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RF Breakdown Studies in Tungsten and Copper Structures

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Abstract. This paper reports on experimental results from the SLAC NLC accelerator structure closeout program, and discusses a study that was conducted to improve the smoothness of machined tungsten for use in high gradient structures. At the Next Linear Collider Test Accelerator (NLCTA), an X-band (11.424 GHz) structure was operated at a lower temperature to determine whether this would decrease the low rate of breakdowns that still occur after initial processing. Also, various vacuum venting experiments were performed to determine the impact of air, airborne particulates, and oxidation on the performance of a processed accelerator structure. As part of a more long-range high-gradient structure development program, alternative materials to copper are being explored. The CLIC study group at CERN has conducted several accelerator experiments at 30 GHz with structures that have tungsten and molybdenum iris inserts [1]. SLAC has also tested versions of the CLIC 30 GHz design scaled to 11.424 GHz. The results have prompted a tungsten material study directed at exploring new fabrication processes that would provide a cleaner and smoother tungsten surface topography suitable for high gradient applications. A significantly improved tungsten surface finish resulted from this material study, and a single cell X-band cavity [2] containing noses with such tungsten surfaces will be high power tested soon.

Keywords: RF Breakdown, Accelerator, Tungsten, Cavity, Electropolishing.
PACS: 84-40.-x, 29.17.+w

NLC STRUCTURE CLOSEOUT PROGRAM

As part of the NLC closeout program at SLAC, an accelerator structure was operated at a reduced water cooling temperature to determine the effect on the breakdown rate. A reduction might be expected, for example, if migration of contaminants on the copper surfaces is a factor in initiating breakdown, which occurs rarely (~ one in a million pulses) at the NLC design gradient of 65 MV/m once a structure has been processed. In this experiment, the structure was first operated at the normal cooling water temperature of 110^{o}F and processed to 75 MV/m with 400 ns long pulses, which includes an initial 100 ns amplitude ramp as required in the NLC. During 100 hours of 60 Hz operation, the breakdown rate ranged from 0.2-0.4 per hour (Fig. 1-diamond markers). At this same water temperature, the gradient was then increased to 80 MV/m to improve the breakdown statistics. Initially, the breakdown rate (square markers) was ~ 0.2 per hour, and then it stabilized to ~ 0.6 per hour during

60 hours of operation. The water temperature was then reduced to 60°F, which is the lower limit of the available cooling equipment. The structure temperature is about 10 degrees higher than the water temperature in both cases. To maintain the same phase advance per cell, the drive frequency was offset by 5.4 MHz. The structure ran at 80 MV/m for almost 200 hours (triangle markers) resulting in a breakdown rate close to that during operation at 110°F.

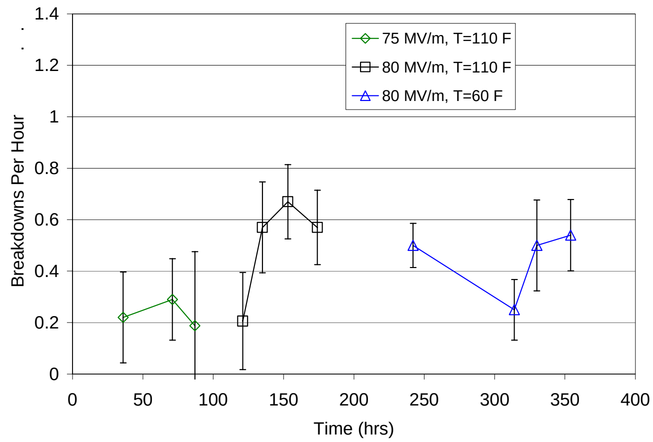


FIGURE 1. Breakdown rate over time at different gradients and water cooling temperatures.

Another NLC closeout program involved venting a structure. For the NLC prototype structures, a vacuum bakeout at 650°C was done primarily to remove hydrogen that was absorbed in the hydrogen brazing furnace during the fabrication process. However, the inner structure surfaces were exposed to air in subsequent assembly steps. To explore what effect this and other types of exposures have on structure performance, a series of venting tests were performed on a structure that had already been rf processed. The results showed that purging with nitrogen or venting to either filtered or unfiltered tunnel air had minimal impact. After a few days of full gradient operation in which 10-100 breakdowns occurred, the rates decreased to a level comparable with that before the vents (~ 1 in 10 hours during 60 Hz operation at 65 MV/m with 400 ns NLC-like pulses). However, when the structure was heated to about 160°C and then vented for an hour to filtered air, the breakdown rate increased substantially, and after a week of rf processing, it had still not fully recovered to its initial level. Presumably, this slow recovery was the result of an oxide layer that formed on the inner surfaces (such layers have been observed in some structures, and are likely the result of small vacuum leaks during brazing or baking).

