Effect of Heat Treatment on Mechanical and Electrical Properties of Compocast Dispersion-Strengthened Coppers

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An investigation was made on the microstructures and electrical and mechanical properties of dispersion-strengthened (DS) coppers compocast at 25 rev/s with the addition of fine ceramic particles of VB, TaB₂, WC, TaC, SiC, TiN, Al₂O₃, and ZrO₂. Homogeneous distribution of all the particles except Al₂O₃ and ZrO₂ was observed in the compocast DS coppers. In the compocast boride particles-dispersed coppers, with the increased addition of 1 to 5 mass% TaB₂, the electrical conductivity decreased from 101 to 94.2% IACS; the hardness increased from Hv64.9 to Hv73.9; the ultimate tensile strength increased from 137 MPa to 229 MPa; the elongation value decreased from 47.1% to 33.0%; and the reduction of area decreased from 70.5% to 31.4%. The compocast 10 mass% WC-dispersed coppers were thermomechanically treated by hot extrusion, cold drawing and annealing. The hardness of the hot-extruded and cold-drawn DS coppers increased up to Hv138, which was nearly twice the value of Hv79.6 of the as-compocast DS coppers. The hardness of the hot-extruded, cold-drawn and annealed DS coppers decreased gradually with increasing annealing temperature except when a fluctuation existed. In the 1 mass% WC-dispersed coppers compocast with addition of alloying elements of 1 to 2 mass% Al, Ni and Fe, the electrical conductivity decreased exponentially with the increase in atomic percent of the alloying elements.

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I. Introduction

Dispersion-strengthened (DS) copper is a commercial engineering material, which provides excellent high temperature strength to copper without sacrificing its electrical and thermal conductivities. Therefore, the development of DS coppers has been made by various kinds of processes since 1950's. This processing researches include mechanical alloying⁽¹⁾, coprecipitation⁽²⁾⁽³⁾, and melting of nitrides⁽⁴⁾. The properties of DS coppers prepared by the above-described processes except internal oxidation⁽⁵⁾⁻⁽⁷⁾ cannot exceed greatly those of the conventional alloys made by precipitation-hardening. The DS coppers produced by internal oxidation of powders provide superior strength properties at room and elevated temperatures. However, the internal oxidation process can not be applied to castings.

Commercial metal-nonmetallic particulate composites are generally prepared using such powder metallurgy techniques as mechanical mixing, sintering, infiltration and mechanical alloying. If the composites could be made by a casting process, there would be a great reduction in the manufacturing costs. When nonmetallic particles are added to a fully molten metal, however, many of them are rejected and cast out onto the surface of the melt because they cannot be wetted by the metal. Five methods have been offered to overcome this difficulty⁽⁸⁾⁻⁽¹⁸⁾. The first method is to improve the wettability between metal and nonmetal by a metallic coating of the nonmetallic

particles before casting⁽⁸⁾⁻⁽¹¹⁾. The second is to add an element promoting wettability to the melt before the addition of nonmetallic particles⁽¹²⁾⁽¹³⁾. The third is to force spray dispersion of ceramic powders in the molten steel as it is poured into a metallic mold using a compressed inert gas⁽¹⁴⁾. The fourth is to improve the wettability by a metallic coating on the graphite particles and addition of a titanium element, and to prevent the floating of graphite from the melt by squeeze casting⁽¹⁵⁾. The fifth is to add non-wetted ceramic particles into the molten metal and solidify them by rotational stirring⁽¹⁶⁾⁻⁽¹⁸⁾.

Representative of the fifth method is the "compocast process," which involves making a homogeneous metal matrix composite using a stirrer rotating in a solidifying alloy and adding nonmetallic particles, whiskers and fibers into the alloy⁽¹⁶⁾⁻⁽¹⁸⁾. However, the compocast process, proposed by Mehrabian and Flemings⁽¹⁷⁾, has heretofore been primarily applied to an alloy with a freezing range between the beginning and the end of solidification. As the previous compocasting experiment had been carried out under the condition of air or reducing atmosphere, excellent mechanical properties in the compocast alloy could not be obtained because of the entrapment of air or inert gas into the partially solidified alloy⁽¹⁸⁾. In recent years, however, several compocasting experiments became to be carried out in vacuum⁽¹⁹⁾⁽²⁰⁾. Especially, Yamada *et al.* proposed an optimum condition of vacuum compocasting method for sound particle-reinforced Al-6%Si alloy matrix composite materials⁽¹⁹⁾.

