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ARTICLE

Effect of Low-Temperature ECAP with Extended Route and Aging Heat Treatment on Structure and Properties of Cu0.6Cr Alloy

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Abstract: The optical microscope and X-ray diffractometer were used to study the microstructure evolution of Cu0.6Cr alloy prepared by low-temperature equal channel angular pressing (ECAP) with extended route. The scanning electron microscope and energy dispersive spectrometer were used to study the grain size, precipitate distribution, and fracture characteristics of Cu0.6Cr alloy after different aging heat treatments. The tensile strength, hardness, and conductivity of the alloy prepared by low-temperature ECAP and low-temperature ECAP+aging heat treatment were analyzed. Results show that the obviously refined and intersecting fibrous structure is formed in Cu0.6Cr alloy after low-temperature ECAP. The alloy maintains the preferential orientation of (111) crystal plane during deformation. In the aging heat treatment, the larger the alloy deformation, the larger the number and size of the precipitates, and the faster the precipitation rate of the secondary phase. After aging at 450 °C for 2 h, the tensile strength of the 5-pass alloy is 568.1 MPa, the Vickers hardness is 1624.8 MPa, and the conductivity is 82%IACS.

Key words: extended route; low-temperature ECAP; aging heat treatment; microstructure; properties change; Cu0.6Cr alloy

Cu has high conductivity, but its strength is inferior in the engineering field[1,2]. The common strengthening methods, such as alloying[3-5], heat treatment[6], and machining[7-12], can increase the alloy strength, but they will also cause the decrease in conductivity. Lu et al[13] found that the twin structure can increase the alloy strength as well as maintain the high conductivity. Since the Cu lattice has face-centered cubic (fcc) structure, the deformation is mainly based on slip. The metals with hexagonal close-packed lattice structure, such as Mg, have only three slip systems during deformation, resulting in the main deformation mechanism of twining. In addition to the effect of lattice structure on deformation mechanism, the stacking fault energy of the metal also affects the deformation mechanism. The materials with low stacking fault energy are prone to twining. Currently, the common methods for stacking fault energy reduction are the addition of alloying elements[3-5] and low temperature deformation[14]. The CuCr alloy has superior performance, which is mainly used in contact materials, lead frame materials, and electronic leads.

As shown in Fig. 1, the equal channel angular pressing (ECAP)[15] is a common method of severe plastic deformation to process compact large-scale submicron or nanoscale materials, because of its high efficiency and process controllability. Currently, the influence of the four existing processing routes (route A, route Ba, route Bc, and route C) on the microstructure has been widely studied. Guo et al[16] found that different routes have different effects on the material organization and strengthening effects. Since the material is always deformed in the same direction in route A, the high-density shear zone with a fixed orientation is formed. Route Ba involves the deformation with alternate clockwise rotation of 90° and counterclockwise rotation in each pass, and the deformation amount is less than that of the route A and the route Bc. Route Bc involves the clockwise rotation of 90° between two passes to form a unit cell structure, and the crystal grains are divided into sub-crystals by a large number

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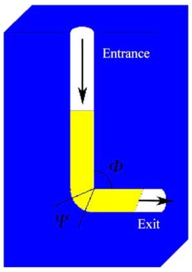

Fig.1 Schematic diagram of ECAP

of dislocations. Route C involves the clockwise rotation of 180° between adjacent passes, so the deformation amount is offset to a certain extent, resulting in small edge deformation and uneven tissue distribution. Based on the advantages of above routes, the extended route (clockwise rotation of 45° between adjacent passes) was designed in this research.

Since the strengthening mechanisms are different based on different strengthening methods, the multiple strengthening methods can be used in the research, such as solid solution+ secondary phase, solid solution+deformation, and deformation+secondary phase[17,18]. Mishnev et al[11] studied the effect of solid solution on Cu0.89Cr0.06Zr alloy after 8 passes of ECAP (673 K) deformation, and found that its strength reaches 535 MPa and the conductivity is 73%IACS. Sun et al[12] revealed that after the Cu1Cr0.1Zr alloy is solid-solution-treated in the liquid nitrogen environment, the strength reaches 700 MPa and the conductivity is 78.5%IACS. Purcek et al[19] prepared CuCrZr alloy by 8 passes of ECAP and found that the alloy strength is increased to 688 MPa after aging heat treatment and its conductivity is basically the same. Guo et al[20] studied the formation of stable {111}<112> texture after deformation of single crystal Cu by ECAP of route Bc. It is found that the strength of single crystal Cu is improved while the electrical conductivity basically remains the same.

