High-Strength Cu–Ta–W Composite

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***Abstract*—High-strength copper conductor composites have been used in pulse magnet applications and as internal reinforcement in superconductor wires. The required property is high strength while maintaining high conductivity. Heavily worked pure copper has a strength of 450–500 MPa. Increasing the strength of copper by alloying additions without affecting the conductivity drastically is a significant challenge. Mixing pure copper with a higher modulus, higher strength tantalum alloys is an option to meet the challenge. This work reports on the use of a tantalum–tungsten alloy to strengthen high-purity copper through a multifilament approach. The tantalum tungsten has a high modulus and very low solubility in copper. A composite wire containing 133 filaments of Ta–W (25% by volume) has a conductivity of 80% International Annealed Copper Standard and ultimate tensile strength of over 650 MPa with a modulus over 140 GPa. The wire has good ductility and toughness. These results are comparable or better than current options, and the potential to improve this product is explored.**

***Index Terms*—Copper–Tantalum–Tungsten, high strength, high conductivity, multifilament wires, pulse magnet.**

I. Introduction

PULSE magnets require conductors with high strength and high conductivity. The obvious strategies for the combination of strength and conductivity are highly cold-worked Cu-based conductors designed to maintain the conductivity as close as possible to the International Annealed Copper Standard (IACS). Solid solution strengthening mechanisms involve elemental mixing with Cu that have a detrimental effect on the conductivity. Current strategies to increase strength in Cu-based systems include oxide dispersion strengthening of Cu by alumina which is available as a commercial product Glidcop (registered trademark of North American Höganäs) [1]. Apart from the Glidcop conductors, there are conductors based on the creation of interfaces in Cu, by mixing of an element that has very low solubility in a Cu matrix, for example: Nb or Ag. Present strategies to increase strength include enhancement of hardening mechanisms by creating fine precipitates in a Cu matrix that restrict dislocation motion [2], [3]. The second method is to create fine interfaces as is the case in Cu-Nb [4]–[7], and Cu-Ag [8]–[11] alloys where the spacing of the Nb in Cu, and second phases of Cu-Ag contribute to blocking dislocation and offer high strengths well over a simple rule of mixtures. To develop high field pulse magnets, wire options are desired which provide high strength, high modulus, and sufficient ductility to be wound into a pulse magnet. Recently, a Ta-W alloy commonly used for corrosion resistance applications in the chemical industry commercially known as NRC76 (registered trademark of H. C. Starck, Inc.) was used to demonstrate methods to reinforce Nb_3Sn conductors for High Energy Physics (HEP) applications [12]. Apart from providing improvements in strength and modulus, Ta-W filaments in a Cu-matrix exhibit ductile deformation compatible with conventional wire drawing processes [13]. NRC76 is a commercial product and available in sheet, rod, and tube form, which could be beneficial for economics, and sourcing of the raw material.

Here we demonstrate that Cu-Ta-W can provide a pathway to obtain high strengths of over 650 MPa while maintaining conductivity of around 80% of Cu-101.

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II. Materials and Methods

A. Fabrication of Cu–Ta–W Composite Wire

Ta-W was obtained in a rod form with nominal dimensions of 9 mm diameter, and 500 mm length. The annealed alloy rod was processed at H.C. Starck, Inc. The rod was encased in a commercial Cu-101 tube of inner diameter 10 mm, 500 mm length, and 1 mm wall thickness. The Cu-Ta-W monofilament is drawn down, and hexed at 2.5 mm. The hexagonal element is then restacked into a seven filament sub-element. This sub-element is drawn down further and hexed to form a 19 element restack. This 19×7 restack is then drawn down to a final wire diameter of 4.7 mm. A schematic of the whole process is illustrated in Fig. 1. Intermediate heat treatments were carried out at 250 °C for 3 hr in an Argon atmosphere at various stages of the restack, and drawing. The heat treatment anneals Cu which reduces the drawing force, and also promote inter-diffusion between Cu interfaces which helps diffusion bonding. Several samples were cut at various intermediate drawing steps for further analysis. The total true strain undergone by Ta-W is calculated by $\ln(A_0/A_f)$, where A_0 is the area of the starting Ta-W rod, and A_f is the final area in the final multi-filament wire.