The authors have paid special attention to the rotating

force of a motor driving the rotor, and have adopted a high power motor with a capacity of 800 W, which is four times larger than the capacity value of 200 W used in the conventional compocasting process. It was confirmed in the preliminary experiment that the rotor can agitate the semi-solid copper without cease until the later stage of solidification because the rotor can rotate at a speed of above 20 s^{-1} , and that excellent mechanical and electrical properties are obtained in the vacuum compocasting process.

In the present work, boride, carbide, nitride and oxide particles are dispersed between copper crystal grains formed during the solidification of vacuum-melted copper with rotational stirring, and the copper composite materials are thermomechanically treated by hot extrusion, cold drawing and annealing. It is confirmed that the compocast dispersion-strengthened coppers produced in this work can provide excellent mechanical and electrical properties.

II. Experimental Procedure

1. Specimen

The metal-ceramic particulate mixtures composed of 99.99 mass% purity copper blocks and boride, carbide, nitride, and oxide particles with 0.5 to 30 mass% of mixture content: TaB_2 , VB, WC, TaC, TiC, SiC, TiN, Al_2O_3 and ZrO_2 were used for the present work. These ceramic particles except the oxides have high electrical conductivity. The size of ceramic particles was 1 to $2 \mu\text{m}$ except WC that was $0.68 \mu\text{m}$. The specimen weighed about 1 kg.

2. Compocast process

Figure 1 shows a schematic illustration of the experimental apparatus used to disperse ceramic particles uniformly and to destroy dendritic copper crystals⁽²¹⁾ formed during the solidification of vacuum-melted copper by the rotation of a stirring bar at a speed of above 20 s^{-1} (1200 rpm).

A chamber provided in the panel of the door permitting insertion of a crucible into the chamber and inspection of the chamber interior constitutes a vacuum container. The chamber is partitioned into the upper cooling and lower heating rooms by a tungsten shutter operated by an air cylinder. In the lower heating room, there is a tungsten mesh heater where two concentric crucibles are set on a support bar for moving automatically. The upper cooling room holds a water-cooling outer tube and a stirring rotor is suspended downward into this tube. The stirring bar can be rotated at a superhigh speed of up to 84 s^{-1} by a motor positioned at its upper end. The motor is on a rotary shaft with a detecting unit connected with a digital unit for simultaneous display and record of the torque of the stirrer and the rotational speed. The temperature measurement is made by a Pt94%Rh6%–Pt70%Rh30% thermocouple 0.5 mm in diameter connected with a recorder, the tip of which is set at the center of the bottom surface of the crucible as shown in Fig. 1. Two

Fig. 1 Experimental apparatus for vacuum compocasting. 1: tungsten mesh heater, 2: reflector, 3: thermocouple for temperature control, 4: automatic shutter, 5: water-cooled outer tube, 6: hopper, 7: cooling water, 8: video camera, 9: sight port, 10: rotor axis, 11: stirrer, 12: electrode, 13, 14: graphite crucible, 15: thermocouple for temperature measurement, 16: chamber, 17: crucible support.

methods were preliminarily examined for the addition of ceramic particles: one was the conventional compocasting process of adding the carbides from a hopper on the chamber into the copper solidifying with rotational stirring, and the other was a new process of heating both copper blocks and carbide particles in the crucible until the copper melted. It was recognized that the tensile properties of the DS copper ingot produced using the new process are superior to those made by the conventional compocasting process. The reason why the new process surpasses the conventional process is considered as follows. In the case of the conventional process, the continuous addition of ceramic particles into the semi-solid copper provides cluster-like aggregate agglomeration of particles formed by instantaneous connection of the neighboring particles occurred by local zones cooled rapidly around the low temperature particles added. On the other hand, the new process provides almost complete isolation of the neighboring particles because there is no difference in temperature between the solid particles and the molten copper.

The experimental procedure was as follows. First of all, pure copper blocks together with one of the ceramic particles were placed in the crucible. Then the chamber was evacuated with a vacuum pump and the shutter above the heating furnace was closed to increase heating efficiency. When the degree of vacuum in the chamber

reached 1×10^{-3} Pa, the raw materials in the crucible were heated to produce a mixture of molten copper and solid ceramic particles on the melt. After the mixture in the crucible had been thoroughly melted and maintained for 1.8 ks at 100 K above its equilibrium melting point, the shutter above the furnace was opened and the support bar was raised by an elevating mechanism until the crucible was inside the water-cooling outer tube. Then the stirring rotor was gradually inserted into the mixture in the crucible until the leading end of the rotor was 0.01 m from the bottom floor of the crucible. Then, a flow of cold water through the water-cooling outer tube was begun to cool the mixture at a rate of 0.5 K/s, while rotation of the stirrer was continued at a low speed of 18 s^{-1} .