The supersaturated alloy elements were used in this research for solid solution and dispersion strengthening, and then the low-temperature ECAP with extended route coupled with aging heat treatment was conducted on Cu0.6Cr alloy. The deformation characteristics of Cu0.6Cr alloy after low-temperature ECAP with extended route were analyzed, and the aging conditions for optimal comprehensive properties of Cu0.6Cr alloy were discussed. The optical microscope (OM), scanning electron microscope (SEM), X-ray diffraction (XRD), and energy dispersive spectrometer (EDS) were used to explore the macro-orientation and microstructure deformation characteristics of the alloy during deformation and aging heat treatment. The mechanical properties of alloys after multiple strengthening methods were also investigated.

1 Experiment

The internal angle of ECAP mold in this research was α= 90°, and the external angle was β=37°. After the Cu0.6Cr alloy was put into the mold channel, it was squeezed and deformed by the YT071-100A hydraulic press. The diameter of Cu0.6Cr alloy specimen was 12 mm. The experiment procedure was as follows: solution treatment at 920 °C for 1 h →immersion in liquid nitrogen for 5~7 min before ECAP and cooling of mold by liquid nitrogen→ECAP with extended route (clockwise rotation of 45° between adjacent passes)→ aging heat treatment. After the multi-treatments, the specimens were cut along the extrusion direction, as shown in Fig.2a. The specimen of 10 mm×10 mm×5 mm was polished by 1000#~7000# sandpaper and then mechanically polished. The electrolytic polishing solution consisted of H_2O, H_3PO_4, and C_2H_5OH with the volume ratio of 2: 1: 1, the polishing voltage was 4 V, and the polishing duration was 5~6 min. The LSM800 OM was used to observe the metallographic structure. The D8ADVANCE XRD was used to detect the diffraction intensity of crystal planes. The WDW-300D electronic universal testing machine was used to detect the mechanical properties. The Quanta FEG-450 SEM was used to observe the microstructure. The INCAEDS EDS was used to analyze the element distribution and precipitated phase composition in the alloy. The Sigma2008B/C metal eddy current meter was used to measure the alloy conductivity.

2 Results and Discussion

2.1 Microstructure after different passes of ECAP

Fig. 3 show OM microstructures of Cu0.6Cr alloys after low-temperature ECAP with extended route. With increasing the extrusion passes, the grains are significantly refined, and a uniform fibrous structure is gradually formed in the alloys.

The Cu0.6Cr alloy can produce obvious deformation bands between different slip systems after deformation due to its fcc structure. After the alloy is deformed for 1 pass of ECAP, the deformation zone is not clear, as shown in Fig.3a. Some grains are broken, as shown in Fig. 3b, presenting the willow-leaf shape along the extrusion direction. Due to the low strain of 1 pass of ECAP, the grains consist of half coarse grains and half fine grains. The distribution of deformation twins with width of 1~3 μm can be clearly observed in Fig. 3c. Because the deformation twins are not completely broken, they are inserted into the large-sized grains. With the deformation proceeding, the deformation twins become the starting points of broken grains. After 2 passes of ECAP, an intersecting

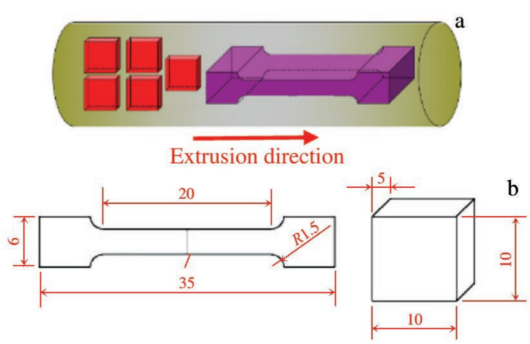

Fig.2 Schematic diagrams of specimens after ECAP (a) and specimen dimension (b)

