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A Survey of Processing Methods for High Strength-High Conductivity Wires for High Field Magnet Applications

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Abstract

This paper will deal with the basic concepts of attaining combination of high strength and high conductivity in pure materials, *in-situ* composites and macrocomposites. It will survey current attainments, and outline where some future developments may lie in developing wire products that are close to the theoretical strength of future magnet applications.

Introduction

The processing of appropriate conductor wires for the winding of the coils of high field magnets is an important aspect of the construction process. This is a difficult task because it requires the attainment of reproducible combination of extremely high mechanical strength and adequate electrical conductivity in large cross sections and long lengths.

Thus, we need to consider both basic descriptions of how to attain the required combination of properties and produce flow charts of feasible manufacturing routes.

We can consider three routes to attaining the goal of combined high strength and high electrical conductivity.

1. Increasing the strength of pure copper either by the addition of second phase particles or by work hardening to increase the dislocation density of pure copper to very high levels
2. Producing ultrafine scale drawn composites with extremely high amounts of internal interphase interfaces.
3. Production of macroscopic composites consisting of Cu which provides the conductivity and a second component which either has a very high strength or work hardens rapidly and provides the strength.

The approaches are dealt with in separate sections below.

Strengthening of Copper

In using the addition of obstacles to copper to raise the yield strength there are two basic problems which must be solved. The obstacles should not significantly increase resistivity, which rules out methods which add substitutional solute elements to the copper, and the obstacles must be stable during temperatures cycle of 77K to 393K in order to be suitable for service in the magnet.

The traditional approach has been to use oxide dispersions in the copper, typified by the use of GlidCop. The materials are fabricated by internal oxidization of Cu-Al powder and the final products are oxide dispersion

strengthened copper. The particle sizes of the Al_2O_3 are about 10 nm. The strength achieved was about 600 MPa with the conductivity of 80% IACS. Previous experimental results revealed that the GlidCop possesses a good resistance to thermal and mechanical fatigue in addition to its moderate strength and high conductivity. However, the quality control of the wire is crucial and difficult in a powder processed material. We have occasionally found large aluminum oxide particles (about 1 μm) in these materials. These large oxides lead to the deterioration of the drawability and ductility of the materials, especially in GlidCop-15+Nb (Cu-10 wt%Nb-0.3wt% Al_2O_3).

In conventional oxide dispersion strengthened materials such as GlidCop, the strengthening phase is equiaxed and provides an obstacle to dislocation motion. However, by changing the morphology of the strengthening phase, strength can be achieved by load transfer at the particle interface. Thus, the 3M Inc. have recently developed both aluminum based materials containing continuous fibres of Al_2O_3 [1] which can be produced economically in tape form and which have potential application as high strength high conductivity materials.

In addition, it may be possible to develop tape technologies based on functional graded materials in which gradients of strength can be produced by using internal oxidation of a copper based tape which has a composition gradient on one side prior to internal oxidation.

A new alternative approach to the strengthening of copper was recently suggested by Embury et al in a research proposal to NHFML. In this method, it was proposed that a wire drawing facility would be developed to operate at 77K and a pure copper conductor could be fabricated by cryogenic drawing. The liquid nitrogen used for cooling may serve as a lubricant, but alternative solid lubricants such as lead or graphite may also be required. The conductors fabricated in this way have the potential advantage of having strength levels of order 1GPa and conductivity of order 85% IACS. At first sight, using pure Cu would seem out of the question because when drawn at room temperature, Cu develops a maximum strength level of order 450-500 MPa. However, based on the earlier work of Blewitt et al [2], the deformation group at McMaster has studied the deformation of both Cu single crystals and polycrystals at 4.2K and found that even in uni-axial tension, strength levels of order 850-950 Mpa can be developed. If larger strains can be imposed, as in wire drawing, it should be possible to develop these strength levels at 77K. The work hardening rate of polycrystal Cu is about 0.8GPa at 77K (calculated from $M^2\mu/200$, where $\mu=33\text{GPa}$ and $M=2.5$). Therefore, in order to achieve the strength level of 1GPa, a true strain of only 1.5 is needed. An important observation in the 4.2K deformation studies is that the strength developed at 4.2 K is stable after allowing the sample to be heated up to 298K. Also it should be noted that the scattering due to dislocations is weak compared to solute atoms. Thus, if the contribution to the resistance of the dislocations is of order $10^{-19} \Omega\cdot\text{cm}$ per cm of dislocation line and at large strain the dislocation density is 10^{12} to 10^{13} cm/cm^3 , the total resistivity change is of order $10^{-7} \Omega\cdot\text{cm}$. This can be compared with the scattering due to solutes, which is of order $10^{-6} \Omega\cdot\text{cm}$ per atomic % solute. Thus,

heavily cold drawn pure copper should retain a high percentage of IACS. Hence, the exploration of cryogenic working processes for pure Cu may be of value in providing a new approach to high strength – high conductivity wires.