This rotational rate was raised within 10 s to a high speed in two stages of 20 and 25 s^{-1} after the copper had substantially reached the temperature where it would begin solidification. The rotational speed was then increased at an even rate so as to prevent the semi-solid mixture from being scattered by a sharp increase in rotation speed. The rotational stirring was continued for a period of 20 s after the beginning of solidification. The stirring period was confirmed by reading the cooling curve of the recorder and the torque value on the digital display device. Then the support bar was lowered until the leading end of the stirring rotor was 0.2 m from the bottom floor of the crucible in order to prevent from the rotor adhering to the compocast ingot.

The graphite stirring rotor has a thickness of 30 mm at the upper end to 25 mm at the lower end, with the four corners cut as illustrated in Fig. 2. The graphite inner crucible is 78 mm in outer diameter, is tapered from a magnitude of 60 mm in inner diameter at the upper end to 55 mm at the lower end, and 130 mm in depth. The values of torque induced by the viscosity of solidifying mixtures were recorded on a digital printer and the standard value of torque during the rotation of the stirrer was based on an empty crucible under the same conditions as those when the mixture was compocast.

Fig. 2 Transverse sections of mold and stirrer used in the present work.

Microscopic observation was then made of the top, middle and bottom sections cut transversely from the compocast ingots. The mechanical and electrical properties of compocast dispersion-strengthened copper ingots were measured as follows. The Vickers hardness values were measured at four locations from the top to the bottom of the compocast ingots by a microhardness tester with a load of 9.8N-15s. The electrical conductivity values were measured in the transverse section at a distance of 10 mm from the bottom of the ingot. The measured values of electrical conductivity were converted to a unit of %IACS on the basis of 99.9% purity copper as 100%IACS. Tensile test pieces were also machined from the compocast ingots as illustrated in Fig. 3. The tensile test was carried out in air at room temperature using a strain rate of $1.67 \times 10^{-2} \text{ s}^{-1}$.

3. Forming processes and heat treatment

In order to investigate the effect of hot and cold working and heat treatment on the dispersion-strengthened copper ingots, a graphite crucible of 80 mm in inner diameter, 100 mm in outer diameter and 157 mm in depth and a hot extrusion machine with an extrusion ratio of 100 were used in the present work. The experimental procedure was as follows. First of all, a mixture of pure copper blocks and ceramic particles weighing 5 kg was inserted into the above-described crucible. The crucible was set in a chamber of the experimental apparatus as shown in Fig. 1. Subsequently, the copper-ceramic mixture was heated until the copper melted and compocast in vacuum by the same procedure as the present compocasting process described in the Section II.2. The compocast dispersion-strengthened copper ingots were hot-extruded under the condition of the test temperature of 1123 K, the extrusion speed of $1.4 \times 10^{-2} \text{ m/s}$, and the extrusion ratio of 100. The extruded dispersion-strengthened copper rods were cold-drawn at a ratio of 1.31, so that the value of reduction area was 23.4%. The cold-drawn dispersion-strengthened copper rods were annealed for a period of 3.6 ks at a temperature in the range of 573 to 1173 K in nitrogen atmosphere. The values of Vickers hardness were measured on the transverse section of the annealed dispersion-strengthened copper rods. In order to compare the hardness between pure copper and disper-

Fig. 3 Size (mm) and shape of test piece used in the present work.

sion-strengthened copper, pure copper ingots were also hot-extruded, cold-drawn and annealed under the same condition as dispersion-strengthened copper ingots.

III. Experimental Results and Discussion

1. Microstructure

The microstructural observation was made of the transverse sections in the top, middle and bottom part of DS copper ingots in which the ceramic particles were dispersed between copper crystal grains during the solidification with mechanical stirring. As an example, the microstructures in the middle section of DS coppers compocast at a rotation speed of 25 s^{-1} with the addition of nitride and boride particles by 2 mass% are shown in Fig. 4. Figures 4(a) and (b) show the optical microstructures of TiN- and VB-dispersed coppers, respectively. It is observed that TiN and VB particles are uniformly dispersed between the matrix copper crystal grains.

