Breakdown conditioning of Copper, CuZr and GlidCop®
Effect of mechanical surface treatments

T. Ramsvik, S. Heikkinen, S. Calatroni and M. Taborelli

Abstract
Motivated by the need of novel materials for the CLIC accelerating structures to resist mechanical fatigue, the copper based metals Copper Zirconium C15000 (CuZr) and GlidCop® Al-15 C15715 have been investigated by DC breakdown measurements, and compared with commercially pure Oxygen-free Copper C10100 (Cu-OFE). In all three cases the saturated breakdown fields ($E_{\text{sat}}$) are similar, despite significant differences in their tensile strengths.

In addition, the choice of mechanical surface preparation techniques influences the final breakdown characteristics. For both CuZr and GlidCop® immediate conditioning takes place when the surfaces are prepared by milling. For electro discharge machined (EDM) surfaces, however, several breakdown events are needed to obtain saturation. Specifically, for EDM treated CuZr and GlidCop®, ~50 and ~200 breakdown events are required to reach $E_{\text{sat}}$.

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1. INTRODUCTION

At CERN the feasibility of a multi-TeV e+e− Compact LInear Collider (CLIC) is under investigation [1]. To reach the required energy level within feasible length of the linacs, extremely high accelerating gradients and power flows are needed. As a consequence of these demanding performance requirements, comprehensive material studies of the acceleration structures is being carried out at CERN. In this context, two issues have been given particular attention: fatigue and electrical breakdowns.

The surfaces of the accelerating cavities are exposed to pulsed RF currents, which induce cyclic thermal stress possibly resulting in surface break up by fatigue. In the case of RF cavities, the induced thermal stress is inversely proportional to the electrical and thermal conductivities of the cavity material. Oxygen-free copper has therefore been widely used for normal conducting accelerating cavities. However, early stage fatigue test results indicate that its fatigue strength is not sufficient for the target parameters of CLIC [2]. In addition, high electrical conductivity is important for the overall efficiency requirement of the CLIC machine. Methods susceptible to increase fatigue strength like alloying are generally accompanied by a decrease in electrical conductivity. An optimum compromise has thus to be obtained by the best choice of copper grade, thermal- and surface treatment. The up-to-date results of the CLIC fatigue studies suggest that a precipitation hardenable grade with zirconium content and an oxide dispersion strengthened grade would be candidate materials for the CLIC cavities.

The highest electrical fields within the accelerating structures are located at the iris of the cells, where the RF currents are minimal. A comprehensive study is ongoing to find suitable materials able to sustain the maximum surface fields in this region within acceptable breakdown rates [3]. However, field simulations show that the materials outside the iris region can be subjected to surface fields of up to roughly 50% of those found within the irises [4]. It is therefore important to investigate their breakdown characteristics.

Whilst the breakdown characteristics of oxygen-free Copper have been studied intensively [5-8], few comparable experiments using GlidCop® and CuZr electrodes are found. One exception is a study of K. G. Bouchard [9] who compared the breakdown characteristics of dispersion-strengthened copper cathodes with those of OFHC1 copper. It was concluded that the breakdown voltage in the gap range of 76-178 μm is 21% higher for dispersion-strengthened copper than for OFHC copper.

The present article reports DC breakdown measurements performed using GlidCop® Al-15 C15715, Copper Zirconium C15000 (CuZr) and commercially pure Oxygen-free Copper C10100 (Cu-OFE) as both anodes and cathodes, and their properties are compared and discussed. For the two latter materials the influences of two different surface treatment techniques, electrical discharge machining (EDM) and milling, were examined.

2. EXPERIMENTAL SETUP

The breakdown experiments reported in this paper are performed using an experimental setup described in detail in [10]. The UHV chamber houses two electrodes of tip-plane geometry, where their relative distance can be adjusted at sub-micrometer precision using a custom-made mechanical micro-positioning tool. The tip anode can be subjected to voltages ranging from 0 to 15 kV by discharging a 27 nF capacitor through a series of high voltage relays. Applied electrical fields up to 1 GV/m in the gap junction between the electrodes can thus be reached. A true electrical breakdown over the gap is acknowledged when a full

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1 OFHC = Oxygen-Free, High-Conductivity copper, brand name for OFE-Cu
discharge of the capacitor takes place, and a high current pulse is measured over the gap junction. Automated data acquisition and control are accomplished with LabView data acquisition software using an IEEE-488 interface bus. In the following the breakdown field is defined as the maximum applied field that can be applied to the electrodes before breakdown. Since this value changes by repeating breakdown events along a conditioning curve on the same sample site, a saturation field, $E_{\text{sat}}$, is here defined as the breakdown field obtained by a Gaussian fit over a histogram of many single breakdown field events [11].