Fig.3 OM microstructures of Cu0.6Cr alloys after 1 pass (a~c), 2 passes (d~f), 4 passes (g~i), and 5 passes (j~l) of low-temperature ECAP with extended route

deformation zone with the intersection angle of 45° can be clearly observed in Fig.3d. The grains still present the willow-leaf shape and the number of coarse grains is significantly reduced, compared with that after 1 pass of ECAP. The grains after 2 passes of ECAP deformation are inlaid into each other, as shown in Fig.3f. Most grains are deformed into the willow-leaf shape with the width of 2~10 μm. Due to the dense deformation inside the alloy, it is difficult to slip and form a lot of deformation twins. After the alloy suffers 4 passes of ECAP deformation, the contrast between the two deformation zones is clearer due to the increased strain (Fig. 3g). The crystal grains are refined, and a certain number of irregular small deformation bands are also generated inside the alloy (Fig. 3h). Because of the finer grains, it is difficult to form twin boundaries. Thus, no obvious deformation twins can be observed in Fig.3i. The grains continue to refine after 5 passes of ECAP deformation, so a large number of irregular but inapparent deformation bands can be observed (Fig.3j).

According to the results, it is found that during the low-temperature ECAP of Cu0.6Cr alloy, the original grains of the alloy firstly rotate to form a large number of deformation twins under the low strain. With increasing the strain, the deformation twins become the starting point for the breakup of coarse grains. After the alloy is deformed by ECAP with extended route, the interaction between the grains during extrusion deformation causes the rotation of grains in different phases, since the rotation angle between each pass is smaller than that of the traditional route Bc. Therefore, a large number of deformation bands in the alloy intersect with each other in ECAP, and the shear deformation along different directions completely refines the grains.

It is also found that Cr is distributed on the Cu matrix

(Fig. 3l). Firstly, a large amount of deformation heat is generated during ECAP to increase the storage energy in the alloy, which promotes the segregation and precipitation of solute atoms. Secondly, the number of defects, such as vacancies and dislocations, in the alloy during ECAP increases, which provides sufficient locations for the precipitation of the secondary phase under the required thermodynamic conditions. According to the high deformation storage energy and the numerous defects in alloys after different passes, the number of precipitates in alloys is arranged from large to small as follows: 5 passes>4 passes>2 passes>1 pass.

2.2 Property variation after different passes of ECAP

The tensile strength, hardness, and conductivity of Cu0.6Cr alloys after different passes of low-temperature ECAP with extended route are shown in Fig. 4. With increasing the number of deformation passes, the tensile strength and hardness of the alloys are increased. The tensile strength of Cu0.6Cr alloy before and after 1 pass of ECAP is increased from 280.91 MPa to 434.80 MPa, which increases by 54.8%. The Vickers hardness of Cu0.6Cr alloy before and after 1 pass of ECAP is increased from 684.24 MPa to 1001.56 MPa, which increases by 46.4%. The tensile strength of Cu0.6Cr alloy after 5 passes of ECAP is 530.00 MPa and the hardness is 1491.6 MPa, which increases by 88.7% and 117.9%, respectively, compared with those before ECAP. The alloy conductivity is decreased obviously when the alloy suffers the first pass of ECAP, and then it is decreased slightly with increasing the number of ECAP passes. The conductivity is 65.6%IACS and 44.5%IACS for the Cu0.6Cr alloy before and after 1 pass of ECAP, respectively, inferring an obvious reduction. The conductivity of Cu0.6Cr alloy after 5 passes of ECAP deformation is only 41.8%IACS, which is 36.3% lower than that of Cu0.6Cr alloy before ECAP.

