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Development of a multi-scale simulation model of tube hydroforming for superconducting RF cavities

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ABSTRACT

This work focuses on finite element modeling of the hydroforming process for niobium tubes intended for use in superconducting radio frequency (SRF) cavities. The hydroforming of tubular samples into SRF-relevant shapes involves the complex geometries and loading conditions which develop during the deformation, as well as anisotropic materials properties. Numerical description of the process entails relatively complex numerical simulations. A crystal plasticity (CP) model was constructed that included the evolution of crystallographic orientation during deformation as well as the anisotropy of tubes in all directions and loading conditions. In this work we demonstrate a multi-scale simulation approach which uses both microscopic CP and macroscopic continuum models. In this approach a CP model (developed and implemented into ABAQUS using UMAT) was used for determining the flow stress curve only under bi-axial loading in order to reduce the computing time. The texture of the materials obtained using orientation imaging microscopy (OIM) and tensile test data were inputs for this model. Continuum FE analysis of tube hydroforming using the obtained constitutive equation from the CP modeling was then performed and compared to the results of hydraulic bulge testing. The results show that high quality predictions of the deformation under hydroforming of Nb tubes can be obtained using CP-FEM based on their known texture and the results of tensile tests. The importance of the CP-FEM based approach is that it reduces the need for hydraulic bulge testing, using a relatively simple computational approach.

1. Introduction

1.1. Fabrication of superconducting RF cavities

Superconducting radio frequency (SRF) cavities provide energy to the particles in high energy particle accelerators. Continuing efforts in terms of fabrication technique are ongoing to improve cavity performance and achieve the needed high accelerating gradients and quality factors [1–3]. Electron-beam (EB) welding is the most common and well-established technique for the fabrication of multi-celled cavities. However, associated with it are some problems that limit cavity performance. Welding provides opportunities for the formation of defects such as foreign material inclusions and topological surface imperfections. Since the RF surface magnetic field is concentrated along the equatorial weld of the cell, the surface quality of the welded region is a major concern. In recent years advanced cavity treatment techniques including electropolishing have permitted accelerating gradients to approach the theoretical limit [4]. However, higher accelerating fields and drastic reductions in cavity production time and costs are needed for the further development of more powerful accelerators. For these reasons, hydroforming, a seamless weld-free fabrication technique, is being considered as an approach to improve electric field gradients and expedite the fabrication of multi-celled cavities [5–7]. The use of hydroforming would eliminate the multitude of EB welded seams which introduce performance-reducing defects. The resulting reduction in post-process operation, including electropolishing, is expected to reduce the manufacturing cost and time for the production of SRF cavities. Hydroforming offers many advantages. The basic mechanical problems have been solved. However, to date the ability to model tube deformation has not been sufficient. Required is a reliable way to model the hydroforming of a tube into a multi-cell cavity that is based on measured materials properties and takes into account the complexities of loading condition and material geometry for tube hydroforming.

1.2. Evolution of the modeling approach

Our earlier research focused on the determination of the constitu-

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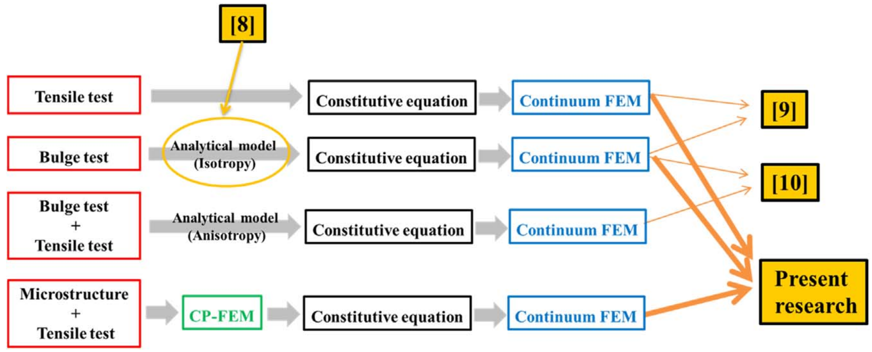

Fig. 1. Evolution of our research on the hydroforming of tubular materials.

Table 1
Dimensions of starting Cu alloy and Nb tubes.