For all the experiments reported in this paper, identical materials were chosen for the anode and the cathode. The cathodes and anodes consist of polycrystalline sheets of 1-1.5 mm thickness, and 2.3 mm thick rods with hemispherical apex, respectively. The samples are OFE-copper (C10100), GlidCop® Al-15 (C15715) and CuZr (C15000) (see Table 1). In the case of the cathodes, the OFE-Cu was cold rolled, while the surface finishing of GlidCop® and CuZr were done by both wire EDM in water and milling. All the anodes were milled. Prior to installation in the UHV chamber, all materials were cleaned according to the CERN standard procedure for UHV components [12].

The reported roughness results were measured using a white light interferometer of type Veeco NT 3300. The uncertainty during sampling was about 10 nm.

Table 1 gives some selected physical and mechanical properties of Cu-OFE, GlidCop® and CuZr. The differences are seen to be minor with three exceptions. The most prominent differences are found for the tensile and fatigue strength where the value for copper is significantly smaller compared to the other two metals. In addition, the solidus melting point for CuZr is ~100 K lower than for Cu-OFE and GlidCop®. The electrical and thermal conductivities of Cu-OFE are slightly higher than for GlidCop® and CuZr.

Table 1: Selected properties of Cu-OFE, GlidCop® and CuZr [13-20, 2].

<table>
<thead>
<tr>
<th>Material UNS C</th>
<th>Chemical Composition</th>
<th>Density</th>
<th>Melt. Point</th>
<th>Conductivity</th>
<th>Tensile Strength</th>
<th>Fatigue Strength (ultras. tests)</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu-OFE (C10100)</td>
<td>Cu &gt; 99.99% O$_2$ &lt; 5 ppm</td>
<td>8.94</td>
<td>1356</td>
<td>1356</td>
<td>0.59 (101%)</td>
<td>391 (cold worked 50%)</td>
<td>240-280</td>
</tr>
<tr>
<td>GlidCop® Al-15 (C15715)</td>
<td>Cu = 99.85 % Al$_2$O$_3$ = 0.15 %</td>
<td>8.90</td>
<td>1356</td>
<td>1356</td>
<td>0.54 (90%)</td>
<td>365 (hot extruded, no cold working)</td>
<td>393</td>
</tr>
<tr>
<td>CuZr (C15000)</td>
<td>Cu = 99.8-99.9 % Zr = 0.1-0.2 %</td>
<td>8.89</td>
<td>1253</td>
<td>1355</td>
<td>0.54 (93%)</td>
<td>367 (aged and cold worked 40%)</td>
<td>340</td>
</tr>
</tbody>
</table>

* Solidus
** Liquidus
3. RESULTS

3.1 Copper, CuZr and GlidCop

Figure 1 shows the breakdown conditioning curves for the three electrode materials. The Cu-OFE was prepared by cold rolling, while both CuZr and GlidCop® were milled to obtain a smooth surface. The similarities in the breakdown characteristics are striking. In all three cases, an immediate conditioning takes place to breakdown fields in the range 140-180 MV/m, followed by a slow decrease. For these set of data, the breakdown fields for copper, CuZr and GlidCop® are found to be (142±2), (125±4) and (115±3) MV/m, respectively, determined by fitting a Gaussian distribution over the histogram of the first 250 breakdown fields. The uncertainties are the standard deviations of the fits².

![Figure 1: Breakdown conditioning curves for cold rolled Cu-OFE C10100 (left), milled CuZr C15000 (mid) and milled GlidCop® C15715 (right). Their respective saturated breakdown fields are (142±2) MV/m, (125±4) MV/m and (115±3) MV/m, determined by fitting a Gaussian distribution over the histogram of the breakdown fields. The given uncertainties are here the standard deviations of the fit, and are hence based on single conditioning curves. For each material the gap distance was checked at start and end of the conditioning by going to contact with the electrodes. Any gap instability was corrected by assuming a linear interpolation between the initial and final gap distance.](image)

² For GlidCop®, the first 13 breakdown events are omitted in plotting the histogram.
Typical enhancements factors at saturation were determined from field emission measurements, and are given in table 2 together with the saturated breakdown fields and local fields:

Table 2: Enhancement factors ($\beta$), average saturated breakdown fields ($E_{\text{sat}}$) and local fields ($E_{\text{local}}$) of Cu-OFE, CuZr and GlidCop®. The uncertainties give the variations all values deduced when saturation fields are obtained. Note that the surface treatments prior to the breakdown conditions are different.