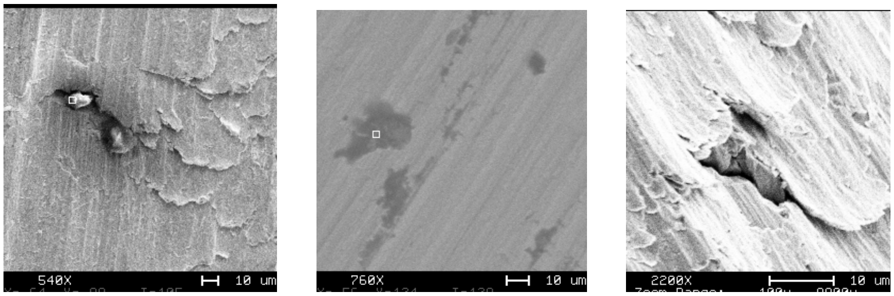
A study looking beyond the NLC copper structure designs involved examining tungsten irises that were used in high gradient structure tests. The CLIC study group at CERN has conducted accelerator experiments at 30 GHz with structures that have tungsten and molybdenum iris inserts [1]. Each iris insert is mounted into a copper disk which forms one cell of a 30-cell accelerator that is clamped together. At short pulses (16 ns), they report that the molybdenum structure achieved a field gradient of 195 MV/m and the tungsten structure achieved 150 MV/m, which are substantially higher gradients than that reported for their copper structure (110 MV/m). To explore longer pulse operation, scaled X-band versions of the 30 GHz design with molybdenum and tungsten irises were rf tested at NLCTA. A photograph of the 11.424 GHz, tungsten iris structure without the input and output waveguides attached is shown in Fig. 2a, and one of the copper cells with the tungsten iris insert is shown in Fig. 2b. This structure was fabricated at CERN and the tungsten iris inserts were machined and polished by an outside company. In contrast with the 30 GHz structures, the experimental results at X-band were not encouraging for either a molybdenum [3] or tungsten [4] iris structure. In particular, after several months of rf processing the tungsten iris structure, there was no significant improvement beyond that achieved during the first few weeks. The structure was gassy and required reprocessing when coming back on in power after brief shutdowns. It also required reprocessing when changing back to previously processed pulse lengths. The maximum gradient achieved with 200 ns long pulses was 63 MV/m with a breakdown rate of 10-20 per hour during 60 Hz operation. A prototype NLC copper structure being processed in parallel performed significantly better, achieving 100 MV/m with 250 ns duration pulses and less than 10 breakdowns per hour.

(a) (b)

FIGURE 2. A CERN fabricated (a) 30-cm X-Band accelerator using (b) cells with tungsten iris inserts (iris diameter ~ 1 cm).

SEM analysis was conducted on a sample tungsten iris insert which was subjected to the same fabrication process as the inserts inside the accelerator. The sample insert has never been rf processed. Four main features were observed on the sample (Fig. 3) and are common problems when working with tungsten. Embedded carbon particles (Fig. 3a) and dark patchy areas (Fig. 3b) of carbon (having the appearance of liquid droplets) were frequently observed. The source of carbon in the dark patchy areas remains unknown; however, the embedded carbon particles probably come from the cutting tool during machining. It is also common to find tearing, fractures (Fig. 3c), and sharp edges on machined tungsten surfaces.

