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MODELING THE HYDROFORMING OF A LARGE GRAIN NIOBIUM TUBE WITH CRYSTAL PLASTICITY*

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Abstract

Current SRF cavities are made from fine grained polycrystalline niobium half-cells welded together. Hot spots are commonly found in the heat-affected zone, making seamless hydroformed cavities attractive. Large grain cavities usually perform as well as fine grain cavities, often having a higher Q, presumably due to fewer grain boundaries. Large grain Nb forms non-uniformly, which introduces problems in manufacturing. A model that could realistically predict the deformation response of large grain Nb could facilitate the design of large grain hydroformed tubes.

To this end, a crystal plasticity model was developed and calibrated with tensile stress-strain data of Nb single crystals. A seamless large grain tube was made from rolling a fine grain sheet into a tube, welded, and heat treated to grow large grains. The heat treatment resulted in a large grain tube with a single grain orientation in the center. The tube was hydroformed until it cracked. The hydroforming process was simulated with the crystal plasticity model, which was able to predict the deformed shape of the tube, the location of the crack and other localized areas with heterogeneous strain.

INTRODUCTION

The International Linear Collider (ILC) project will require a very large amount of niobium (Nb) to fabricate cavities in a limited time. This large future demand has stimulated alternative cavity fabrication strategies such as directly slicing disks out of as-cast Nb ingots [1] which eliminates the costly Nb sheet rolling process [2] and reduces waste for axisymmetric parts. It has been shown that cavities manufactured from large grain (grains larger than 5-10 mm) sheets often have a better superconducting radio frequency (SRF) performance than the fine grain (grain size in range of 50 μm) sheets [2, 3]. This increase in performance is correlated with the presence of fewer grain boundaries in the material. Also, the sheet rolling process can introduce impurities to the material. Slices that are cut form from an ingot potentially have fewer defects per unit volume.

Nb ingots are manufactured by electron beam melting of a Nb feedstock. This molten Nb drips into a continuous casting mold. The ingot made with this process has a nearly columnar grain structure. As single crystal ingots are routinely fabricated in other materials, it may be possible to fabricate ingots with a preferred orientation [1]. However, the intrinsic plastic anisotropy of Nb single crystals [4, 5] will lead to non-uniform forming, which must be anticipated.

Particle accelerator cavities are traditionally made from deep drawing of a Nb sheet into bowl shapes having a hole in the center. Two bowls are welded together to make an elliptical cavity. Then a tube with the inner diameter equal to the diameter of the holes is welded to each end to make a single cell cavity.

The standard deep drawing process for manufacturing particle accelerator cavities, is not an optimal process. A manufacturing process like tube hydroforming has the potential to fabricate a cavity from a single piece of tube, and the lack of welding could lead to better reproducibility and improve the performance of the cavity while reducing the manufacturing costs. Tube hydroforming is a forming process in which an internal hydraulic pressure imposes the deformation force.

The goal of this research is to study the possibility of making a particle accelerator cavity from the large grain tube that was previously made [6]. The current study uses a crystal plasticity model with dynamic hardening rule that was presented in [7] to predict the hydroforming of a large grain Nb tube.

MAKING A LARGE GRAIN TUBE

To provide a means to examine effects of large grain material on hydroforming, a seamless large grain Nb tube with an outer diameter of 38 mm was made from a 2 mm-thick polycrystal Nb sheet. The tube was manufactured by Dr. Jim Murphy at University of Nevada, Reno.

A rectangular Nb sheet was bent into a 38 mm (1.5 inch) outer diameter tube and arc welded. To grow the crystals and convert the initial microstructure to a large grain structure, the tube was locally heated to a very high temperature (near the melting temperature) in a high vacuum (~5×10^{-6} torr) furnace. The vacuum reduced impurities that have a lower melting point and a higher vapor pressure. The hot zone was then moved along the length of the tube with a fixed velocity, which encouraged recrystallization and grain growth parallel to the tube axis. More details about the tube making process is given in [6].

CHARACTERIZATION OF THE TUBE

After the heat treatment, the orientation of the tube was examined with a Laue camera. Laue measurement is an X-ray diffraction based technique and does not need to be performed in a vacuum.