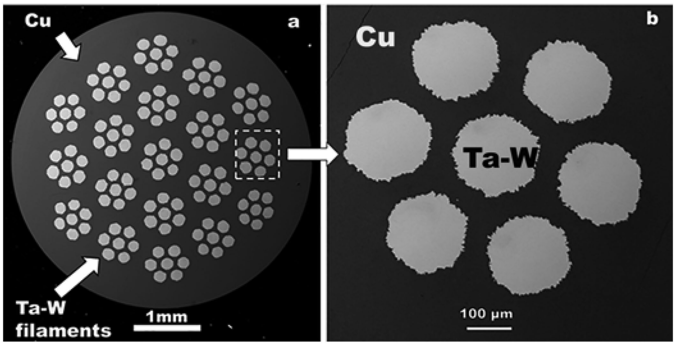

Fig. 1. BSE image of Cu-Ta-W multi-filament drawn down to a final diameter of 4.7 mm. The Ta-W filaments maintain their shape during the re-stack and drawing operations.

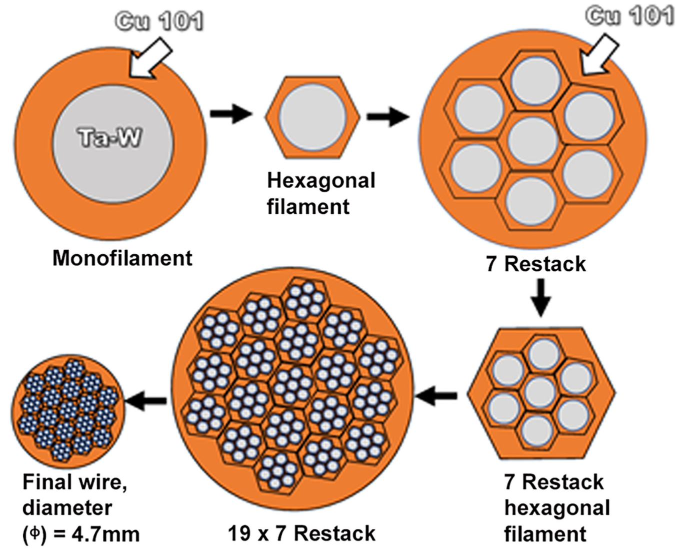

Fig. 2. Schematic of fabrication of Cu-Ta-W multifilamentary restack conductor. The initial Cu-Ta-W monofilament underwent two separate restack steps to form a 19 × 7 restack conductor with a final wire diameter of 4.7 mm.

B. Mechanical Testing

To estimate the strength and work hardening rate of the Ta-W, Vickers micro-hardness measurements (load $>$50 g) were performed on the Ta-W filaments samples at various drawing stages, and the diameters were recorded.

Room temperature (295 K) tensile tests were also conducted on the final wire. The tensile sample dimensions were 150 mm long, and 4.7 mm in diameter. A clip-on extensometer measured strain over a gage length of 25 mm. The tests were carried out at a strain rate of 3.3E-4/s. The tensile test was not performed on a reduced cross-section specimen, which could lead to an under-prediction of tensile strength. The final elongation of the specimen cannot be determined by a non-standard tensile specimen. In this paper, we report the elastic modulus (E), yield strength (σ_y, 0.2%), and the ultimate tensile strength (UTS).

C. Resistivity Measurements

Four point resistance measurements on the final multi-filament wire of diameter 4.76 mm were measured at 295 K, and 77 K. The distance between the voltage tap was 100 $\pm$ 1 mm. Resistivity was calculated based on resistance measurements made by passing currents of 1 A, 2 A, and 5 A, and measuring the voltage drop over the tap length. Resistance measurements at 77 K were made by immersing the setup in liquid nitrogen.

The 295 K resistivity was expressed in terms of percent IACS. The standard 100% IACS (295 K) equals 17.2E-9 $\Omega\cdot$m. For our tests, a maximum error of 1% is estimated for the IACS value. A Residual Resistivity Ratio (RRR) defined as the ratio of resistivity at 77 K to that at 295 K was calculated for the manufactured composite.