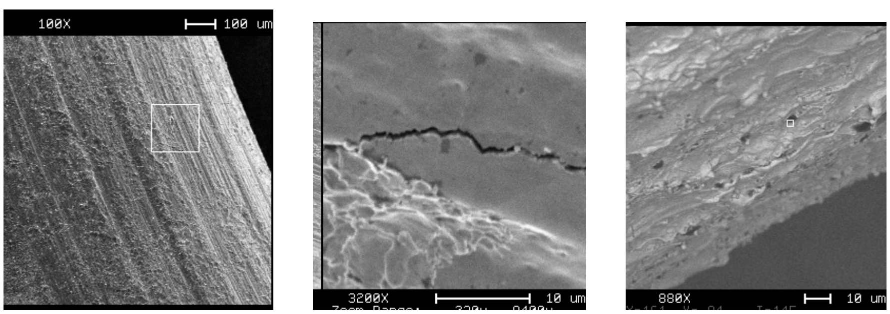
After rf testing, the accelerator was unclamped and three of the tungsten iris inserts were removed, photographed, and SEM analyzed. SEM images of Iris 1, Iris 2, and Iris 15 are shown in Fig. 4 and Fig. 5. Iris 2 sustained substantially more breakdown damage (Fig. 5a,b) than the other two irises as would be expected. Iris 1 (Fig. 4) is the input coupler iris and has a larger iris diameter and consequently a lower surface field gradient. Iris 15, which is located near the center of the structure, shows breakdown damage similar to that on the input coupler iris. The accelerator is a constant impedance structure so the field gradient decreases as power flows down the structure. At high magnification, the areas that appear untouched by breakdown on both Iris 1 and 15 do not have the same surface texture as observed on the tungsten sample. Although machining lines remain evident, surface heating and melting has occurred at



(a) (b) (c)

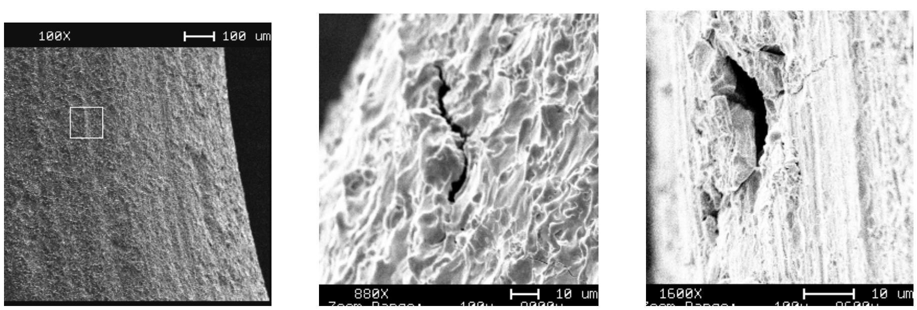
FIGURE 3. SEM photos of a tungsten iris insert sample not exposed to rf. Numerous (a) embedded carbon particles, (b) dark patchy areas of carbon, surface tears and (c) fractures were observed.

these locations and the sharp edges seen on the sample (Fig. 3) are not apparent on the irises that have been rf processed. Surface fractures and carbon spots were observed on all three of the irises that were inspected. It is especially interesting to see carbon spots clearly visible on top of many layers of breakdown as shown in Fig. 4c. The source of carbon is currently being investigated as part of a tungsten material study that is discussed in the following section. The SEM image of Iris 15 (Fig. 5c) shows a damaged area that probably occurred from the cutting tool during machining.



(a) (b) (c)

FIGURE 4. SEM images of Iris 1 at (a) 100x magnifications and at higher magnifications (b and c).



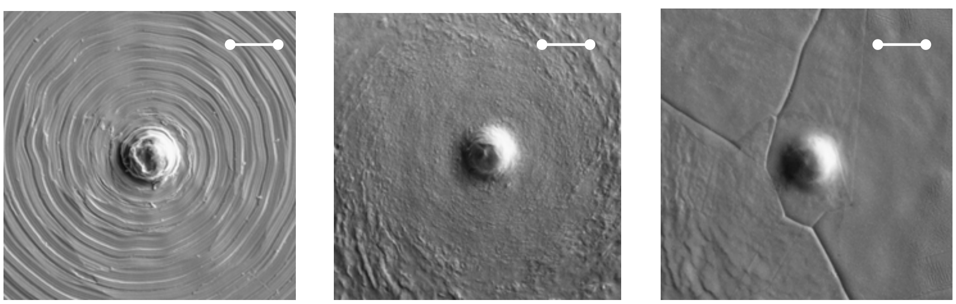
(a) (b) (c)

FIGURE 5. SEM images of Iris 2 (a, b) and Iris 15 (c).

Surface tearing is not uncommon when working with brittle materials such as tungsten. The fractures and tears may be responsible for trapping gas and would explain why the structure was gassy and required reprocessing after brief shutdowns. Since the structure was clamped together instead of brazed, it is possible that this might also be responsible for some of the gas problems; however, this would not explain the increase in gas when changing pulse lengths which would be more consistent with a localized surface phenomena. The much higher gradients achieved in the 30 GHz tungsten iris structure relative to those at X-band is likely due to its short pulse (16 ns) operation at very high breakdown rates. In a recent test of a 30 GHz molybdenum iris structure [5], the gradients achieved are much closer to those in the X-band molybdenum iris structure at comparable pulse lengths and breakdown rates.

