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HEAVILY COLD WORKED HIGH-PURITY Ta AS A REINFORCING STABILIZER

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Abstract - Mechanical and electrical properties have been studied for a heavily cold worked high-purity Ta wire. Tensile test at room temperature shows a large 0.2% proof stress of about 70 kg/mm^2, which is probably caused by work-hardening in the wire drawing process. Our observations of fracture surfaces using a scanning electron microscope indicate that this material is very ductile. Moreover, this sample has a low resistivity of about 0.4 $\mu\Omega$ cm even at the high field of 15 T. The residual resistivity ratio is about 80, which is consistent with high purity of the sample. Therefore, it has been found that the cold-worked Ta wire is applicable to a reinforcing stabilizer for conductors of large scale and/or high-field superconducting magnets.

1. INTRODUCTION

In designing the large-scale and/or high-field superconducting magnets, it is desirable that the superconductors have two properties, high strength and cryogenic stability. In other words, the superconductors should resist the large hoop stress due to Lorentz force and also stable against the possible thermal disturbances such as wire movement, flux jumping etc. Usually, oxygen free high conductivity (OFHC) copper after work hardening is used as an adequate material to reinforce and stabilize the superconductors in the magnets. Recently, it has been found that the Al_2O_3 dispersion strengthened copper (Al_2O_3-Cu) is more suitable for the reinforcing stabilizer than the OFHC copper [1]. Moreover, different combinations of stainless steel and Molybdenum (Mo) have been examined as the internally reinforcing materials [2,3]. We have also reported in [4] that the in-situ processed Cu-Nb composites are excellent materials because of their high-strength and high-conductivity.

In this paper, mechanical and electrical properties are studied for a high-purity Ta wire after heavy cold-work. This material has the advantage of less contamination of surrounding materials because of its high melting point. In addition, Ta exhibits a smaller coefficient of thermal contraction (6.3×10^{-6}/K) than stainless steel or Inconel ($\sim 16\times 10^{-6}$/K), which is comparable with that of Nb_3Sn (7.64×10^{-6} /K). This implies that it is possible to make internally reinforced Nb_3Sn conductors without any degradation of critical current compared with unreinforced wires.

2. EXPERIMENTAL

The high-purity Ta wires were prepared by Kobe Steel Ltd. The cross-sectional area of the sample is about 0.22 mm^2 with its bar shape. Samples were annealed at 650 or 700 ℃ for 1 hour. These annealing temperatures nearly correspond to those of diffusion and reaction heat treatments to form the Nb_3Sn layers. The heat treatment effect was examined only for electrical properties of samples and the temperature was considered as a parameter of heat treatment. An apparatus for tensile test at the liquid He temperature had been developed by one of the authors to evaluate the strain effect of critical current in superconducting wires in magnetic fields up to 16.5 T [5]. The fracture surface resulting in tensile test was observed by a scanning electron microscope (SEM). The tensile tests were made for the as-drawn samples.

The electrical resistivity was measured by a standard four-terminal method. The potential leads soldered on the specimens were located from 5 to 8 mm apart from each other. The temperature dependence of electrical resistivity was measured in the range from 77.3 K to room temperature. The magnetic field up to 23 T was applied to the samples in the transverse direction. The resistivity measurment in the middle-field region up to 14 T and that of the high-field up to 23 T were made in the 16.5 T-SM magnet and the hybrid magnet HM-2, respectively, at IMR, Tohoku University.

3. MECHANICAL PROPERTIES OF HIGH-PURITY Ta

The results of the tensile tests are listed in Table 1. Figure 1 shows an example of the tensile stress-strain curves for the high-purity Ta at 4.2 K and room temperature. In Table 1, the data of the Al_2O_3-Cu at room temperature are also listed for comparison. As-drawn sample has a 0.2% proof stress of about 70 kg/mm² at room temperature which is almost two times larger than that of the Al_2O_3-Cu. It is considered that the high strength of the Ta wire is attributed to heavy cold-work in the wire-drawing process. It is noted that Young's modulus obtained by our apparatus at room temperature is in good agreement with that (190 GPa) in the data base [6]. It is also found that the strength of the sample increses at 4.2 K in comparison with that at room temperature. This phenomenon is explained as follows: thermal activation which helps the external forces to unlock a dislocation is reduced at low temperature [7].

