HYDROFORMING OF LARGE GRAIN NIOBIUM TUBE*

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Abstract

Currently most of Niobium (Nb) cavities are manufactured from fine grain Nb sheets. As-cast ingots go through a series of steps including forging, milling, rolling, and intermediate annealing, before they are deep-drawn into a half-cell shape and subsequently electron beam welded to make a full cavity. Tube hydroforming, a manufacturing technique where a tube is deformed using a pressurized fluid, is an alternative to the current costly manufacturing process. A whole cavity can be made from a tube using tube hydroforming [1,2].

This study focuses on deformation of large grain Nb tubes during hydroforming. The crystal orientation of the grains is recorded. The tube is marked with a square-circle-grid which is used to measure the strain after deformation. The deformation of the tube is going to be modeled with crystal plasticity finite element [3–5] and compared with experiments. This paper only covers the characterization of the tube and the hydroforming process.

INTRODUCTION

Large grain cavities often show better quality factor (Q) than their polycrystalline counterparts. This is due to having fewer defects per unit volume or area in the form of grain boundaries.

Seamless Nb cavities are more favorable than the welded ones, as hot spots are commonly correlated with the heat affected zone. Also, the absence of a weld potentially decreases the cost of manufacturing in the long run. Also the performance of a cavity potentially increases because the weld line is a possible source of contamination and other rare defects.

Tube hydroforming can be used to make cavity from a tube. Singer et al. [1,2] made seamless polycrystalline Nb tubes by spinning and flow forming of a disk. The tubes were then hydroformed into single-cell, or up to three-cell units. The initial values for hydroforming parameters were found from FEM simulation and were further tuned in experiments. The processing and properties of the seamless tube is critical to the success of the hydroforming process. Variations in properties of the tube such as the yield strength, thickness and grain size can result in failure of the tube or irregular final shapes [2].

Large grain Nb is even more anisotropic than polycrystalline material. Therefore, a number of issues have to be addressed before the hydroforming of large grain Nb could be industrialized. Large grain seamless Nb tubes are not readily available in the market. Therefore, the first half of this paper focuses on developing a method to make large grain seamless Nb tubes and fully characterizing them. This prototype tube also provides essential data for comparing the experiment with numerical simulations using crystal plasticity models. The Second half of this paper investigates forming behavior of the tube under the hydroforming conditions.

The results of this study will be to be used as input to the crystal plasticity models developed in [4,5] that was published in SRF 2013 and this proceeding respectively. This series of studies will provide the foundation for designing a seamless large grain tube hydroformed cavity.

MAKING A LARGE GRAIN NIOBIUM TUBE

A polycrystalline Nb sheet 2 mm thick was used to make a Nb tube. The sheet was bent into a 38 mm (1.5 in) outer diameter tube and welded using full penetration electron beam welding. The tube then went through a special vacuum heat treatment to grow the grains. The heat treatment involved using a very high temperature vacuum furnace and moving a hot zone along the tube to encourage the growth of the grains in the axial direction. Figure 1 shows this tube, which is not perfectly straight. Also, the surface of the tube shows ledges and grooves that appeared to be grain boundaries. The black lines on the tube in Figure 1 trace these larger ledges and grooves. The surface of the tube also had smaller grain boundary ledge features shown in an enlargement of a portion of this tube.

Figure 1: The large grain Nb tube. In addition to deeply grooved grain boundaries marked with black ink, the lower enlargement shows evidence for smaller grains with a few mm dimension at some point prior to growing the large grains.

Figure 2 shows these lines unrolled into a sheet. The white line shows the location of the weld line. Black lines correspond to the major surface features of the tube. Each color in this figure represents an individual grain, but the colors are arbitrary. The surface of the tube also had smaller grain boundary ledge features shown in an enlargement of a portion of this tube.
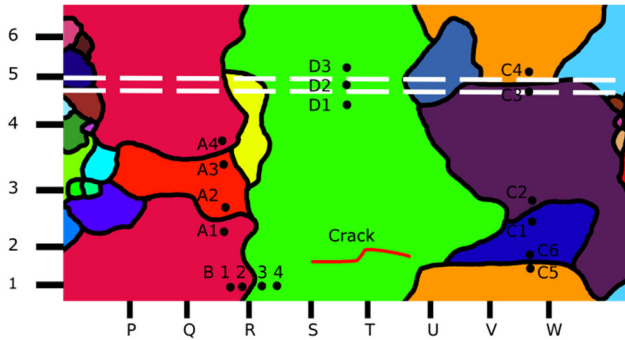

Figure 2: Grain structure of the large grain Nb tube. Black lines show major grain boundaries, white dashed lines show the weld, and red line show the location of failure after hydroforming.