TUNGSTEN MATERIAL STUDY

The experimental findings discussed in the previous section prompted further studies to explore new fabrication processes that would provide a cleaner and smoother tungsten surface topography without carbon, tears and fractures. Achieving a surface finish equivalent to that in copper structures was the initial focus of this study. An example of a typical copper surface at various fabrication stages is shown in Fig. 6. The SEM images were taken after machining (Fig. 6a), chemical etching (Fig. 6b) and heat cycling (Fig. 6c).

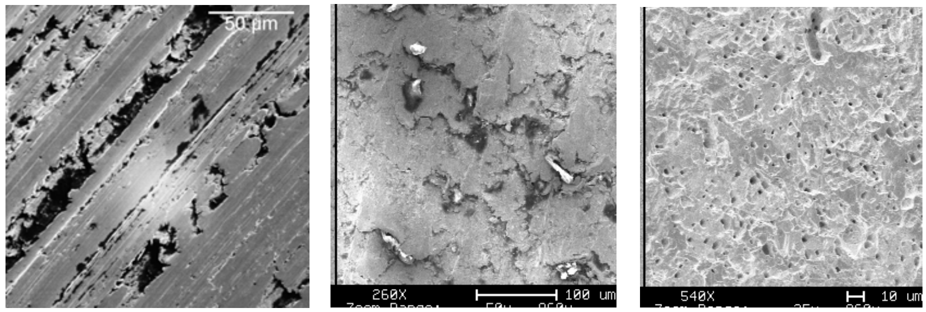


(a) (b) (c)

FIGURE 6. Typical copper surface topography at various stages of fabrication: (a) after machining, (b) after chemical etch, and (c) after heat cycling. All SEM images were taken at 1000x magnification (scale bar =10 μm).

In an effort to improve the surface finish, a variety of machining, etching, and polishing techniques were explored using tungsten rods. During the machining phase, different cutting speeds, feed rates, cutting tools and cutting fluids were used. Initial attempts at machining showed that the cutting tool had a tendency to tear the surface (Fig. 7a). All of the cutting tools used at SLAC left tungsten and/or carbon particles embedded in the surface (Fig. 7b). To remove the embedded debris picked up during machining, electropolishing was used, however, this resulted in numerous etch pits on the surface (Fig. 7c).

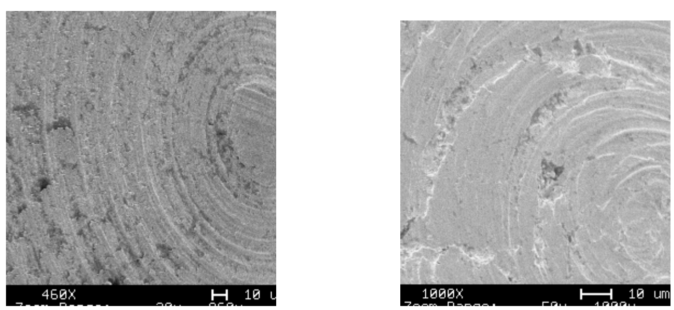
Two companies that have many years of experience working with tungsten contributed to this material study. Both were asked to supply a tungsten rod with their best possible surface finish. One of the companies polished a tungsten rod with a grinding wheel, which resulted in numerous gashes on the surface. The other company provided two tungsten samples: one that had been machined and one that had been machined and polished. Both samples consisted of a 0.375 inch diameter tungsten rod that was machined with a full radius at one end of the rod. An SEM image of the machined sample is shown in Fig. 8a and the sample that was machined and polished



(a) (b) (c)