The property change is due to the small strain in the early deformation stage in the Cu0.6Cr alloy. The original grains are crushed, elongated, and rotated after extrusion in the early deformation stage. Therefore, the dislocation density increases rapidly, resulting in the rapid increase in tensile strength and hardness of the alloys. With further increasing the deformation

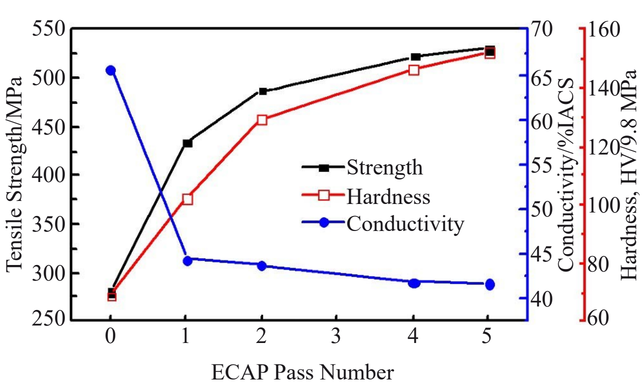

Fig.4 Properties of Cu0.6Cr alloys after different passes of low-temperature ECAP with extended route

amount, the dislocation movement is hindered by the secondary phase. The intersecting and entanglement of dislocations cause the obvious dislocation movement, thereby continuously increasing the tensile strength and hardness of alloys. As shown in Fig.4, the tensile strength and hardness of alloys are increased slowly in the later deformation stage, because the dislocation multiplication and dislocation annihilation inside the alloy reach a dynamic equilibrium. The grains are obviously refined, and some strengthening phases are precipitated. However, the strengthening mechanism in the whole process is mainly the deformation strengthening and fine grain strengthening. The continuous decrease in conductivity is due to the distortion of the crystal lattice and the increasing crystal defects. The crystal grains also produce a large number of grain boundaries due to crushing, thus increasing the scattering probability of moving electrons and then leading to the reduced conductivity.

In ECAP, the free path of electrons is shortened due to the large number of grain boundaries and point defects caused by the crushing of crystal grains, resulting in the significant reduction in the velocity of electron movement and therefore the decrease in electrical conductivity. At the later deformation stage, the conductivity is barely decreased, because the grains are obviously refined, i. e., the dislocation density reaches the dynamic equilibrium.

2.3 Microstructure after aging heat treatment

Fig. 5 show SEM microstructures of Cu0.6Cr alloys after low-temperature ECAP and aging at 450 °C for 1 h. The number and the size of Cr phase are increased with increasing the number of ECAP passes.

After 1 pass of ECAP deformation and aging treatment at 450 °C for 1 h, some grains are distributed in long strips along the extrusion direction and the degree of grain refinement is low. Obvious granular precipitates are pinned on the grain boundaries, as shown in Fig. 5b. Besides, the small granular precipitates with the width of about 2 μm are distributed on the surface of crystal grains. The grain boundaries and deformation twins can be clearly observed in Fig. 5c. The deformation twins are obvious and less precipitated phases can be observed in Fig. 5d. The grain morphologies are different in the alloy after 4 passes of ECAP and aging treatment: the annealing twins appear during the grain growth, and they are complete annealing twins penetrating the grain. The granular precipitates are distributed on crystal planes and grain boundaries. In addition, the rod-like precipitates with the length of about 8 μm are also precipitated. It can be clearly seen that many grain boundaries are surrounded by aggregated granular or rod-like precipitates (Fig. 5h). The aging treatment process can be divided into three stages: recovery, recrystallization, and grain growth. The recovery stage reduces the dislocation energy inside the alloy and basically eliminates the elastic strain. The unreleased storage energy of the deformed alloy after recovery becomes the driving force for recrystallization. When the temperature reaches the recrystallization temperature, new crystal grains without distortion are regenerated. After the recrystallization, the grain