It was also recognized by microscopic observation at the same magnification that TaB_2 particles were dispersed uniformly in the microstructure of DS copper ingot compocast at 25 s^{-1} with addition of 2 mass% TaB_2 . In the microstructures of DS coppers compocast with ad-

dition of 2 mass% carbides, uniform dispersion of WC and TaC particles was observed, but heterogeneous dispersion of SiC particles was partly seen. On the other hand, it was recognized by microscopic observation at low magnifications that oxide particles were scattered with local aggregate agglomeration in the microstructures of DS coppers compocast with addition of 2 mass% oxides of Al_2O_3 and ZrO_2 .

The reason why the distribution of ceramic particles dispersed between copper crystal grains depends on the kind of ceramics is considered as follow. First of all, in the uniformly-dispersed ceramic particles, TaC and TiN particles have NaCl structure⁽²²⁾⁽²³⁾, which is the similar structure as the face-centered cubic structure of copper, WC particle has a cubic structure formed by rapid cooling⁽²⁴⁾, TaB_2 and VB have a crystal structure which is similar to the cubic structure⁽²⁵⁾⁽²⁶⁾. Therefore, TiN, TaC, WC, TaB_2 and VB particles with the cubic crystal structures provide uniform dispersion between copper crystal grains without local aggregate agglomeration because of good compatibility of interface between the ceramic particles and the copper matrix with f.c.c. structure. On the other hand, in the heterogeneously-dispersed ceramic particles, SiC particle has ZnO structure⁽²⁷⁾, which is similar structure as hexagonal close-packed structure, Al_2O_3 particle has corundum structure⁽²⁸⁾, and ZiO_2 particle has fluorite structure⁽²⁹⁾, which is a distorted monoclinic structure. Thus, SiC, Al_2O_3 and ZiO_2 particles would trend to provide heterogeneous dispersion with local aggregate agglomeration between copper crystal grains because of extreme incompatibility of interface between the ceramic particles and the copper matrix with f.c.c. structure.

Now, it is necessary to discuss with the reason why the crystal structure of particle controls the dispersion of it. Its reason is considered as follows. The dispersion of particles proceeds with transportation of the particles through the remaining liquid between copper crystal grains. However, whether the particle will be fixed between the copper crystals or not is determined by the degree of adhesion of the particles onto the copper crystals. The degree of adhesion is controlled by crystal structure of the particle. The adhesive particle, i.e. the particle having similar crystal structure as copper, is fixed smoothly between the copper crystals. On the other hand, the non-adhesive particle, i.e. the particle having dissimilar crystal structure as copper, is rejected from the surface of copper crystals and is transported to another position on the copper crystal surface. Thus the coalescence of the particles increases steeply with repeated rejection of particles from the copper crystal surface. Finally, the cluster-like particles are entrapped forcibly between the copper crystals.

2. Microanalysis

The distribution of elements in the transverse sections in the top, middle and bottom parts of DS coppers compocast with the addition of ceramic particles up to 10 mass% observed by a scanning electron microscope. As an example, the X-ray images of three elements and the

Fig. 4 Microstructures in the middle section of dispersion-strengthened coppers compocast at 25 s^{-1} with addition of 2 mass% ceramic particles of (a) TiN and (b) VB.

Fig. 5 X-ray images of (a) carbon, (b) tantalum and (c) copper element and (d) back-scattered electron image in the middle section of a dispersion-strengthened copper compocast at 25 s^{-1} with addition of 2 mass% TaC.

back-scattered electron image in the middle section of the DS copper compocast at a rotation speed of 25 s^{-1} with tantalum carbides added by 2 mass% TaC are shown in Fig. 5. Figures 5(a), (b) and (c) show the X-ray images of carbon, tantalum and copper, respectively. Figure 5(d) shows the back-scattered electron image. The tantalum carbide particles were seen to have relatively uniform dispersion and local aggregate agglomeration. This ingot was recognized as a homogeneous DS copper ingot, because the same dispersion of TaC particles as seen at its top and bottom sections.