TABLE 1
MECHANICAL PROPERTIES OF A PURE Ta WIRE

Sample	0.2% proof stress (Kg/mm²)	Ultimate tensile stress (Kg/mm²)	Elongation (%)
as-drawn Ta wire (at ~ 293 K)	68.0	90.0	3.19
(at 4.2 K)	94.0	167.0	1.25
Al_2O_3-Cu (at ~ 293 K)	37	40	16

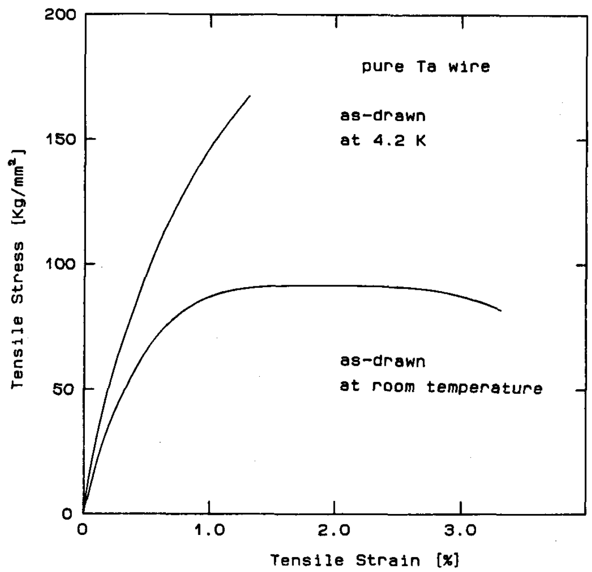

Fig. 1. Tensile stress-strain curves of pure Ta wire at room temperature and 4.2 K.

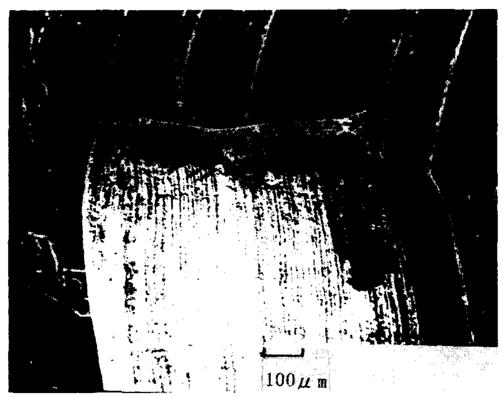

Fig. 2. A scanning electron micrograph of pure Ta wire fractured in the tensile test at room temperature.

Furthermore, the decrease of elongation at low temperature is related to the fact that Ta has a body-centered cubic crystal structure. In other words, a face-centered cubic crystal such as copper does not become brittle at low temperature. Figure 2 shows a scanning electron micrograph of the fracture surface for the sample fractured in the tensile test at room temperature. In the fractograph, a chisel edge partly covered with dimples is observed, which indicates that this material is very ductile.

4. ELECTRICAL PROPERTIES OF HIGH-PURITY Ta

Figure 3 shows temperature dependence of the electrical resistivity of the high-purity Ta. In Fig. 4, the resistivity up to 23 T is presented for as-drawn and annealed samples. Ta is a type I superconductor with T_c = 4.48 K. This sample remains in the normal state even at zero-field due to the residual magnetic field in the superconducting magnet. Resistivity increases slowly with field and reaches a low value of about 0.4 $\mu\Omega$ cm at 14

