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THERMOMECHANICAL PROCESSING OF $YBa_2Cu_3O_x$/Ag SHEATHED WIRES*

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ABSTRACT

Silver-sheathed $YBa_2Cu_3O_x$ (YBCO) powder was thermomechanically processed by rolling wire into flat tapes from sealed 6.3mm diameter, 76mm long billets. Transport J_c values at 77 K in zero applied magnetic filed reached about 500A/cm^2.

Mechanical processing of powder-in-tube specimens involves fracture, densification, and sliding of powder particles as well as deformation and work hardening of the metallic sheath. A model of these effects has been developed and the experimental results suggest that the deformation properties of the powder dominate the stresses to fabricate the tapes.

INTRODUCTION

Silver-sheathed YBCO wires and tapes have been found to have J_c values up to about 10^4A/cm^2 at 77 K.[1-3] Conventionally consolidated and sintered forms generally have lower J_c values,[4,5] but the reasons for the improved performance of powder-in-tube wires are not well understood. It is thought that texture may play a role,[3] but factors such as fracture and abrasion of the superconductor particles during processing may also be important. Cold rolling is often used as a final step in fabricating Ag-sheathed wires.[2,3] This study was undertaken to examine the effects of rolling on YBCO powder packed within Ag tubes. Emphasis has been placed on characterizing the as-rolled structure of the YBCO core and on understanding the processes that produce that structure.

EXPERIMENTAL METHODS

Powder used in this experiment was synthesized under a reduced oxygen pressure.[6] The powder was phase pure as determined by X-ray diffraction and differential thermal analysis. The average particle size was 3 to 4μm. Sheaths were made from 99.99% pure Ag electrodes, 50.8mm long, 6.3mm outer diameter and

5.3mm inner diameter, which were bored out into closed-end tubes. Each tube was loaded with YBCO powder by a combined ramming and vibration technique.[7] The tubes were then evacuated and sealed.

The tubes were cold rolled in a two-high rolling mill and the load for each pass was recorded at the exit side of the rolls. After rolling, coupons in the shape of flat tapes were sectioned and the total reduction versus J_c was measured. The thickest samples for which a continuous superconducting core could be maintained were about 350μm. Tubes were rolled at 0.51, 0.25, 0.13, and 0.025mm per pass to quantify the relationship between percent deformation and J_c.

Tube specimens were also placed in a furnace and held at and elevated temperature for 1 hour prior to rolling. The peak heating temperature was 850°C. Each sample was removed from the furnace, passed through the rolls within 2s of exit from the furnace, returned to the furnace, and again allowed to reached the rolling temperature. Samples were deformed at reduction of 0.25 and 0.051mm per pass.

All YBCO/Ag tapes were sintered at 910±10°C, which is below the incongruent melting point of the superconductor.[8] Cooling rates to the annealing temperature of 450°C were kept at or below 240°C/h to avoid thermal shock. It was found that oxygen requires substantial time to diffuse through Ag at 450°C. Oxygen contents were verified by iodometric titration.

The YBCO/Ag superconductors were characterized by several techniques. Core density measurements were made by the Archimedes' method. Scanning electron microscopy (SEM) was performed on exposed cores to assist in defining the ceramic morphology as a function of processing condition. X-ray diffraction analysis was done to determine grain alignment, phase purity, and residual stresses. J_c measurements were performed by a four-point probe technique at 77 K in the absence of an applied magnetic filed.

RESULTS AND DISCUSSION

The YBCO core density prior to rolling was determined to be 40%. The as-rolled green densities varied from 88 to 95%, depending on the percent reduction and final thickness (Fig. 1). The post-sintered densities of the cold and hot rolled wires were about 90 and 95%, respectively.

Scanning electron microscopy of exposed superconductor cores revealed that the YBCo powder fractured and densified during rolling. A SEM micrograph of a typical cold rolled core in Figure 2 shows that presence of striation and microcracks transverse to the rolling direction. The striations resulted from the combined effects of a lack of lateral constraint during deformation and elongation in the rolling direction. The cracks appear to have initiated along existing striation bands. Striations transverse to the rolling direction also occurred in the hot rolled cores, but no evidence of cracking, as occurred in the cold rolled wire, was found.