<table>
<thead>
<tr>
<th>Electrode Material</th>
<th>Enhancement factor ($\beta$):</th>
<th>$E_{\text{sat}}$ [MV/m]</th>
<th>$E_{\text{local}}$ [GV/m] (average):</th>
<th>$\sqrt{2\sigma/\varepsilon_0}$ [GV/m] (average) [21]:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu-OFE</td>
<td>$46\pm5$</td>
<td>(151±39)</td>
<td>6.9</td>
<td>7.4 - 8.0</td>
</tr>
<tr>
<td>CuZr</td>
<td>$86\pm23$</td>
<td>(120±26)</td>
<td>10.3</td>
<td>9.4</td>
</tr>
<tr>
<td>GlidCop®</td>
<td>$32\pm3$</td>
<td>(114±7)</td>
<td>3.6</td>
<td>8.8</td>
</tr>
</tbody>
</table>

* Milled
** Electro Discharge Machined

The results for Cu-OFE of $\beta$ and $E_{\text{sat}}$ are somewhat lower than the results obtained by M. Taborelli et al. [11]. The number of breakdown events reported in this paper is considerably more than previously reported [11]. Hence a lower $E_{\text{sat}}$ is not surprising since degradation as function of breakdown events have been confirmed. In both reports [11, this paper] the $\beta$ is based on few data points. Hence high uncertainties make an accurate comparison doubtful. This includes also the resulting local fields, which, compared to reported values in literature [22], seems reasonable for CuZr, but too low for Cu-OFE and GlidCop®. However, the reported local field of [11] is more in the expected range.

According to [23], local fields above $\sqrt{2\sigma/\varepsilon_0}$ (where $\sigma$ and $\varepsilon_0$ are the tensile strength in Pa and vacuum permittivity in F/m, respectively) will induce tensile stresses high enough to evaporate materials in form of clusters and fragments. These again act as triggers for runaway processes culminating in electrical breakdowns. In the rightmost column such field limits [23] are calculated using the reported macroscopic tensile strengths of the Cu materials. With the possible exception of CuZr, direct comparisons with the obtained local fields do not support cluster-field evaporation as being the dominating mechanism to trigger a runaway process.

3.2 Influence of surface finishing technology on breakdown characteristics

Correct choice of electrode materials are of crucial importance to obtain good vacuum insulation. The type of surface treatments plays an equally vital role since they may alter the initial surface conditions such as the materials topography and presence of foreign species [see e.g. 22]. For example S. Kobayashi succeeded to increase the ultimate breakdown fields and decrease the conditioning time of Cu-OFE by a combination of improved mechanical surface finishing, ion-bombardments and heat treatments [5, 6].

In the present work the copper based materials GlidCop® (C15715) and CuZr (C15000) cathode plates were prepared by two different surface techniques, electrical discharge machining (EDM) and milling. The anodes were all prepared by milling since it is known that the anode has a negligible role in the final breakdown characteristics in the case of micrometer sized gaps.

Figure 2 shows breakdown conditionings of CuZr, where the upper and lower two graphs present the results from EDM and milled fabricated plates, respectively. After ~ 50 breakdown events the saturated breakdown fields ($E_{\text{sat}}$) are (142±7) MV/m and (113±1) MV/m for EDM CuZr, and (125±4) MV/m and (121±2) MV/m for milled CuZr. The initial conditioning
is observed to be different as a consequence of the two techniques: In the case of EDM treated cathodes $E_{sat}$ is obtained after ~ 50 breakdowns, while an immediate conditioning is observed for those prepared by milling.

![Figure 2](image_url)

**Figure 2**: Breakdown conditioning of CuZr (C15000) electrode materials with different mechanical surface treatments of the cathode plate. The figures show two positions on the cathode surface where the surface is prepared by (A, B) Electro Discharge Machining (EDM) and (C, D) Milling.

Similar trends are seen for GlidCop® electrodes prepared in the same ways (Figure 3). Also here the final $E_{sat}$ are roughly the same, but EDM treated cathodes show slower conditioning speeds. The difference between EDM and milled surfaces is more extreme for GlidCop® compared to CuZr. Figure 3 shows that at least 200 breakdown events were needed to reach $E_{sat}$, while also in this case an immediate conditioning was observed on milled surfaces.

The initial evolution of the breakdown fields for milled GlidCop® has a characteristic that is not as marked in milled CuZr and rolled Cu-OFE, namely breakdown fields significantly higher than its final $E_{sat}$. The breakdown events have thus a destructive effect on GlidCop®, indicating that the conditioning produces rather than remove breakdown sources. Why this is the case is not clear. Note however that these results do not contradict the reported breakdown voltages of K. G. Bouchard for dispersion-strengthened copper [9], since the experiments reported there only considered the first 20-25 breakdown events.
Figure 3: Breakdown conditioning of GlidCop® (C15715) electrode materials with different mechanical surface treatments of the cathode plate. The figures show two positions on the cathode surface where the surface is prepared by (A, B) Electro Discharge Machining (EDM) and (C, D) Milling.