3. Electrical and mechanical properties in compocast DS coppers

The mechanical and electrical properties were measured of the DS coppers compocast at a rotation speed of 25 s^{-1} with addition of ceramic particles up to 10 mass%. As a result, the measured properties in TaB₂-dispersed coppers are shown in Fig. 6. The electrical conductivity of the pure copper blocks used in the present work was 103.3%IACS. The electrical conductivity of the DS coppers decreased from 101 to 94.2%IACS with increased addition from 1 to 5 mass% TaB₂, i.e. from 2.0 to 9.4 vol% TaB₂. On the other hand, with increasing addition from 1 to 5 mass% TaB₂, the Vickers hardness increased from Hv64.9 to Hv73.9, the ultimate tensile strength increased from 137 to 229 MPa, the elongation decreased from 47.1 to 33.0% and the reduction of area decreased

Fig. 6 Electrical and mechanical properties of dispersion-strengthened coppers compocast at 25 s^{-1} with addition of 1 to 5 mass% TaB₂.

from 70.5 to 31.4%.

The mechanical and electrical properties were also evaluated of the DS coppers compocast at a rotation speed of 25 s^{-1} with addition of WC particles⁽³⁰⁾. The electrical conductivity decreased from 98.9 to 89.5%IACS with in-

creased from 1 to 10 mass%WC, i.e., from 0.6 to 6.0 vol%WC. With increasing addition from 1 to 10 mass%WC, the ultimate tensile strength increased from 163 to 249 MPa and the elongation decreased from 50.0 to 28.9% in the tungsten carbide-dispersed coppers.

The measured values of properties in the two DS coppers were compared at the same volume fraction of TaB₂ and WC particles. It was recognized that the TaB₂-dispersed copper provides better electrical conductivity, lesser ultimate tensile strength, and better elongation than the WC-dispersed copper.

In the 2 mass%VB-dispersed coppers, the values of electrical conductivity and Vickers hardness were 101% IACS and *Hv*70.3, respectively. These values were slightly higher than those in the 2 mass%TaB₂-dispersed copper ingot. The electrical conductivity and the Vickers hardness in the 2 mass%TiN-dispersed copper were 99.6%IACS and *Hv*66.8, respectively.

The values of electrical conductivity and the Vickers hardness were 73.5%IACS and *Hv*57.3 in the 0.5 mass% Al₂O₃-dispersed copper. The electrical conductivity and the hardness of the nickel-coated 0.5%ZrO₂ particle-dispersed copper were 75.8%IACS and *Hv*51.8, respectively. Therefore, the steep decrease in electrical conductivity was observed in the DS coppers with very small content of oxides. It was considered that this steep decrease is due to the low electrical conductivity⁽³¹⁾ and the incompatibility of interface between the copper matrix and the oxides as explained previously in Section III.1.

The effect of metallic coating on the electrical and mechanical properties of DS coppers was also investigated. As a result, the Ni-coated and non-coated 0.5 mass%WC-dispersed coppers provided 100.7 and 97.9%IACS of the electric conductivity and *Hv*57.5 and *Hv*62.6 of the hardness, respectively. It was recognized by the microstructural observation that non-coated WC particles formed a cluster-like local agglomeration, and the Ni-coated WC particles tried to isolate the cluster-like agglomeration. It was considered that the increase in electrical conductivity occurred by Nickel-coating was due to the improvement of the compatibility of interface between the particles and copper matrix and the homogenization of the particle distribution. It is also deduced that the decrease in hardness was due to the separation of locally-connected WC particles.

4. Effect of heat treatment on the worked DS coppers

The 10 mass%WC- and the 5 mass%TaB₂-dispersed coppers provided the most superior properties in the compocast DS coppers produced in the present work. There was no difference in property values between them. The 10 mass%WC-dispersed copper of which the volume fraction is smaller than that of the 5 mass%TaB₂-dispersed copper was selected to investigate the effect of heat treatment on the worked DS copper, because the possibility of cracking during hot and cold working of the compocast DS coppers is expected to increase with increasing volume fraction of ceramic particles. As a result, the heat treatment properties of the worked 10 mass%WC-dis-

Fig. 7 Thermomechanical properties of a dispersion-strengthened copper compocast at 25 s⁻¹ with addition of 10 mass%WC.

persed copper and pure copper are shown in Fig. 7.