D. Metallography and Microscopy

Short sections of the conductor were cut at various stages of fabrication. The samples were extracted from approximately 50 mm from the back-end of the conductor during drawing ensuring representative conductor cross-sections for optical and scanning electron microscopy (SEM). Hardness examinations were conducted on polished sections. Back Scattered Electron (BSE) imaging was performed in a Field Emission Scanning Electron Microscope (FESEM), with a high spatial resolution of 1 nm. Images of fracture surfaces were obtained from the tensile tested specimens to evaluate the nature of fracture in the composites produced.

III. Results

A. Characteristics of Multi-Filament Cu–Ta–W Conductor

The multi-filamentary Cu-Ta-W conductor, at the final diameter of 4.7 mm, is as indicated in Fig. 1. The interface between the Cu-Ta-W indicates no delamination, however, the Ta-W interface with Cu is jagged. BSE images have high atomic number sensitivity and Ta-W appears brighter than Cu in these images. Image analysis indicates that the Cu: Ta-W area ratio is 26:9. The Cu area of the conductor corresponds to 74.3% of the overall area of the conductor. The average diameter of the Ta-W rod in the final wire is 152 $\pm$ 8 μm and the variation in the Ta-W area is within 5% among all the filaments examined. Ta-W alloy underwent a total true strain of 2.2 during the multi-filamentary wire fabrication.

B. Mechanical Behavior of Ta–W, and Cu–Ta–W Multi-Filaments

The hardening behavior of Ta-W was tracked by measuring Vickers micro-Hardness (HV) at various stages during the drawing process. The hardness versus strain plot is as shown in Fig. 3., where the hardening behavior of Ta-W is linear up to a strain of 2.2. The as-received Ta-W rod was in the annealed form with a starting HV of 87 $\pm$ 9, and an HV over 400 in the final wire. The final hardness HV values of Ta-W is comparable with some varieties of age-hardened steels [14]. The hardness of Cu101 saturated around HV 110.

Representative room temperature tensile tests of Ta-W (Φ = 2.3 mm), and the Cu-Ta-W multi-filament composite are indicated in Fig. 4. Ta-W has an elastic modulus (E) of 204 GPa,

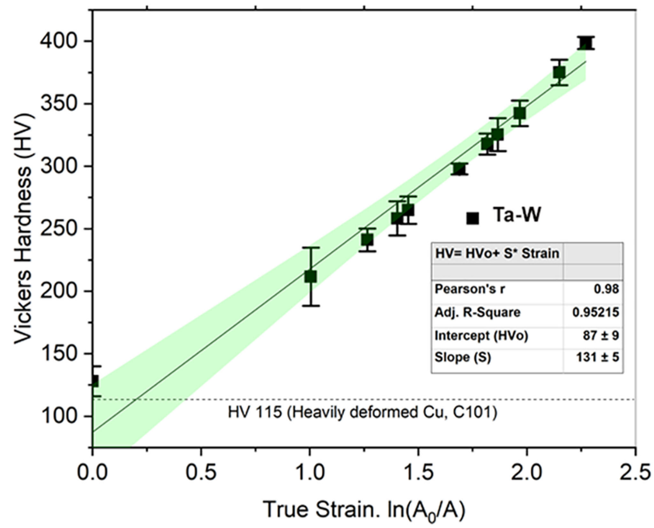

Fig. 3. Vickers micro-hardness HV of Ta-W rod as a function of true strain as the multi-filamentary conductor is fabricated. The hardness of Ta-W increases linearly with strain up to 2.25. The hardness of fully worked Cu101 is exceeded by Ta-W at very low strains.