CHRACTERIZATION OF THE TUBE

The crystal orientations of the tube were measured using a Laue camera. The measurements were done on a grid defined by outside markings P-W and 1-6 in figure 2. The points along the tube (P-W) are 50 mm (2 in) apart and the neighboring points around the tube circumference were (1-6) approximately 60° apart. The Laue patterns were semi-automatically indexed using "Orient Express" software as described in more detail in [6]. The crystal orientations are rotated back to a common reference orientation by 0, 71, 152, 213, 263, 315 degrees about the longitudinal axis. The x,y,z crystal directions are plotted on a stereographic projection with the poles aligned with the tube axis as shown in Figure 3. Each plot shows 6 measurements made circumferentially around the tube, representing a pole figure at each longitudinal position.

Another set of Laue camera measurements were performed to make sure the visible ledges on the tube surface are grain boundaries. To do so, the crystal orientation was measured on either side of some of the visible grain boundaries. The location of these measurements are shown with the black circles A1-A4, B1-B4 and C1-C6 in Figure 2. Also, to study the growth of the grains through the weld line, the orientation of points below, on and above the weld line were measured. These measurements are denoted with D1-D3 in Figure 2. Pole figures showing the orientations of these points are presented in Figure 4.

By inspecting Figure 4 A1-A4, it is evident that A2, A3 and A4 are rotated about the long axis on the same circle. A3 can be rotated ~50° around the tube axis to match A2. This is expected because these two points are within one grain. A rotation of ~80° brings A4 and A2 into correspondence, indicating that the misorientation between the two grains is a rotation about the long axis.

B1 and B2 are located in the same grain and to the left of a grain boundary, and .the orientation of these two points match. B3 and B4 are two are points just to the right side of the same grain boundary. The orientation of these points matches which proves the visible groove is a grain boundary.

Measurements C1-C6 are made on either side of three visible ledges or grooves. Comparing the orientation of these points in a similar way as above using the pole figure confirms the location of these grain boundaries.

D1-D3 measurements were performed at just below, on and just above the weld line, to study the effect of the heat treatment on grain growth through the weld line. Pole figure D in Figure 4 shows that these points are on the same circle. Rotations of ~30° and ~50° around the tube axis match D2 and D3 with D1.This confirms that during the heat treatment the prior grain structure of the weld line and the Heat Affected Zone (HAZ) have recrystallized and become a part of a large grain which spans the middle section of the tube. This grain is shown with a light green color in Figure 2.

TUBE BULGING WITH PRESSURIZED WATER

Hydroforming is a type of forming process which uses a pressurized fluid to force the material into the desired shape. In tube hydroforming, a tube is deformed freely or into a die with an internal fluid pressure. The hydroforming process is widely used in the automotive industry, but more research is needed before it can be used for large grain Nb tubes. The ultimate goal is to make seamless cavities with this process.

After all the Laue camera measurements were done, a square-circle gird was put on the tube. This grid will be used to measure the local strains in future work.

Figure 5 schematically shows the tube hydroforming process. Figure 6 shows the setup used in this study to form the Nb tube. To insure a seal, the inside of the ends of the tube were sanded to make the interior surface smooth (sufficient to remove grain boundary ledges and grooves). To create a pressure seal, the conical end fixtures were used to flare the ends of the tube before clamping fixtures were put in place to create a seal between the loading fixtures and the tube. Because the tube was not straight, it bent and compressed during the flaring process, and it was then stretched out to become nearly straight again after the clamps were put in place and before they were tightened. Thus, prior to pressurization, the material was compressed and then stretched in a complex way due to the bending. The bulging then commenced and was recorded at 2s intervals with a pair of GoPro cameras. The pressurized fluid was pumped into the tube with incremental pressure increases. One of the fixtures was moved axially to maintain a nearly constant compressive load. The incremental increase of pressure and axial load was

continued until the tube cracked. The bulged tube is shown in Figure 7, and the crack is shown in Figure 8. The location of the crack is shown schematically in Figure 2, which is in the large central grain some distance from a grain boundary.

