-scale protrusions would probably make RF processing to high powers interminable.

A moderately successful cure for the field emission problem implemented in E1 cryostat was *lapping* the ridges of the grooves to at least remove their hone. This has allowed propagation of greater RF power with less processing than experienced in the E2 cryostat. Since lapping a sandblasted surface would simply make microscopic mush, a better way to eliminate sharp protrusions is the familiar SRF cavity treatment of acid etching. This removes microscopic jagged shards and leaves a gently rolling smooth surface.



(a) (b)

Figure 5. a) Sandblasted and then etched side of a copper disc as seen by IR camera. Arrows denote a chord on the right side of the disk that was re-sandblasted after etching. b) The non-sandblasted, etched side of the same copper disc specularly reflecting a thermal image of the IR camera.

4.1 Acid Etching and IR Reflectivity

To study the microscopic effect of acid etching copper, a sample plate was IR studied before and after sandblasting as well as before and after acid etching. As was seen in Fig. 3, a sandblasted, but unetched, copper plate is quite IR diffuse and the non-sandblasted side is IR specular. The same plate is shown again in Fig. 5 after acid etching. In Fig. 5a the sandblasted side is still IR diffuse after etching, but less so than unetched sandblasted, as seen by the chord on the right side of the disk (denoted by arrows) that was re-sandblasted after etching. In Fig. 5b the non-sandblasted side is seen to remain IR specular after etching, despite being fairly diffuse in the visible range. Thus, acid etching sandblasted copper slightly reduces IR diffusivity, but fortunately does not make it IR specular, at least for the mild etch used in this test. Further, etching alone is not enough to make a non-sandblasted surface IR diffuse, though it becomes optically diffuse.

4.2 Optical Examination of Effect of Acid Etching

The sandblasted copper disk was next examined with an optical microscope to view jagged edges that could enhance field emission. Shown in Fig. 6a is an optical microscope photograph of the sandblasted copper plate shown in Fig. 3a at a magnification of 750×. The loose Al_2O_3 sand particle in the figure is approximately 170 μm in diameter. Although

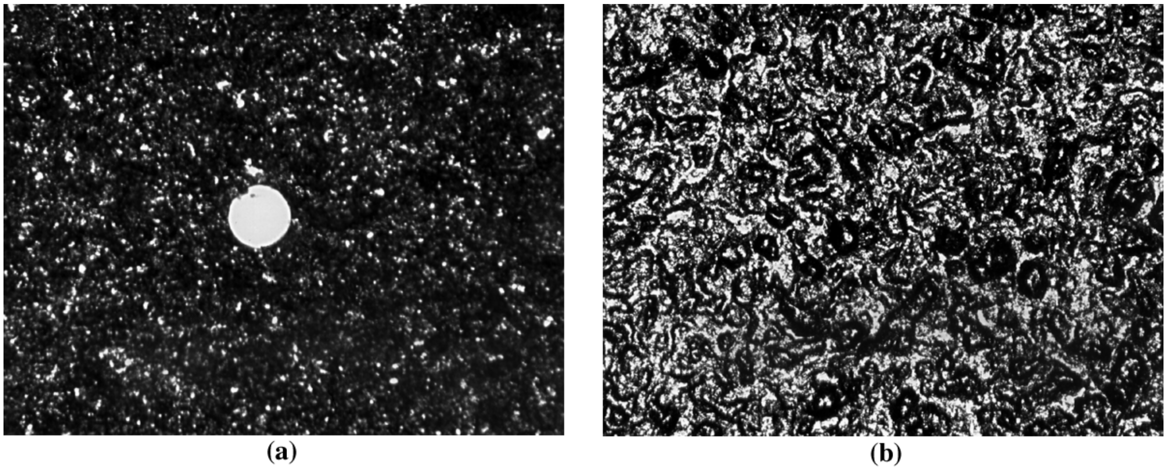


Figure 6. a) Optical microscope 750× image of the sandblasted copper plate with a loose 170 μm diameter Al_2O_3 sand particle. b) Similar image of the same sandblasted copper plate after being acid etched.

difficult to distinguish in the figure, the sandblasted sample is full of jagged peaks and sharp edges, discernible with the microscope by vertically scanning the focal plane. Shown in Fig. 6b is an optical image, again at 750× magnification, of the same sandblasted copper plate after acid etching. As can be seen in the figure, etching the sandblasted copper dramatically reduced the sharpness of the peaks and valleys, leaving a more gradual hill-like contour with clearly visible round pits caused by impacting spherical Al_2O_3 sand particles. Thus, acid etching a sandblasted surface greatly reduces jagged peaks, leaving a surface with contours rounded typically to the diameter of the sand particles used for blasting.

This study of sandblasting and etching suggests a technique to make a vacuum waveguide simultaneously IR diffuse and high RF power compatible. Thorough RF processing tests of vacuum waveguide should be performed to explore the parameter space of sand size, etching duration, and RF power propagation. Indeed, using sand particles with diameters closer to IR wavelengths (10 μm) may impart tremendous IR diffusivity to the surface.

5 Conclusions

The IR propagation properties of various waveguide surface conditions were experimentally studied, confirming ray tracing simulations that showed a surface dull to IR has a much greater effect on attenuating IR than a macroscopically grooved (1/16") inner surface. The surface dulling technique used here was sandblasting with 170 μm diameter Al_2O_3 particles. Further, measurements demonstrated that macroscopic grooves provide only a factor of 2 additional attenuation of transmitted power.

Concerns arose as to the high RF power compatibility of a jagged sandblasted surface. Electric field enhancement at sharp micro protrusions on a sandblasted surface are likely to be as deleterious to RF transmission as the macroscopic sharp protrusions of grooved waveguide. Acid etching of sandblasted copper was shown to have the benefits of both rounding off sharp micro protrusions yet maintaining IR diffusivity. This study gives hope that a sandblasted, acid etched copper waveguide inner surface will both reduce the potential for RF field emission due to sharp protrusions and serve as a good attenuator of thermal radiation through the waveguide.