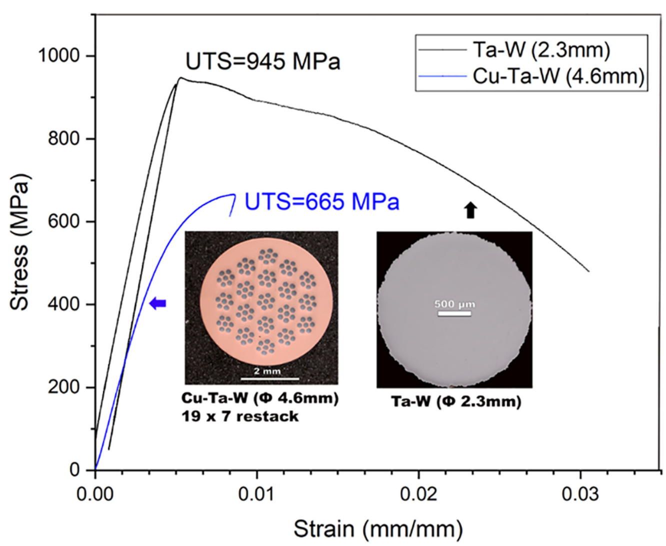

Fig. 4. Room temperature (295 K) tensile test curves of Ta-W rod at diameter 2.3 mm, and Cu-Ta-W multi-filament wire at 4.6 mm. The Ta-W reinforcements strengthen the multi-filamentary wire beyond 650 MPa.

and an ultimate tensile strength (UTS) of 965 MPa. The modulus of the multi-filament composite is 143 GPa, which is higher than the Cu modulus of 120 GPa. The UTS of the wire in the final form is 665 MPa. In Table I we summarize the 295 K tensile test results and compare them with other resistive magnet conductors. The room temperature UTS of Cu-Nb, Cu-Ag, and Glidcop can vary significantly. The dependence of strength in Cu-Nb, and Cu-Ag are related to average interface distance [7], and composition [11]. The strength of Glidcop is dependent on the percent of dispersed oxide. A commonly used Glidcop alloy AL60 has a 295 K UTS of 650 MPa [1]. The UTS of Cu-Nb can vary between 500-1600 MPa, and high conductivity Cu-Ag can vary between 850-950 MPa. The modulus of Cu-Nb, Cu-Ag or Glidcop conductors are in the range of 110-125 GPa.

TABLE I
SUMMARY OF 295 K TENSILE TEST RESULTS

Material	Modulus,(E) (GPa)	0.2% Yield (MPa)	Ultimate Tensile Strength, (UTS) (MPa)
Ta-W	204	945	965
Cu-Ta-W	143 (141.5)*	645	665
Glidcop® (AL-60) [1]	111	600	650
Cu-Ag [10]	115	565	850-950
Cu-Nb [5]	110-125	700-1200	500-1600

*Composite Modulus calculated by rule of mixtures, using an area ratio of Cu:Ta-W of 16:9, and Modulus of Cu = 120 GPa, and Ta_W = 204 GPa

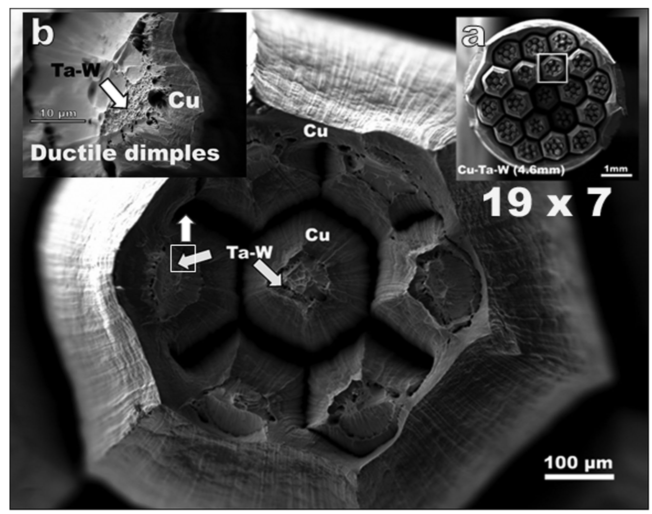

Fig. 5. Fracture of a seven sub-element Cu-Ta-W multi-filament stack after tensile testing at 295 K. Insert (a) is the full cross-section of the wire, and (b) indicates the ductile fracture as observed by dimples in the Ta-W filaments.