The reduction in thickness per pass was fixed and the stresses on the rolled tubes were recorded by a transducer located at the exit end of the rolls. As a result, the strain, and therefore the stress, increased after each pass as shown in Figure 3 for a typical experiment where the reduction per pass was 0.127mm. These roll stress data incorporate the stress-strain behavior of the YBCO and the silver. The roll stresses can also be calculated using a cold, flat rolling analysis (9) and the results of the roll stress, σ_r, can be expressed in terms of n, the number of passes as

$$\sigma_r = P/wh = (1.2/h - n\delta h)S\sqrt{R\delta h} \tag{1}$$

where P, w and h are the roll lead, tape width, and tape exit thickness, and S, R, and δh are the flow stress, roll radius, and reduction in thickness, respectively. This equation may be evaluated from a knowledge of the experimental conditions, and the flow stress of the tape. The flow stress of the silver-YBCO tape is not known but a rough estimate may be obtained from comparisons of σ_r for solid silver and powders with a morphology similar to YBCO. The values of σ_r have been obtained for the silver and ground feldspar from data in reference 10. The compressive strain per pass, ϵ_n, was obtained from

$$\epsilon_n = \ln[(h_o - (n-1)\delta h)/h_o] \tag{2}$$

where h_o is the thickness of the original tube. The flow stress, S, was obtained from the figure on page 124 of reference 10 using these values of ϵ_n. An example of a comparison of the roll stress versus the number of passes is shown in Figure 4. This figure shows the expected roll stress for the silver and the ground feldspar and shows that the experimental results for the YBCO powder-in-tube are similar to the ground feldspar. The characteristic concave upturn of the data up to approximately ten passes is usually ascribed to fracture and the increase in roll stress beyond this point is due to consolidation. The roll stresses for silver are expected to be substantially higher than the measured stresses so it appears that the silver does not dominate the roll stresses.

Transport current measurements were made through the Ag sheath and Figure 5 shows typical J_c data for both the cold and hot rolling. As the reductions per pass were decreased, the J_c increased. Transport current was also examined as a function of final composite thickness. Figure 6 shows J_c versus tape thickness for a tape rolled at 0.025mm/pass. This figure shows that an optimum film thickness of 0.762mm is achieved for the cold rolled tape. The J_c values were substantially higher for the hot rolled samples, but an optimum in J_c could not be determined. Hot rolling results in better superconductors most likely because the YBCO cores were more uniform.

CONCLUSIONS

The conclusions of this study may be summarized as follows: Powder-in-tube processing of YBCO in silver tubes will produce superconducting tapes with densities of 90-95% and reasonable current densities. Hot rolling produces a substantially higher transport current than cold rolling which indicates that strain hardening is occurring during cold rolling. Cold rolling produced an optimum in transport current with final tape thickness with a value that depends on the reduction per pass and the number of passes. The transport current is generally dominated by cracks in the YBCO.

A simplified cold, flat rolling analysis predicts that the YBCO dominated the roll stresses. The powder fractures during the early stages of rolling and consolidation of the powder occurs at subsequent passes.

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This work also was supported by the Illinois Department of Energy and Natural Resources Grant Number SWSC2, and the U.S. Department of Energy (DOE), Conservation and Renewable Energy Division, under Contract W-31-109-Eng-38. The work of M.J.M. was done in partial fulfillment of the requirements of the M.S degree at the University of Illinois at Chicago and was partially supported by the Argonne Division of Educational Programs with funding from DOE.