Figure 4 gives the $E_{\text{sat}}$ of all the reported electrode materials, grouped in type, surface treatments and spot position on the cathode plate. Except for an atypical high value at one breakdown position on Cu-OFE, all the materials show a notable similarity in $E_{\text{sat}}$.

Figure 4: Summary of the saturated breakdown fields ($E_{\text{sat}}$) for the electrode materials Cu-OFE, GlidCop® and CuZr. The horizontal axis shows separate positions on the cathode plate, grouped in different materials and mechanical surface treatments, while the vertical axis gives $E_{\text{sat}}$ in MV/m. The uncertainties give the standard deviations of single measurement spots due to the Gaussian fit.
4. DISCUSSIONS

Surface treatments may alter the surface conditions in several ways, involving changes in micro-topography of the surface, residual stresses and chemical compositions. Each of these effects would result in different pre-breakdown characteristics [24] and thereby influence the final breakdown resistance [25].

To obtain a map of the micro-topography after each surface treatment, careful roughness measurements were performed. The results are given in Table 3.

<table>
<thead>
<tr>
<th>Electrode Material:</th>
<th>Surface Treatment</th>
<th>Roughness Ra [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFE Cu C10100</td>
<td>Cold Rolled</td>
<td>0.176 ± 0.040</td>
</tr>
<tr>
<td>CuZr C15000</td>
<td>Milled EDM</td>
<td>0.212 ± 0.009</td>
</tr>
<tr>
<td>GlidCop® C15715</td>
<td>Milled EDM</td>
<td>0.370 ± 0.023</td>
</tr>
</tbody>
</table>

The average surface roughness (Ra) of cold-rolled OFE Cu, milled CuZr and milled GlidCop® differ within a factor ~2, where OFE Cu is found to be the smoothest with an average Ra of 0.176 µm. Apparently, variations in Ra in the observed range do not lead to any noticeable difference in the breakdown characteristics (figure 1). However, marked differences in the conditioning speed have been observed for EDM treated surfaces (figures 2 and 3), and in these cases Ra of 15-20 times higher than OFE Cu are found. An explanation can thus be that a significant amount of surface smoothing by local melting is necessary to obtain the ultimate breakdown fields. It is further speculated that the difference in conditioning speed between CuZr and GlidCop®, that is ~50 and ~200 breakdown events, can be attributed to the difference in solidus melting point (table 1).

Tensile- and/or fatigue strength do not seem to have any significant effect on the ultimate breakdown fields for the type of materials studied here (table 2, figure 2). Hence, the proposed cluster field evaporation model [23], i.e. removal of clusters or fragments from the electrodes, is not a dominant source for creating the plasma necessary to trigger a breakdown event. It should however be remarked that the widely accepted mechanism initiating breakdown events is based on field emissions sites of some tens of nanometer size. The mechanical properties are measured at macroscopic scale and the extrapolation at such a small scale in a non-homogenous material like CuZr or Glidcop (assuming Zr precipitates or alumina particles of 20 nm size, the respective concentrations for CuZr and Glidcop give an average interparticle distance of the order of 100-150 nm) is not necessarily meaningful.

It can be ruled out that different level of contamination induced by the roughness difference can be of significance. Indeed, a verification of the level of carbon contamination by XPS (X-ray Photoemission Spectroscopy) on the CuZr milled and EDM treated surfaces does not show any significant difference.
5. CONCLUSIONS:

As part of the ongoing study to find suitable materials for the accelerating structure for the future CLIC at CERN, DC breakdown experiments have been performed on GlidCop® and CuZr. These materials are compared with Cu-OFE. The measurements show that the saturated breakdown fields ($E_{sat}$) are similar for all three materials, despite a significant difference in tensile- and fatigue strength.

Cathode plates of GlidCop® and CuZr fabricated by electric discharge machining (EDM) reveal a slower conditioning speed than high precision milling. The latter technique shows a close to immediate conditioning up to $E_{sat}$. This effect is more pronounced for GlidCop®. It is speculated that the origin of the differences between milled and EDM treated surfaces is linked to the dissimilar roughness.

In the context of CLIC, the general conclusions from these two main results can be considered twofold:

- Due to the similar breakdown characteristics of the three materials, a final decision on cavity materials should be based on other parameters such as the on-going fatigue results.
- The choice of mechanical surface finishing techniques is important to shorten the breakdown conditioning time.
REFERENCES


[13] Technical Data, Hitachi Cable, Ltd. 401-0002, 1993-4