Fig. 5. depicts the fracture of the composite. A few key characteristics of the fracture modes are as follows; there is a cup-cone morphology noticed in the seven stack filaments. The presence of dimples on the fracture surface of Ta-W rods suggests ductility of Ta-W. The overall fracture of the composite resembles that of a medium-high fracture toughness material.

C. Electrical Conductivity of Cu–Ta–W Composite at 295 K, and 77 K

Resistivity measurements based on four point resistance measurements conducted at 295 K, and 77 K are presented in Table II. The resistivity values of the Cu-Ta-W multi-filamentary composite was 21.7E-9 nΩ·m at 295 K, and reduced to 2.99E-9 nΩ·m at 77 K. The values of the resistivity of the fabricated conductor compares well with commercial Glidcop AL-60 composition. Percent IACS value of Cu-Ta-W, and Glidcop are also comparable around 80%. The RRR value of the Cu-Ta-W conductor is $\sim$7, which is higher than any other resistive conductor considered here.

TABLE II
SUMMARY OF 295 K, AND 77 K RESISTIVITY MEASUREMENTS

Material	Resistivity, ρ (nΩ..m)		%IACS+ (295K)	RRR = $\rho\ 295K/\rho 77\ K$
	295 K	77 K		
Cu-Ta-W	21.7	2.99	79.5±0.8	7.24
Glidcop® (AL-60) [1]	14.4	3.3	82±1	4.3
Cu-Ag [10]	23.9	7.6	76	3.1
Cu-Nb [5]	20.23-31.27	4.6-7.1	85-55	4.4

+International Annealed Copper Standard (IACS), 100% IACS = 1.72E-8 Ω·m.

IV. DISCUSSION

Ta-W filaments in a Cu matrix deformed uniformly during the drawing process as evidenced by the roundness of the Ta-W filaments and constant cross-section area even after a strain of 2.25. The Cu:Ta-W area ratio of 26:9, could be further modified by additional re-stacking and drawing of the conductor, a potential route for further optimization of properties. From the hardness curve in Fig. 3 it is clear that the Ta-W material has not saturated in its hardening, the cup-cone fracture, and ductile dimples in the fractured material in Fig. 5, which suggests toughness and indicates that Ta-W can be further drawn into finer filaments in a Cu matrix.

The results are shown in Table I indicate that the modulus follows a simple rule of mixtures in a micro-composite, whereas the conductivity values are slightly higher than the Cu area fraction of 74.3%. This could be due to current sharing in Ta-W, or the conductivity of Cu101 maybe greater than 100% IACS. An interesting result is that the RRR value of 7 is higher than Cu-Ag, and Cu-Nb, which could be an advantage if the conductors are operated in a liquid nitrogen environment provided that the Ta-W has sufficient fracture toughness. Transferring load to support structure requires ductility of more than 2% [15]. Further work to quantify the full elongation properties is required.

In this present study, we have shown that the Cu-Ta-W could offer a potential wire alternative where Glidcop AL-60 is currently being used. The added advantage is the higher modulus of 140 GPa [1], which is beneficial for magnet designs where the strain is the control parameter. Due to the availability of Ta-W alloy and the relatively simple re-stacking process, it could also be cost competitive with alternatives.

The simple multi-filament design, with sufficient drawability provides a pathway for conductor design of various strengths and conductivities. The strength could be potentially improved further by drawing the Ta-W down to finer filament diameters and reducing the Ta-W filament to filament distance. This could lead to the interface strengthening mechanisms that are commonly observed in Cu-Nb conductors, where the dislocation motion of Cu is prevented by the Nb filaments leading to increased strength.

V. CONCLUSION

- Design of micro-composites is straight forward and offers better design control to tailor strength and conductivity.
- Cu-Ta-W can be drawn to large strains, and long lengths of wires are possible.
- The reinforcement provided by Ta-W increases the modulus of the composite and could be potential alternative material for pulse magnet applications.
- Cu-Ta-W has the potential to be developed into a conductor with finer Ta-W filament spacing in a Cu matrix. This could enhance the strength further.

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