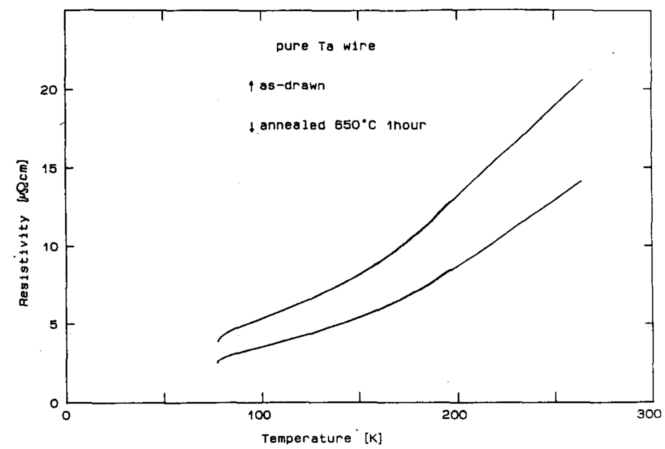

Fig. 3. Temperature dependence of the electrical resistivity for pure Ta wire from 77.3 K to room temperature.

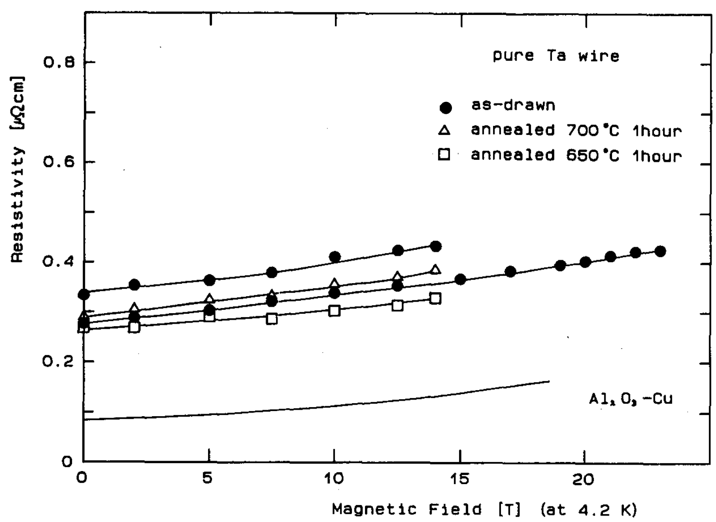

Fig. 4. Magnetic-field dependence of the electrical resistivity for as-drawn and annealed samples up to 23 T at 4.2 K. The data of Al_2O_3-Cu is also shown for comparison.

T for as-drawn sample, comparable with that of the Al_2O_3-Cu. Electric conductivity is improved by annealing which reduces densities of dislocation and thus decreases the contribution of dislocation to electron scattering mechanisms. The residual resistivity ratio (RRR) for each sample were estimated from Figs. 3 and 4. This value is about 80 which is consistent with high purity of the sample. The difference of two as-drawn samples seems to be caused by using the samples cut out from different positions in the same wire, or by the error in reducing the measured value to the resistivity.

5.SUMMARY

In this paper, mechanical and electrical properties were studied for a high-purity Ta wire heavily cold-worked. The results are summarized as follows.

1. As-drawn Ta wire has a large 0.2% proof stress of about 70 kg/mm^2 at room temperature which is almost two times larger than that of the Al_2O_3-Cu. Thus, this material is suitable for the reinfocement of superconductors.
2. Annealed samples yield a low resistivity of about 0.3 $\mu\Omega$ cm even at the high field of 14 T. This indicates that it is possible to use the Ta wire as a composite material for stabilization of superconductors.
3. Therefore, it has been found that the cold-worked Ta wire is applicable as a reinforcing stabilizer for the conductors of large-scale and/or high-field superconducting magnets.

In this report, the heat treatment effect was examined only for the electrical properties of Ta. But, it will be needed to confirm the strength of Ta, by studying the mechanical properties of the annealed samples. Such experiments are in progress.

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