However, it is important to recognize that some basic physical phenomena remain to be explored in regard to materials deformed to large strain at low temperature including the dynamic recovering mechanism operated between 77K and 293K, the role of alternative deformation modes such as twinning and the stability of the dislocation structures produced by cryogenic deformation. The very high densities of dislocations which can be accumulated by cryogenic deformation clearly represent a metastable state but may nonetheless provide a valuable mechanism for producing appropriate conductors.

Drawn Microscopic Composites

Different fabrication routes to produce Cu-Ag in situ composite of the required properties and sizes have been developed and are summarized in reference [3]. The total drawing strain necessary to achieve strength level of 1GPa was estimated by assuming a linear work hardening rate (about 130MPa) which was deduced from previous work [4] and verified for producing large cross-section wire [5]. A Cu-25wt%Ag billet of large diameter was hot forged at a temperature below 625 °C. The temperature of the hot forging operation was chosen in order to decrease the dendrite size of the cast materials, avoid excessive grain growth, and to allow adequate ductility for forging. After forging, the material was cold drawn to 5.2mmx8.6mmx1.6mm corner radius with or without intermediate heat treatment. A total drawing strain of 5 was needed in order to achieve the strength level of 1GPa.

Cu-Nb wires were fabricated by two methods at Bochvar in Russia. *In situ* composites were fabricated by a similar method to that used for Cu-Ag materials. Cu-Nb wires were also fabricated by bundling and deformation, using high purity Cu (99.99%) and Nb, as summarized in reference [3]. A Nb ingot was re-crystallized at about 1200°C and extruded to the rod of 60 mm in diameter at 700-800°C. A composite billet made by inserting a Nb rod in a Cu can was evacuated and extruded to a rod of 20-30 mm in diameter with Nb of 40 vol. %. The composite rod was cold-drawn to a hexagonal shape in a cross-section with the deformation steps approximately 10-15% of reduction area. Hundreds of composite rods were then assembled in a Cu can. The bundled composite was evacuated, welded, extruded at a temperature below 700°C and cold drawn to a hexagonal rod. Such a procedure was repeated however, with different numbers of rods for bundling. The final products were composed of millions of Nb fibres embedded in Cu. In principle, this method can also be used to fabricate Cu-X materials, where X is Ag, Cr, Mo, Ta or Fe.

The detailed structure of heavily drawn in situ composite has been studied by many groups. The seminal work of a number of French researches [6][7][8] clearly indicates the importance of both the scale and the detailed crystallographic relationship between the phases after deformation. In essence, the deformed embedded phases become nanoscale fibres after deformation and

the detailed properties both in terms of plasticity and the electrical resistances are determined by the detailed interfaces between the phases and the complex morphology. This latter aspect is illustrated in Fig. 2 of reference [3]. It is clear that new fabrication methods can be developed which combine rapid or directional solidification and wire drawing to produce a variety of ultrafine scale structures in which the volume fraction, scale, spatial distribution and the interface geometry of the embedded phase can be tailored. Thus, there is a potential to develop new families of high strength high conductivity conductors by processing of *in-situ* composites.

Macroscopic Composites

Macroscopic composite conductors can be fabricated using copper swaged or drawn in steel tubes and such materials may have advantages in terms of their thermal properties and the lower temperatures reached during the pulses involved in energizing the magnet. Some previous research has utilized macroscopic composites based on copper and stainless steels [9]. It is also possible to develop strengths up to 1.6 Gpa using macroscopic composites of copper and eutectic steel [10]. To date neither the selection of the strengthening component or the hardening phase, e.g. the composition of the stainless steels nor the geometric arrangement of the phase has been optimized and the development of new macroscopic composites remains a fruitful area for development. For instance, optimization of the choice of the stainless steel will give the required mechanical properties. An example is shown in Fig.1, which indicates that stainless steels that form martensite on deformation and contain sufficient levels of interstitials such as C, N can attain very high strengths at 58% reduction in area [13]. Using the data from different stainless steels, we can calculate the final strength we can get after a certain amount of deformation (58% cold deformation of Cu+40vol%SS), as shown in Tab. 2.

Tab. 2. Strength of the Cu+40vol%SS after 58% cold work

Steels	304/310/316	302	301
Strength of the Cold Deformed Steels (MPa)	1112	1313	2008
Strength of Cu+SS (Mpa)	625	705	983

The conductivity of stainless steel plus copper should be of the order of 60%IACS at room temperature provided 60% of copper is used. If the stainless steel has a very high work hardening rate, high strength can be achieved with relatively small amount of cold work (e.g. 60-70% reduction in area). The high work hardening rates in stainless steels is complex because it involves four factors (a) the extent of the transformation to martensite (b) The storage of the dislocation in the parent austenite (c) the transformation of the dislocation structure by the martensite transformation and (d) the influence of interstitials on the stability of the dislocation structure.

The detailed crystallography of the transformation of dislocations by twinning has been discussed by Basinski et al [11, 12]. And indicates that some sessile dislocations are formed from the glide dislocations in the parent phase.

Fig. 1 Effect of cold rolling on the 0.2% proof stress and martensite content of austenitic stainless steels [13].

