Fiber-Strengthening of a Cu-Fe-Cr Duplex Alloy by Cold Drawing

MASAHARU YAMAGUCHI, YUKICHI UMAKOSHI, TAKUJI KONDO, AND GENJIRO MIMA

Copper wire containing strong chromium ferrite needles has been produced by aligning the chromium ferrite phase of a two-phase Cu-Fe-Cr alloy into needles by cold drawing and subsequently annealing the wire at 480°C. At this temperature the chromium ferrite needles exhibit marked age-hardening. The volume fraction of the chromium ferrite needles in the alloy investigated was nearly 25 pct. Strength up to 50 kg per sq mm with nearly 8 pct elongation has been achieved in 3 mm-wire annealed at 480°C. The annealed wire can be drawn again to give a further increase in strength up to 73 kg per sq mm.

Many experimental investigations have been carried out to meet the demand for higher-strength materials. One type of material under investigation is the fiber-reinforced metal in which a ductile, relatively weak matrix is reinforced with high-strength fibers.

The principles of fiber-reinforcement have been fully discussed in recent extensive reviews by Kelly and Davies,¹ and Sutton and Chorné.² Presently used methods of manufacturing fiber-reinforced metals can be divided into two groups.³ One comprises processes where fibers are first obtained separately and are subsequently combined with the matrix to form the composite. The second group covers direct processes, which have the advantage that the fibers and matrix are produced together in a single operation, either by growing the fibers in the matrix³-four or by converting the strong phase of a two-phase alloy to fibers by working. Recently Anderson and Caton³ have shown that in the Cu-Fe-Al system it is possible to produce alloys containing strong iron-aluminum needles in a ductile copper-aluminum matrix by hot extrusion followed by cold working. Tensile strengths up to 74 ton per sq in. with 7.4 pct elongation and very high impact strengths have been reported. One of the major characteristics of their technique for fabricating the fiber-strengthening alloy is the high hot extrusion temperature necessary to plastically deform an iron-aluminum intermetallic compound and align it in the direction of working. Extrusion of billets, therefore, has to be carried out in the temperature range 900° to 950°C, moreover with a high reduction ratio.

The present paper describes the production of copper wire containing fibers of strong secondary phase in a ductile copper matrix by cold drawing followed by annealing treatment. A useful composite requires the solid solubility of alloying components in copper to be small, the secondary phase to be plastic at cold-drawing temperature, and furthermore, the secondary phase to exhibit age-hardening during annealing of cold drawn wire.

We chose the Cu-Fe-Cr system as one system which seems to be suitable for producing fiber-strengthened copper wires for the following reasons:

a) We can make some assumptions about the ternary system itself from the binaries. It can be expected from the three component binaries of the Cu-Fe-Cr system that at low temperatures the equilibrium tie-line phases in the Cu-Fe-Cr system could be pure copper and ferritic iron-chromium solid solution.

b) The chromium ferrite can be deformed plastically at room temperature, and, in particular, the chromium ferrite containing 15 to 80 at. pct chromium exhibits marked age-hardening when aged around 500°C. This age-hardening phenomenon has been considered to be attributed to a coherent precipitate consisting of a chromium-rich ferrite formed in a miscibility gap in the Fe-Cr system below about 550°C.⁷-¹² In the Fe-Cr system the σ phase is evident in the equiatomic region but the production of σ phase is sluggish⁶ and usually cannot be observed during aging around 500°C.¹⁰-¹²

EXPERIMENTAL PROCEDURE

The Cu-Fe-Cr alloy was prepared by vacuum induction melting 5-kg heat using electrolytic grades of copper, iron, and chromium as charged materials. The chemical composition of the alloy is given in Table I. The ingots were hot forged to 12 mm-diam billets and finally cold drawn to 3 mm-diam wire from which specimens for tensile tests and dynamic modulus measurements were made. The cold-drawn wire specimens were then annealed isothermally in evacuated quartz tubes at 480°C for various periods of time.

A binary Fe-Cr alloy was prepared to obtain independent information about the mechanical behavior of the chromium ferrite reinforcing phase in the composite alloy. The chemical composition of this alloy is also given in Table I.

Room-temperature tensile tests were carried out at low strain rate of 1 x 10⁻⁷ per min and stress-strain curves were obtained. Dynamic modulus of elasticity, based on the resonant frequency induced in the flexural mode of vibration, was also determined for the alloys. Optical and electron microprobe examination were made. Scanning electron fractographs were made of the fracture surfaces of various specimens.
RESULTS AND DISCUSSION

The typical microstructure of alloy A as-cast is shown in Fig. 1. Electron microprobe pictures and scan of alloy A as-cast are shown in Fig. 2. The results of this electron microprobe examination confirm that at low temperatures the equilibrium tie-line phases in the Cu-Fe-Cr system are chromium ferrite and almost pure copper. Therefore, the structure of alloy A as-cast consists of dendrites of chromium ferrite and a matrix of almost pure copper. The volume fraction and chromium content of the tie-line chromium ferrite can be roughly estimated from the chemical analysis shown in Table I by making two assumptions, namely, 1) the equilibrium tie-line phases in the Cu-Fe-Cr system are essentially pure copper and chromium ferrite at low temperatures and 2) the density of the Fe-Cr alloy can be shown approximately as follows:

\[ d = (1-x)d_{Fe} + xd_{Cr} \]

where \( d \), \( d_{Fe} \), and \( d_{Cr} \) are the density of the Fe-Cr alloy, iron and chromium respectively and \( x \) is the atomic fraction of chromium in the Fe-Cr alloy.

The obtained chromium content and volume fraction of the tie-line chromium ferrite are roughly 40 at. pct and 25 vol pct, respectively. The chemical composition of alloy B is therefore close to the tie-line chromium ferrite in alloy A.

Ferritic Fe-Cr alloys show considerable change in properties after aging in the vicinity of 500°C. Fig. 3

Table I. Chemical Composition of Alloys Investigated, wt pct

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Cu</th>
<th>Fe</th>
<th>Cr</th>
<th>C</th>
<th>N</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Bal</td>
<td>12.00</td>
<td>8.86</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>-</td>
<td>Bal</td>
<td>34.89</td>
<td>0.007</td>
<td>0.008</td>
<td>0.01</td>
<td>0.01</td>
<td>0.002</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Fig. 1—Microstructure of alloy A, as-cast. Magnification 200 times.

Fig. 2—Electron microprobe picture and scan of alloy A, as-cast. (a) Using copper Kα X-rays. Magnification 470 times. (b) Using iron Kα X-rays. Magnification 470 times. (c) Using chromium Kα X-rays. Magnification 470 times.