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The orientations of grains were measured systematically using a coarse grid. The grid lines are on the surface of the tube, parallel to the tube axis and approximately 60° apart. The orientation was measured at eight points along each axial line. The points are 25.4 mm (1 inch) apart from each other and the ends. Figure 1 schematically shows the grid defined by outside longitudinal locations 25.4 mm apart (P-W) and circumferential markings (approximately 60° apart, 1-6) at which the orientation was measured. The axis of the tube is horizontal (Y-direction). Red circles show the approximate locations of X and Z axes.

The commercial software "Orient Express" was used to index the Laue patterns and identify the crystal orientation. These measurements were used to identify grain boundaries which are shown with black lines in figure 1. Each color in this figure represents one distinct grain orientation.

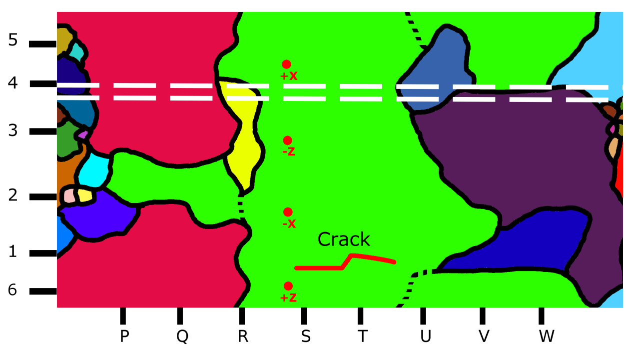


Figure 1: This map shows the grain structure of the large grain Nb tube. Major grain boundaries and other major surface ledges are shown with solid and dashed black lines respectively. The weld is shown with the white dashed lines. The red line shows the location of the crack after hydroforming. Each color represents one grain. The axis of the tube is horizontal (Y-direction). Red circles show the approximate locations of X and Z axes.

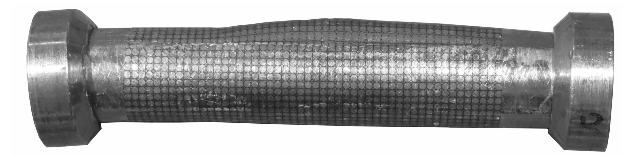
TUBE BULGING WITH PRESSURIZED WATER

A standard approach to the tube hydroforming process was used to study the deformation of the large grain tube and as a first step towards designing a tube hydroforming manufacturing process. A square-circle grid was put on the tube to facilitate the measurement of local strains after deformation.

The tube was mounted in a custom-built tube hydroforming machine. The tube bulging process started with incrementally increasing the fluid pressure. The left ram was also incrementally moved along the tube axis to maintain an approximately constant compressive load. Both fluid pressure and axial load were incrementally increased until the tube cracked. The tube cracked in the middle of a bulged section within the center single crystal region, about 10 mm from grain boundaries, and far from the prior weld line. The crack is shown in Figure 2a and schematically presented in Figure 1. A side view of the deformed tube is shown in Figure 2b.

The data acquisition software recorded the fluid pressure, ram displacement and reaction force. More detail about the hydroforming experiment can be found in [6].

(a)



(b)

Figure 2: The tube was hydroformed until it cracked. (a) The cracked region is shown in the enlarged image looking down on to the top of the tube. (b) The side view of the tube shows the bulge. The location of the crack is at the top of this image. The crack location is schematically shown in Figure 1. The collars shown at either end are a part of the clamp design.

CRYSTAL PLASTICITY MODELING OF THE TUBE HYDROFORMING

The tube was modeled with 60012 solid eight-node brick elements with reduced integration (C3D8R). The mesh is composed of three layers with 20004 elements each.

As a first approximation, smaller grains were neglected and the boundaries were modeled with straight lines using the grid shown in Figure 3. In the experiment, the clamp system constrained the smaller grains near the ends of the tube, so they did not contribute to the overall deformation. The implemented boundary conditions in the model similarly limit the deformation of these grains.

Next, mechanical boundary conditions were imposed on the model of the tube. The rams and the clamps were ignored, but the boundary condition imposed by the collars were modeled.

The Schmid-type crystal plasticity model with the Dynamic Hardening rule [7] was used to predict the deformation of the tube. This model was previously calibrated with single crystal Nb tensile specimens described in the [7]. The deformed geometry predicted by this model is shown in Figure 4. The color bar in this figure represents the equivalent plastic strain of the outer surface of the tube. In Figure 4a, the location that corresponds with the location of the crack in the experiment is shown with a purple ellipse. This area has a light blue strain contour.