While the amount of inflation is not impressive, the deformation history was complex, and it will provide a good way to determine if crystal plasticity models described in [5] can effectively simulate the strains that will be measured from the grid patterns, and if thinning can be predicted where it was experimentally observed.
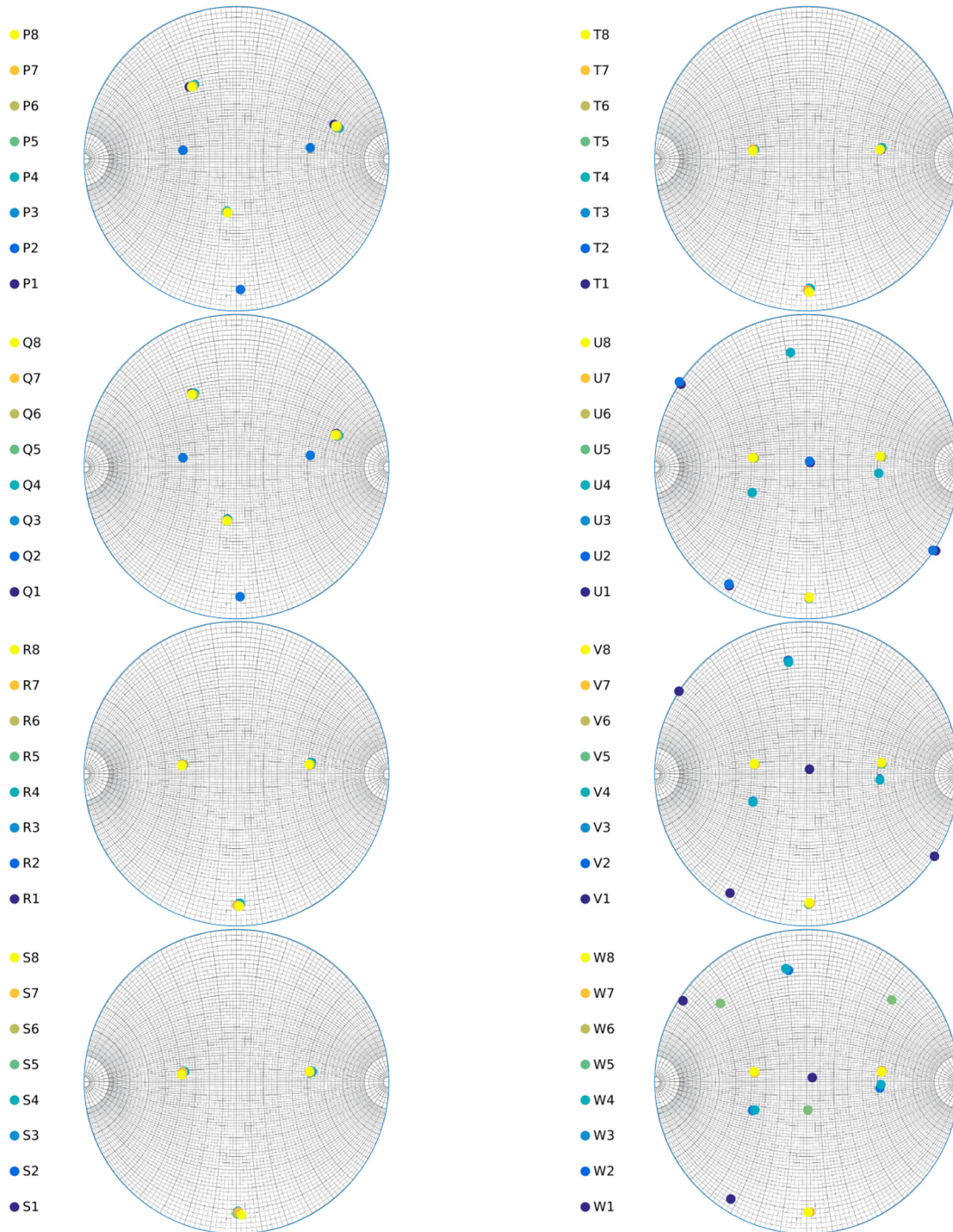

Figure 3: Pole figures show the Laue camera measurements of crystal orientation. Each pole figure shows 6 measurements made around the tube at positions P-W. The crystal orientations plotted in these pole figures are rotated back to a common reference orientation by 0, 71, 152, 213, 263, 315 ° for circumferential positions 1-6.