Thus the detailed understandings of the hardening of austenite-martensite mixture will require extensive high-resolution TEM studies in order to establish the details of the structure. As the martensite transformation depends on both the degree of deformation and the further hardening may be achieved by quenching the materials in liquid nitrogen to increase the amount of martensite at an intermediate drawing stage. Quenching the materials also increases the stability of the materials in liquid nitrogen so that no phase transformation

occurs during the service. It is important to realize that the methodology of combining deformation and phase transitions represents a very fruitful area for further development materials such as Mp35N which have a composition 35wt%Co, 20wt%Cr, 10wt%Mo and 35wt%Ni possesses attractive elastic properties with a Youngs modulus of 240 GPa. These material is cold rolled to 85% and aged at 482°C to develop very high strength levels and is an example of achieving strength by a combination of extensive cold work and precipitation and represents a potential useful strengthening phase for macroscopic composite

The law of mixtures can predict the properties such as elastic modulus, strength or conductivity of macroscopic composite and this provides a valuable range of accessible properties. For example, the elastic modulus along the wire axis of the macroscopic composite will be given by $E_{Comp} = E_{Cu} V_{ICu} + E_R (1 - V_{ICu})$, where E_R is the modulus of rapidly work hardening phase and E_{Cu} is the elastic modulus of Cu and V_{ICu} is the volume fraction of Cu. As an example if we have a composite with 25% stainless steel as the rapidly hardening phase, the elastic modulus will be: $E_{Comp} = 124 \times 0.60 + 210 \times 0.40 = 158 \text{ GPa}$. This can be compared with a value of $E = 115$ for currently available Cu-Ag wires.

Geometric Arrangement of Phases in Mesoscopic Composite

The geometric arrangement of the copper and steels can be optimized so that the composites can be produced with the strength level in excess of that estimated from a simple law of mixtures. The basic concept is to combine copper with materials which have a very high strain hardening rate and co-deform the materials so that the copper is geometrically constrained by the highly work hardening material.

An essential feature of such a macroscopic composite is the utilization of plastic constraint. A simple analogy is in a soldered joint where a thin layer of Pb constrained between two layers of copper yields at the yield stress of the Cu not of the softer Pb due to the constraints exerted at the Cu-Pb interface. This concept can be applied to the case of macroscopic composites based on Cu plus a rapid work hardening phase.

If configurations such as those illustrated schematically in Fig. 2 are deformed to a strain of order 3 and the scale of the copper rod is reduced to a scale of 1-5 μm in a diameter, then the overall strength level will be governed by the strength level of the rapidly hardening phase and the distance between the copper fibres. Thus, the plastic constraint leverages the strength level attained in the hard phase so that it is this which controls the strength of the composite not simply the volume fraction of the rapidly hardening phase and thus high strength levels can be attained if the reinforcing phase is only 20-25vol% provided the geometries of the composite results in constrained flow.

Finally, the Jellyroll technique, which is currently used in the manufacture of superconductors [14], may also be used for the fabrication of the high strength high conductivity materials.

Fig 2. Schematic diagram showing the configuration of the composite made of Cu and R=rapid work hardening phase

Testing of the Properties of the Conductors

In order to assess the merit of the conductors fabricated by different methods, a systematic testing method has to be established. This should be undertaken in connection of the magnet design.

The principle properties which need to be assessed are stress-strain curves at room temperature and -196°C , the elongation at room temperature and -196°C the reduction in area at room temperature and -196°C and the conductivity. Thermal expansion coefficients in the ranges from room temperature to 200°C and from -196°C to room temperature should also be determined.

The fatigue properties of the drawn material are important both in terms of fatigue life and the fatigue softening. Strain controlled fatigue tests can be performed using true plastic strain amplitudes of 0.001-0.01 up to 10,000 cycles to determine the fatigue behavior and test in tension after fatigue to determine the change in the true stress- true strain curve, elongation and % reduction in area. The stability of the materials should be assessed when they are cycled from -196°C to 100°C , through 100 cycles.

For the materials with the mechanical bonded or thermal bounded interfaces, we can perform compression tests along the drawing axes to determine the point of de-cohesion of the bonds. After samples are compressed to certain reduction in height (e.g., 20, 30, 40 and 50%) and a cross section should be cut and examined to determine the integrity of the bonding between different components.

We need to make a series of combined mechanical and electrical joints and test the mechanical properties and electrical conductivity of the material sections containing joints.

In addition to the examination of the compression test samples, the integrity of the interface should be determined by microscopy technique. The integrity of the bond between different components in macrocomposite as a function of drawing strain should also be examined. This can be done by metallographic sections cut so that we examine the bonds along the drawing axis.

Fabrication of the Magnet

In addition to above tests which can be tested according to a standard, there are special needs for magnet design. For instance, in addition to the joints mentioned in the last section, bending has to be considered for the conductor because of the fabrication of the magnet. The bending radius should be similar to the radius of the magnet coil. The surface coating of the insulation also has to be considered in various experimental conditions.

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