The colors used to illustrate plastic strain contours are set to discern the strain gradients in the bulged center of the tube. The gradient occurs in the equivalent strain range of 0-0.3. The gray and red parts of the contour are mainly compressive strain, which arose due to the axial compressive

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displacement applied during the deformation. Most of the hoop strain happens in the mid-section of the tube, where the tube has bulged the most. The spatial orientation of the tube is the same as the deformed tube shown in Figure 2b.

Although the equivalent plastic strain in the mid-section of the tube is less than other parts, the bulging happened in this section. Therefore, the type of strain experienced by elements in the center is different from the strain experienced by elements closer to the ends (in red and gray parts of the contour).

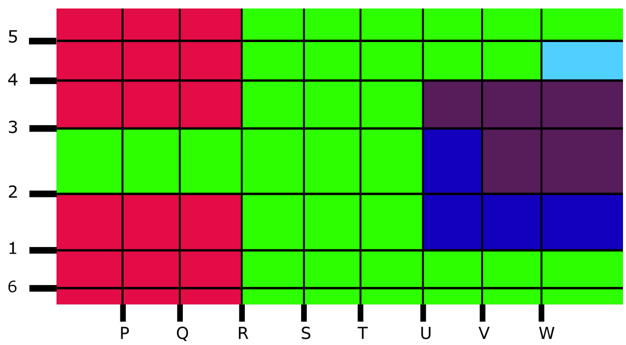

Figure 3: A grid was credited from the orientations measured with the Laue camera. The smaller grains were neglected. This grid was then mapped on the model of the tube.

DISCUSSION

The goal of the initial heat treatment was to obtain a seamless large grain tube. The Laue camera investigations confirmed that this goal was achieved. During the heat treatment, the fine grains grew and formed large grains. A few of these large grains grew and consumed most of the remaining microstructure. The Laue camera measurements showed that the grain growth fully consumed the weld line and the heat affected zone.

During the hydroforming process, the tube deformed inhomogeneously and asymmetrically and eventually cracked in the large grain in the middle of the tube and away from the grain boundaries. This is the largest grain of the tube. It has the same crystal orientation with respect to an external coordinate frame for every point around the circumference of the tube.

The applied internal fluid pressure exerts a circumferential stress normal to the interior wall of the tube. Consequently, the crystal has a varying orientation at each point around the tube with respect to the radial stress exerted by the internal fluid pressure. Thus, the resolved shear stress and the active slip systems are different at each location around the circumference of the tube. This is evident in Figure 5 which shows the variation of Schmid factor for $\langle 111\rangle\{1\bar{1}0\}$ and $\langle 111\rangle\{11\bar{2}\}$ slip systems around the tube for the large grain in the middle of the tube. As can be seen in this figure, the maximum Schmid factor (or resolved shear stress on a slip system) varies with azimuthal location. There are four regions with high values and four regions between them with low values. Two of the regions with higher values have multiple peaks from different slip systems near each other, while the other two have only two peaks with two slip directions. In most azimuthal locations of the grain, there is at least one slip system that is favorably oriented for dislocation slip and will yield with increasing fluid pressure. The positions with the highest Schmid factor (resolved shear stress) yield earlier than other locations, resulting in thinning the material locally. This increases the stress in that location and makes it more susceptible to further strain and eventual cracking.

Another reason for the failure of the tube in the center of a large grain could be the arrangement of the grain orientations and boundaries, and the distribution of the strain in the in the vicinity of a boundary dividing soft and hard orientations. Based on the contour levels around the crack, it seems to have developed in a soft region adjacent to harder regions.

In Figure 4a, the horizontal light blue area noted with a purple arrow shows the highest circumferential strain. This is also the area where the tube cracked in the experiment. As can be seen in Figure 4b, the predicted deformed geometry of the tube matches qualitatively with the experiment.

Nb is a very anisotropic BCC material. Nonetheless, the crystal plasticity model with the Dynamic Hardening rule that was developed in [7] gives satisfactory predictions of deformation of large grain Nb tube. One can use this model to find an optimum grain orientation for forming a large grain tube. This information can be used as a guide to identify desirable orientation as an experimental goal.

CONCLUSION

In this study the possibility of making a large grain Nb cavity was explored. The Laue camera measurement of the tube showed that the heat treatment successfully favored the growth of a few grains that consumed the weld line and created a large grain tube.