DISCUSSION

The Laue camera measurement showed that the heat treatment process was successful in obtaining large grains from the starting fine grain polycrystal structure. Furthermore, the orientation measurements around the weld line show that the grain growth consumed the weld and effectively made the tube seamless. Therefore, this heat treatment can potentially be used as method to create large grain seamless tubes if the process is optimized.
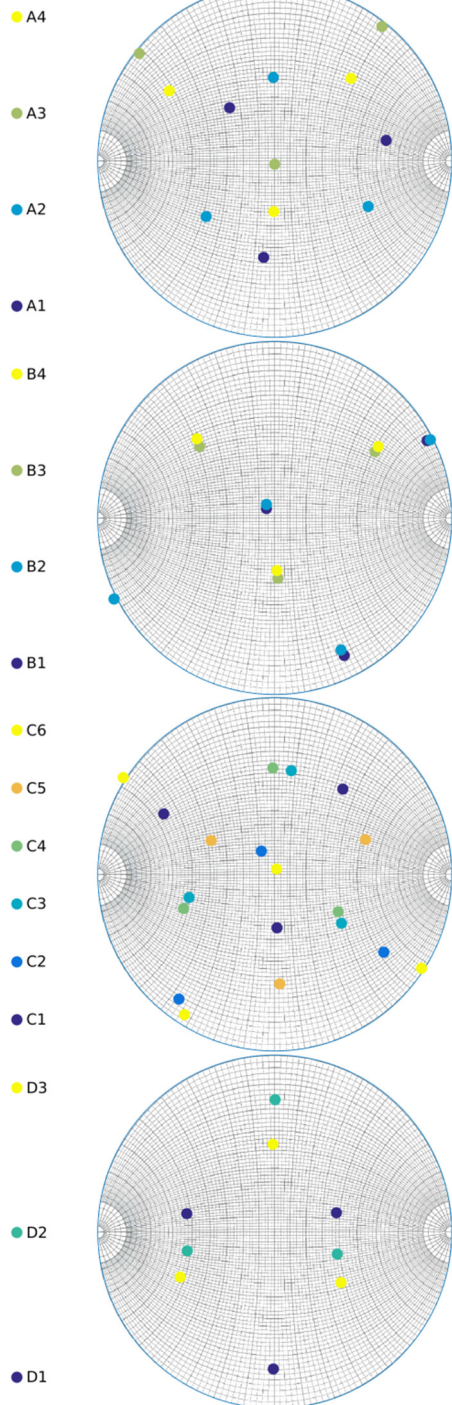

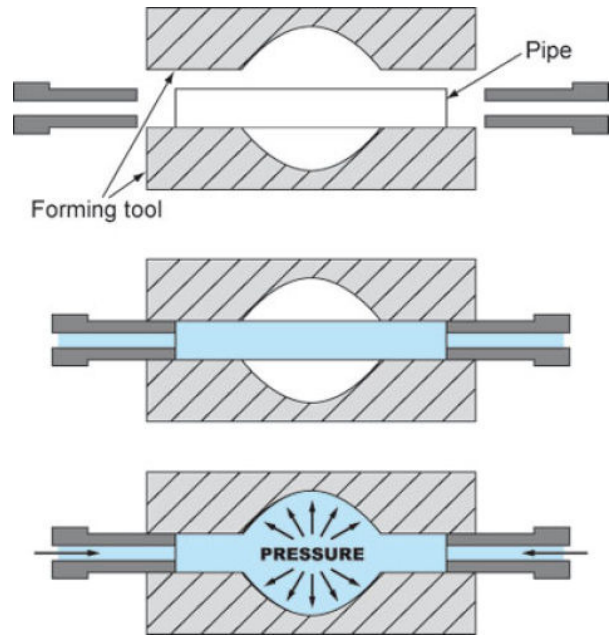Figure 4: Pole figures show the Laue camera measurements of crystal orientation at locations A-D.