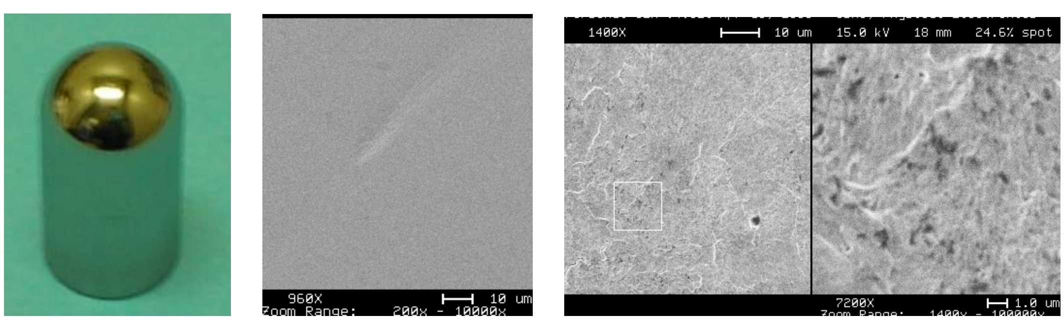
FIGURE 7. Typical features observed after machining tungsten were (a) surface tearing and (b) and embedded particles. After electropolishing for 2-minutes, etch pits (c) were observed over the entire surface.

is shown in Fig. 8b. On the polished sample there were large gashes on the surface containing a significant amount of aluminum. The aluminum presumably came from the polishing agent that was used. On the sample that was not polished (Fig. 8a), carbon, fractures, and tears were observed on the surface similar to the accelerator inserts discussed above. The sample that was not polished was later hand polished at SLAC to a mirror finish using a diamond polishing paste (Fig. 9a). SEM analysis after hand polishing revealed a surprisingly smooth surface (Fig. 9b). High magnifications were required to locate surface features necessary for focusing. There were no fractures or tears observed on the surface; however, at very high magnification, dark patchy areas of carbon were detected. An example of one of these areas is shown in Fig. 9c, which was taken after electropolishing the part for 5 seconds.



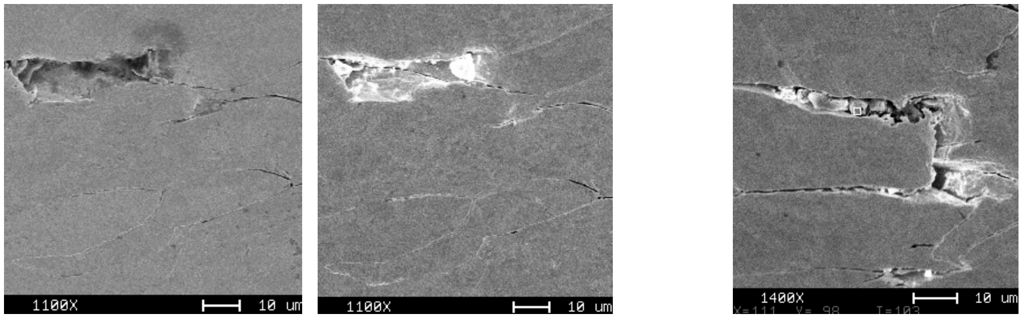
(a) (b)

FIGURE 8. A tungsten sample machined (a) and polished (b) by an outside company.



(a) (b) (c)

FIGURE 9. Hand polished tungsten rod to a mirror finish (a) before (b) and after (c) electropolishing for 5 seconds.

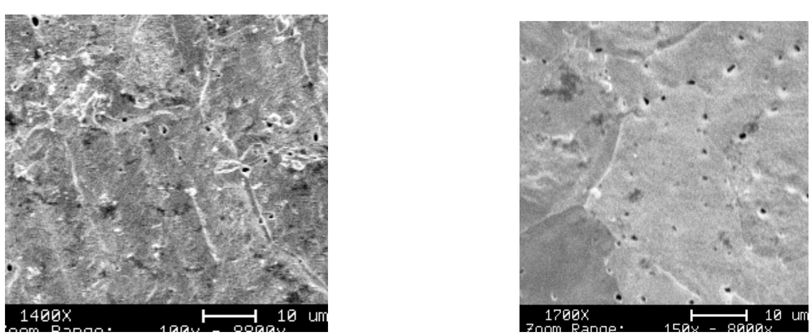


(a) (b) (c)

FIGURE 10. SEM images of a tungsten surface before (a) and after (b, c) wet hydrogen firing at 1000°C for 2 hours.

In an effort to identify the source of carbon, a tungsten rod was forcibly cracked apart, avoiding contamination from cutting tools. SEM and chemical analysis revealed no signs of carbon located in the bulk of the tungsten rod. Wet hydrogen firing was used on several tungsten rods in hopes of removing the carbon from the surface. An SEM image taken prior to hydrogen firing is shown in Fig. 10a. The same location was imaged again after hydrogen firing for two hours at 1000°C (Fig. 10b). At elevated temperatures, it appears that particle migration occurs on the surface and that the particles lodge inside cracks and fissures. In both of the images taken after hydrogen firing (Fig. 10b,c), the white areas and the embedded particles are all carbon. There were no significant changes in the size or appearance of compression boundaries or fractures after the wet hydrogen firing process.