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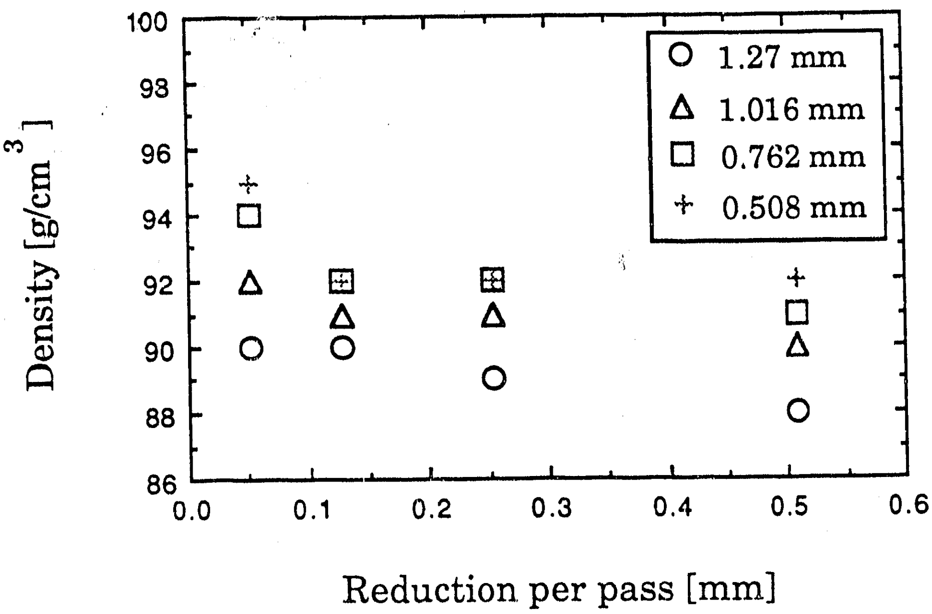

Figure 1. Density (g/cm$_3$) versus reduction per pass (mm) for the final thickness indicated.

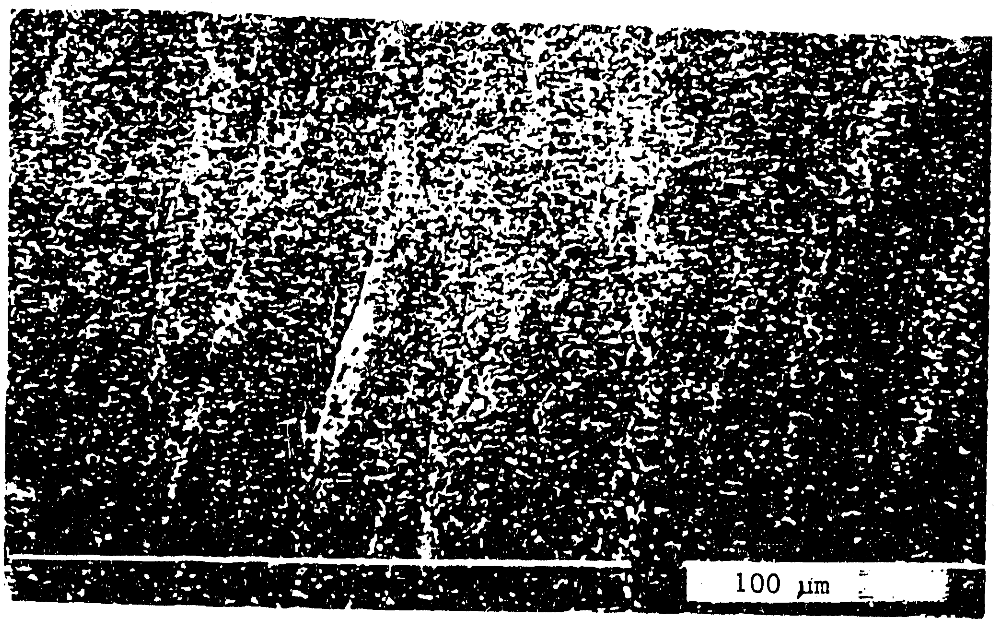

Figure 2. Scanning electron micrograph of a typical cold rolled YBCO core.