Figure 5: This figure schematically shows the tube hydroforming process [7]. A tube is placed in the die (if there is a die) and secured between the rams. A pressurized fluid forces the tube into the desire shape, with the aid of axial feed.
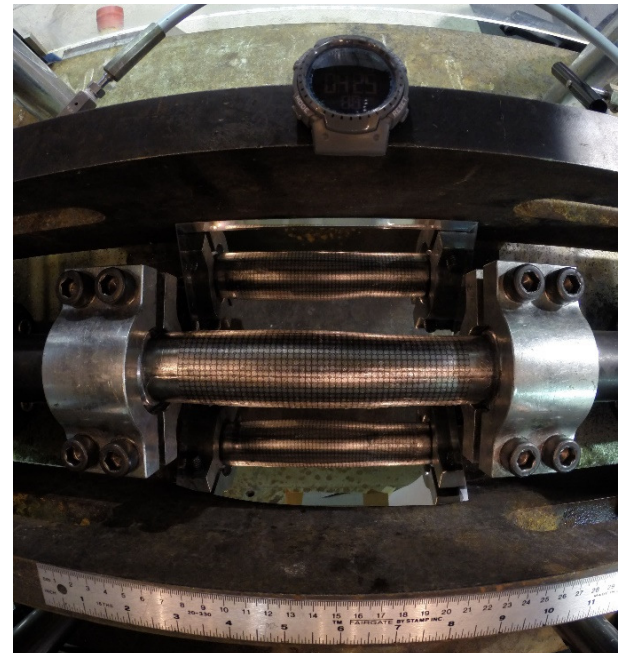
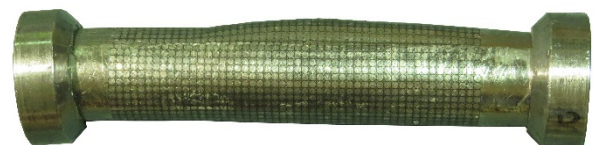

Figure 6: Setup of the large tube hydroforming test.

Figure 7: The large Nb tube was deformed in the tube hydroforming process. The rings at the ends of the tube are a part of the fixture that holds the tube in place during the deformation

The deformation of the tube was very asymmetric and inhomogeneous. The tube broke form the center of a grain, rather than at the prior weld or a grain boundary. It did not fail at the weld because the grain growth fully consumed the weld line during the heat treatment. Also this is a large grain the goes all the way around the tube. The grain is under circumferential loading; the resulting shear stress will be maximum on at least one slip system within the grain that is most favorable for dislocation slip in a particular azimuthal location. This point would yield before other parts of the same grain and may locally thin the tube in this particular orientation of the crystal. This may account for the higher localized stress and eventually to a crack, but this will be assessed in future analysis.

Another possible explanation can be the strain evolution at the combination of specific grain orientations and boundary orientations near the crack location. The local strains to the right of the crack in neighboring grains were very anisotropic, so the crack may have developed near a region of a hard and soft grain. As the behavior of Nb is highly anisotropic, this makes the large grain Nb sheet challenging to form and model, though with a model, an optimal grain orientation could be discovered, to provide guidance for growing a desirable single crystal tube.

Figure 8: The pressure of the tube hydroforming process was incrementally increased until the tube cracked. This image shows the crack.

CONCLUSION

A tube was made from bending a fine grain polycrystal Nb sheet into a tube and e-beam welding it together. This tube then when through a specially designed heat treatment to generate grain growth that successfully consumed the old grain structure, the weld line and the Heat Affected Zone (HAZ). Laue camera measurements confirmed that the tube made with this process is a large grain seamless tube.

The tube cracked within a large grain that spans the middle section of the tube. The reason may be due to the anisotropy of the middle grain orientation with different hoop stress directions that lead to a location with a highly favored slip system, or it could result from the heterogeneous deformation among neighboring hard and soft grains. This needs to be thoroughly analyzed to identity the most likely damage mechanism.

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[7] Schematic Image of Tube Hydroforming. URL: http://www.designlight.se/files/ror01.jpg