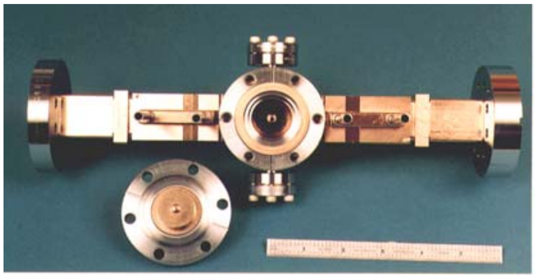
A combination of hand polishing and electropolishing has thus far provided the best tungsten surface finish. An example of two tungsten rods that were hand polished and then electropolished is shown in Fig. 11. The electropolishing was done with both a 2 V (Fig. 11a) and 4 V (Fig. 11b) source, while the remaining parameters (e.g. time and temperature) were kept the same. The tungsten rod that was electropolished at 4 V has a smoother surface compared to the electropolished sample at 2 V. However, the surface has a large number of etch pits. Further experiments are being conducted to determine the optimum parameters.



(a) (b)

FIGURE 11. Tungsten samples electropolished using (a) 2 V and (b) 4 V.

The next step in this tungsten material study is to compare the high gradient properties of the smoother tungsten to that of copper. The experiments will be conducted in an X-band TM_{020} cavity (Fig. 12a) configured as a “windowtron” [2] and fed directly by a SLAC 50-MW X-band klystron. The cavity has two removable field enhanced noses that enables analysis of the high gradient surface areas before and after rf testing. The cavity noses are replaceable, making this an ideal setup for rf testing different materials. Tungsten rods with the same nose profile as the cavity noses are currently being used to optimize the polishing parameters (Fig 12b) in preparation for fabricating the cavity noses.



(a)

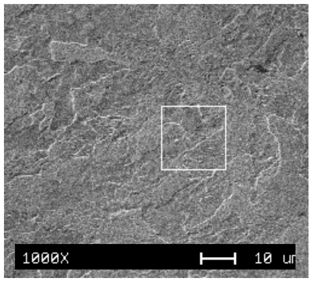
(b)

FIGURE 12. Cavity with two removable noses (a) to be used to study high gradient properties of tungsten. Polishing techniques are being finalized with (b) tungsten rods having the same cavity nose profile.

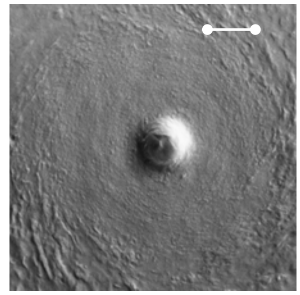
CONCLUSIONS

Experimental results from the NLC accelerator structure closeout program at SLAC were presented. This program included the operation of an X-band structure at a lower water cooling temperature to determine whether this would reduce the breakdown rate, as might be expected if breakdowns are related to migration of surface contaminants. However, no significant difference in breakdown rate was seen when operating at the normal structure cooling water temperature of 110 ^{o}F and the reduced temperature of 60 ^{o}F. Various vacuum venting experiments were also performed and showed that purging a structure with nitrogen or venting to either filtered or unfiltered tunnel air had minimal impact on high gradient operation. However, when the structure was heated to ~ 160 ^{o}C and vented to filtered air, the breakdown rate increased substantially and never fully recovered after a week of rf processing.

Tests at CERN and SLAC of accelerator structures with tungsten iris inserts revealed a need to develop a better fabrication process for high gradient tungsten structures. A tungsten material study was conducted at SLAC that focused on machining, etching and polishing processes to minimize the carbon contamination, and the surface tears and fractures that are commonly found on tungsten surfaces. A combination of hand polishing and electropolishing provided the best surface finish. A tungsten surface prepared with this procedure is shown in Fig. 13a. The surface finish is comparable to a typical chemically etched copper surface (Fig. 13b). Remnants of carbon still persist but are generally small in size (< 1 μm). Tungsten cavity noses are currently being fabricated for installation in a TM_{020} cavity, and will be rf processed soon. The results will be compared to prior experiments using copper cavity noses.



(a)



(b)

FIGURE 13. Tungsten rod after (a) hand polishing and electropolishing compared to a (b) typical chemically etched copper surface (scale bar = 10 μm).

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