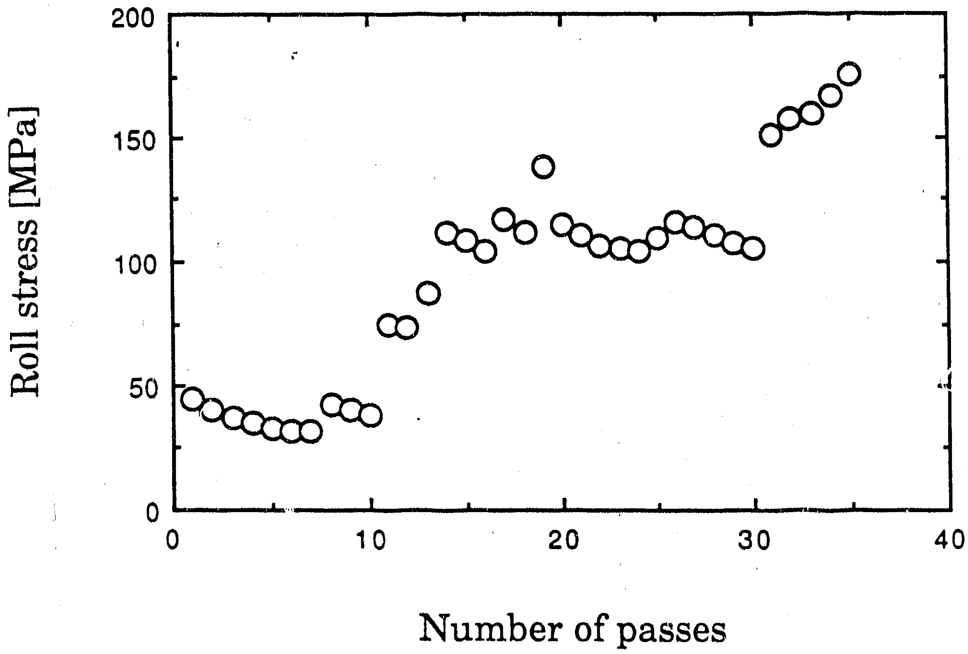

Figure 3. Roll stress (MPa) vs. n, the number of passes for a reduction per pass of 0.127mm.

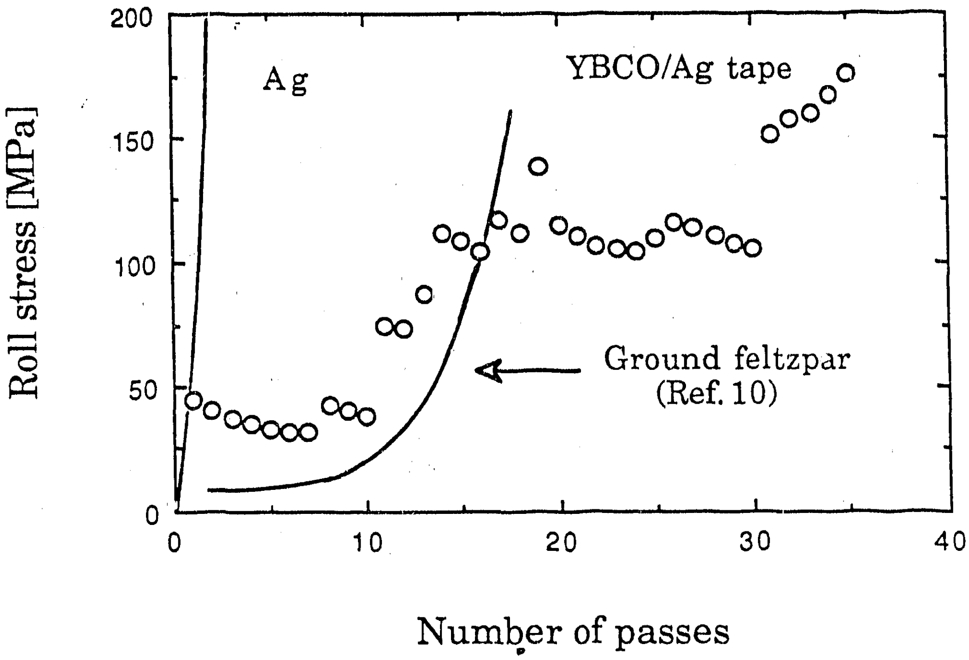

Figura 4. Comparison of the roll stress (MPa) versus n, the number of passes (h = 0.0127cm/pass) for solid Ag and ground feltzpar with the YBCO-Ag tape.