The tube was hydroformed until it cracked in the middle grain. This is the only grain in the mid-section of the tube and spans the entire circumference of the middle section. Due to variation of the crystal orientation with respect to the hoop stress resulting from the applied pressure, slip systems at different material points around the tube experienced different resolved shear stresses and have regions of distinctly favored dislocation slip activity. Such anisotropy is one of the reasons for the failure of the tube in the middle of a large grain. Another reason may be the deformation characteristics of the neighboring grains that may have been softer or harder, and influenced the magnitude of hoop strain where the failure occurred.

The Schmid-type crystal plasticity model with the Dynamic hardening rule that was developed and calibrated in [7], was used to simulate the tube hydroforming process. The location of the crack predicted by this model matches with the experiment. Therefore, this model can be used to give insight in designing new manufacturing processes for large grain Nb cavities.

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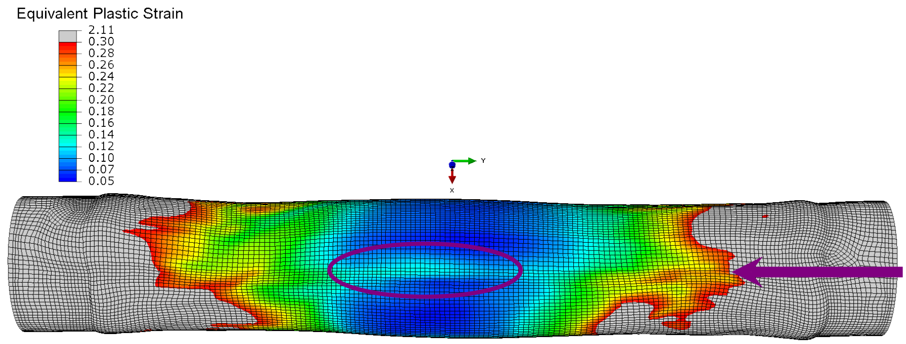
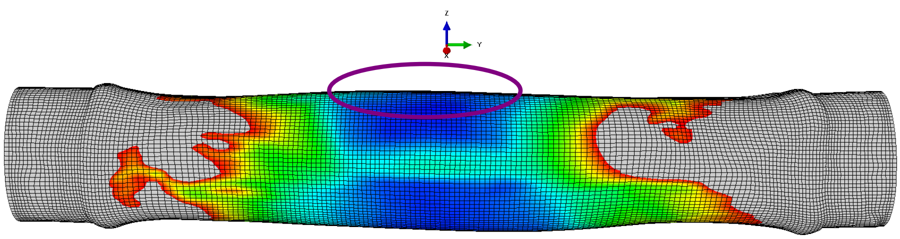


(a) Top view



(b) Side view

Figure 4: Contours of the equivalent plastic strain of the (a) top view and (b) side view of the deformed tube as predicted by the model. The purple ellipses show the location of the crack. The color bar on the left shows the contour of the equivalent plastic strain of the tube. The light blue area along the purple arrow in the center of (a) is where the tube cracked.

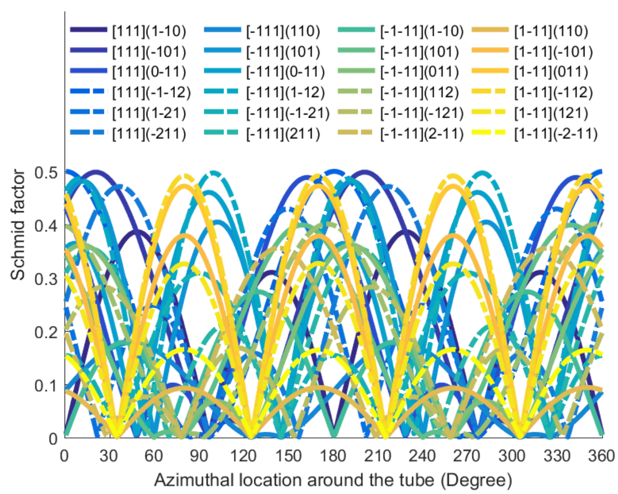


Figure 5: Variation of the absolute value of Schmid factor around the tube for slip systems $\langle 111\rangle\{1\bar{1}0\}$ and $\langle 111\rangle\{11\bar{2}\}$.This plot only shows the slip systems of the large single crystal in the middle of the tube.

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