Length [mm]	Outer radius [mm]	Wall thickness [mm]
240	31.75	1.65

tive relationships of hydroformed tubular materials and a prediction of deformation using a continuum model. This approach was based on the acquisition of data from hydraulic bulge testing, Fig. 1. We first examined the validity of various analytical models for obtaining the flow stress curve from the tube bulge test results [8]. Subsequently, the constitutive relationships of tubular materials were obtained from the tensile and tube bulge tests using a previously verified and selected analytical model [9]. The continuum numerical simulation analyses were performed using these constitutive equations. The results of the study emphasized the importance of bulge testing, at the time, rather than tensile testing when deriving the constitutional relationships eventually needed for continuum modeling the hydroforming of SRF cavities. We subsequently went on to include the material's anisotropic properties and used an anisotropy coefficient to determine the flow stress curve of anisotropic materials [10]. It was demonstrated that a more accurate flow stress curve can be obtained by considering anisotropic properties.

Although the previous studies showed that the flow stress curve from the tube bulge test represents more accurate deformation behavior of hydroformed tubular materials rather than that from the uniaxial tensile test, there wasa divergence between experimental results and numerical simulation at high strain. This may be due to the effect of anisotropy which evolves during the deformation due to the complex SRF-relevant geometry and loading conditions. Therefore, this present study focusses on a simulation strategy which uses a crystal plasticity finite element method (CP-FEM) for analyzing the anisotropy in all directions under various loading conditions. Of course, it is possible to consider the evolution of orientation during deformation as well as anisotropy of tubes in all directions and loading conditions. However, the computing time for the detailed replication of hydroforming applied to the local texture with the additional constrains is very high, and a convergence problem may occur due to the complexity of geometry and loading condition for tube hydroforming [11]. Therefore, this work proposes a multi-scale simulation approach which uses both microscopic CP and macroscopic continuum models. In this approach the CP model was used only for determining the flow stress curve under bi-axial loading. Continuum FE analysis of tube hydroforming using the obtained constitutive equation from the CP modeling was then performed. This approach was demonstrated using the results of tensile, bulge tests and microstructural analyses performed on Cu and Nb tubes. Tables 1, 2 list the sample dimension, preparation, testing, and numerical simulation analyses performed in this and related studies. Some data from [9] were used in this study.

2. Outline of the present paper

Fig. 2 shows an outline of the present paper. Three different models were used to simulate the hydroforming process. The first and second are macroscopic continuum models using the constitutive equations (strain-stress relationship) as an input to the simulation. The constitutive equations for the first and second models were obtained from the tensile test and bulge test, respectively. The third model is multi-scale simulation using both continuum and CP-FEM models. In it, the constitutive equation was obtained from the microscopic simulation model (CP-FEM) using microstructural information (i.e., orientation) of materials from the orientation image mapping (OIM) and tensile test data for determining the material parameters. Continuum FE analysis based on the obtained constitutive equation was then performed. In order to reduce the computing time, a cubic shaped CP model was constructed and an applied bi-axial force replicated the actual stress state during the bulge test. Details of each simulation model are presented in the numerical simulation section.

3. Experimental

3.1. Materials

Copper (Cu) alloy and niobium (Nb) tubes were used in this study. In order to increase their formability, the Cu alloy tubes were heat treated at 600 °C for 1 h in flowing nitrogen gas containing a small amount of hydrogen in order to prevent oxidation. The Nb samples (tubes and test coupons) were heat treated under the conditions listed in Table 2. One sample was heat treated for 3 h/800 °C, and another for 2 h/1000 °C. Some samples were heat treated multiple times to increase the formability: one was first heat treated for 3 h/800 °C and then for 2 h/1000 °C ("3 h/800 °C+2 h/1000 °C"), another was heat treated three times for 2 h/1000 °C ("2 h/1000 °C X3"). The experimental tensile and bulge data of Nb samples heat treated for 2 h/1000 °C in previous work were used for this study [9]. For the Nb samples heat treated multiple times, numerical analysis based on the microstructure and tensile test data was performed.

3.2. Tensile and tube bulge tests

The samples for tensile tests were directly cut to ASTM-standard dimensions from the tube wall parallel to the tube axis. The obtained engineering strain–stress curves of samples were converted to the true strain–stress curve as input to the simulations.

Fig. 3 depicts the tube bulge system including a hard tooling set, hydraulic pressurization system, and data acquisition (DAQ) system. The clamping dies confined the tube deformation when hydraulic pressure was applied. Axial movement of both ends of the tube was prevented by the clamping dies while the center section of the tube expanded freely. The ends of tubes were sealed by axial punches. Lead foil provided a seal between the punches and the tube. Hydraulic