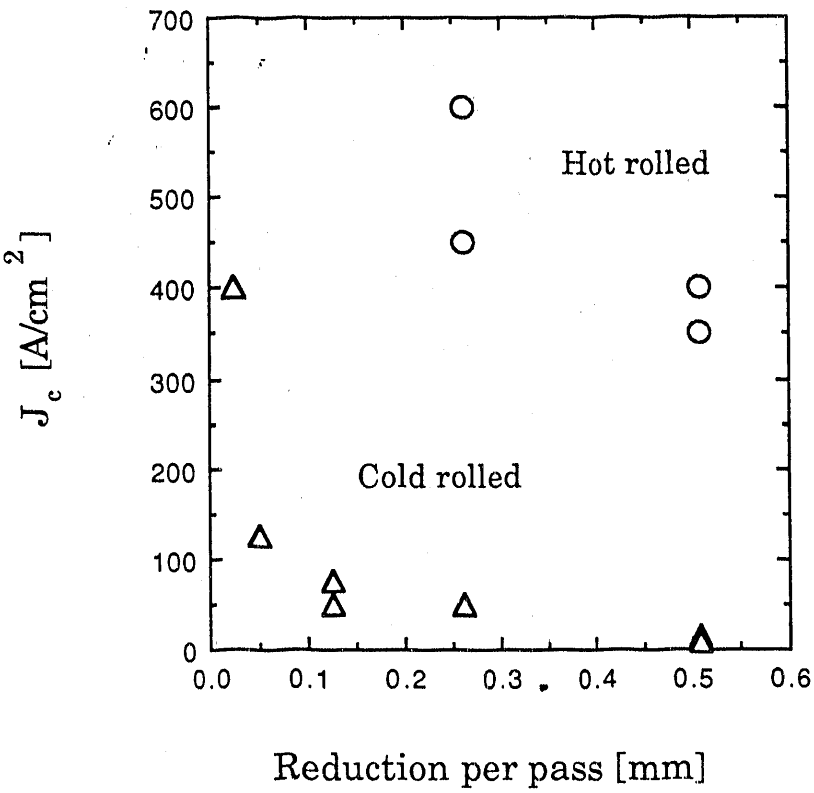

Figure 5. Current density, J_c (A/cm^2) vs. reductions per pass for cold and hot rolling. The final thickness in all cases was 0.0762cm.

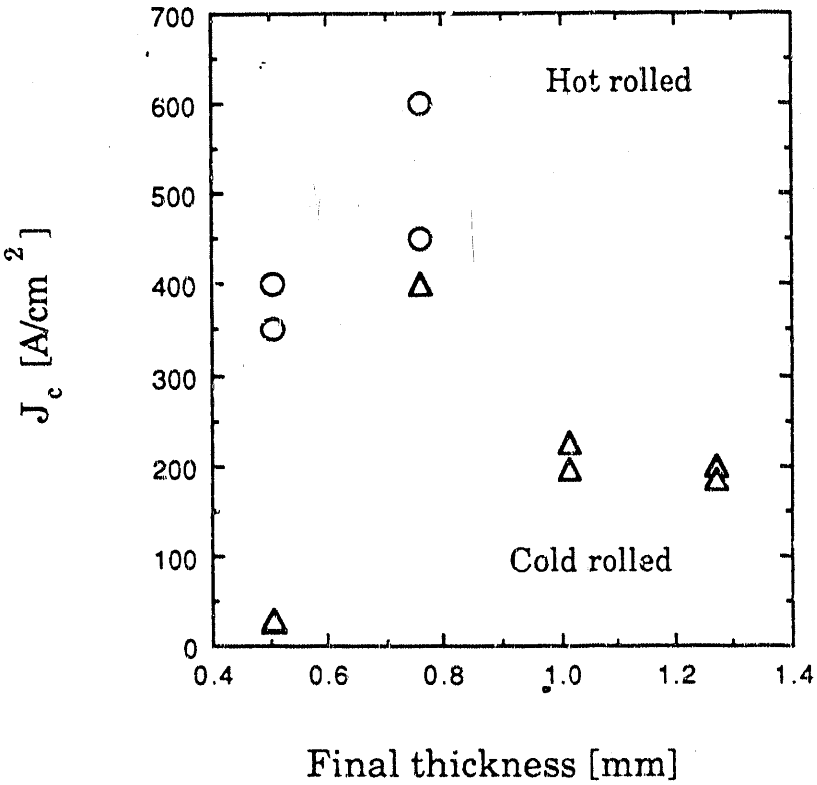

Figure 6. Transport current, J_c (A/cm^2) vs. final thicknesses (mm) when the reduction per pass was 0.025mm.

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