The Vickers hardness of the hot-extruded and cold-drawn 10 mass%WC-dispersed copper is *Hv*138, which is nearly twice the value of *Hv*79.6 in the as-compocast 10%WC-dispersed copper. This hardness value is higher than the value of *Hv*130 in the powder metallurgy processed commercial oxide-dispersion-strengthened copper with the same electrical conductivity as the value of 90% IACS, i.e. ODS II⁽³²⁾. The hardness value of the annealed WC-dispersed copper is decreased gradually with the increase in annealing temperature except when a fluctuation existed. It becomes to be the value of *Hv*80.4 at an annealing temperature of 1173 K. It is the most important outcome for us to find out that the annealing condition at 673 K for a period of 3.6 ks in the nitrogen atmosphere is an effective heat treatment to alleviate the strain energy stored in the interior of the DS copper by the hot and cold working without decrease in hardness below a value of *Hv*135.

The hardness values of hot-extruded, cold-drawn and annealed pure copper are also represented in Fig. 7. The hardness is decreased gradually with increasing annealing temperature from a value of *Hv*95.6 in the cold-drawn condition to a value of *Hv*52.8 at 1173 K.

5. Effect of alloying element on the electrical conductivity

The effect of alloying elements on the electrical and mechanical properties of DS coppers compocast with the addition of ceramic particles and alloying elements was investigated. In order to suppress the decrease in electrical conductivity by alloying, three metallic elements of Al, Ni and Fe with almost the same electrical conductivity as the copper were selected⁽³³⁾.

As a result, the effect of alloying element on the electrical conductivity in the 1 mass%WC-dispersed copper compocast with the addition of 1 to 2 mass%Al, Ni or Fe is shown in Fig. 8. It is recognized that the electrical

Fig. 8 Effect of alloying elements of 1 to 2 mass% Al, Ni and Fe on the electrical conductivity of dispersion-strengthened copper alloys compocast at 25 s^{-1} with addition of 1 mass% WC.

conductivity is decreased exponentially with increasing atomic percent of the alloying elements.

The effect of alloying element on the hardness of these DS copper alloys was also investigated. The hardness value remained unchanged with only 1 to 2 mass% addition of the alloying elements.

IV. Conclusions

Dispersion-strengthened (DS) coppers were vacuum-melted and compocast at a rotation speed of 25 s^{-1} with boride, carbide, nitride and oxide particles. The electrical and mechanical properties of the DS coppers were evaluated. The results are as follows.

(1) In the microstructures of the dispersion-strengthened coppers compocast with addition of 2 mass% ceramic particles of VB, TaB_2 , TaC, WC and TiN, homogeneous dispersion of ceramic particles was observed at lower magnification. On the other hand, local aggregate agglomeration of oxide particles was seen in the microstructures of dispersion-strengthened copper compocast with 2 mass% Al_2O_3 and ZrO_2 . In the VB-, TaB_2 -, TaC-, WC- and TiN-dispersed coppers, almost uniform dispersion of ceramic particles was observed in the whole part of the DS copper ingot, although some ceramic aggregates were scattered locally at a high magnification.

(2) In the compocast boride particles-dispersed coppers, with increased addition of 1 to 5 mass% TaB_2 , the electrical conductivity decreased from 101 to 94.2% IACS, the hardness increased from $Hv64.9$ to $Hv73.9$, the ultimate tensile strength increased from 137 MPa to 229 MPa, the elongation value decreased from 47.1% to 33.0%, and the reduction of area decreased from 70.5% to 31.4%. In the carbide particles-dispersed coppers, with the increased addition of 1 to 10 mass% WC, the electrical conductivity decreased from 98.9 to 89.5% IACS, the ultimate tensile strength increased from 163 to 249 MPa, and the elongation value decreased from 50.0 to 28.9%.

(3) The compocast 10 mass% WC-dispersed coppers were thermomechanically treated by hot extrusion, cold drawing and annealing. The hardness of the hot-extruded and cold-drawn dispersion-strengthened coppers increased up to $Hv138$, which was nearly twice the value of $Hv79.6$ of the as-compocast DS coppers. The hardness of hot-extruded, cold-drawn and annealed DS coppers decreased gradually down to the value of $Hv80.4$ at an annealing temperature of 1173 K with increasing annealing temperature except when a fluctuation existed. Especially, it was noted that the annealing condition for 3.6 ks at 673 K is the most effective heat treatment that is enable to decrease the strain energy stored in the as-compocast DS copper ingots without the decrease in hardness.

(4) In the 1 mass% WC-dispersed coppers compocast with addition of alloying elements of 1 to 2 mass% Al, Ni and Fe, the electrical conductivity decreased exponentially with the increase in atomic percent of the alloying elements, but the hardness remained almost unchanged with increasing alloying elements.

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