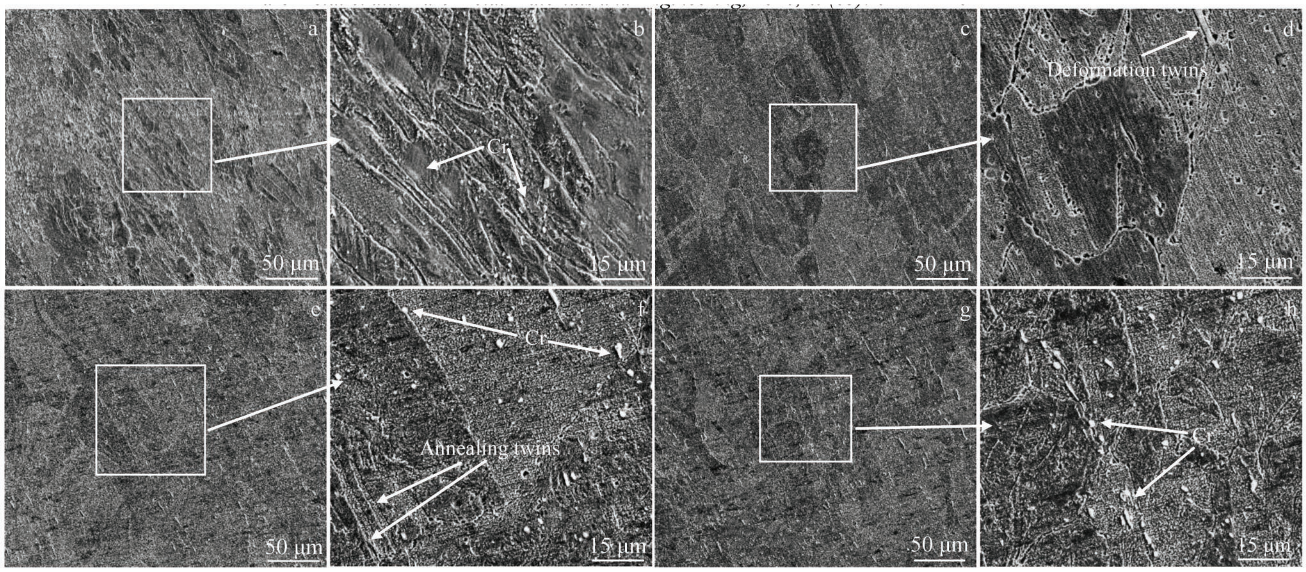

Fig.5 SEM microstructures of Cu0.6Cr alloys after 1 pass (a, b), 2 passes (c, d), 4 passes (e, f), and 5 passes (g, h) of low-temperature ECAP with extended route and aging treatment at 450 °C for 1 h

growth spontaneously starts. According to Fig. 5c and 5d, the number and the size of the precipitated phases in Cu0.6Cr alloys after 4 and 5 passes of ECAP are both increased. The size of the precipitated phase is mainly 5~10 μm, and the number of rod-shaped precipitated phases is large. This is because the Cu0.6Cr alloys after 4 and 5 passes of ECAP have large deformation amount and high storage capacity. Because the alloys have fine grains and a large number of grain boundaries, there are more places for the secondary phase to precipitate. Therefore, the recovery stage of the Cu0.6Cr alloy is fast during the aging process. The recovery of the Cu0.6Cr alloy after 1 pass of ECAP is incompleted, and the recrystallization may occur in Cu0.6Cr alloy after 5 passes of ECAP.

2.4 XRD analysis

XRD patterns of Cu0.6Cr alloys after low-temperature ECAP with extended route are shown in Fig. 6a. Since Cu has fcc structure, the main sliding surface is {111}. It can be seen that the strongest orientation of Cu0.6Cr alloy during ECAP deformation is the (111) crystal plane. The (200) and (220) diffraction peaks are also obvious. This phenomenon is caused by the dislocations in ECAP. It can be seen that after the solid solution strengthening, the strengthening phase in the Cu0.6Cr alloy is mainly composed of Cr phase. With increasing the number of ECAP passes, the intensity of diffraction peaks is firstly increased, and then decreased. The highest intensity is achieved for the alloy after 2 passes of ECAP deformation. The crystal grains begin to break after 1 pass of ECAP. A large number of crystal grains are broken and rotated after 2 passes of ECAP deformation, and the strongest orientation is the (111) plane which is easy to slip, resulting in the substantial increase in the intensity of (111) diffraction peak. As the dislocation density is increased after 4 passes of ECAP deformation, the blockage and entanglement of the dislocations

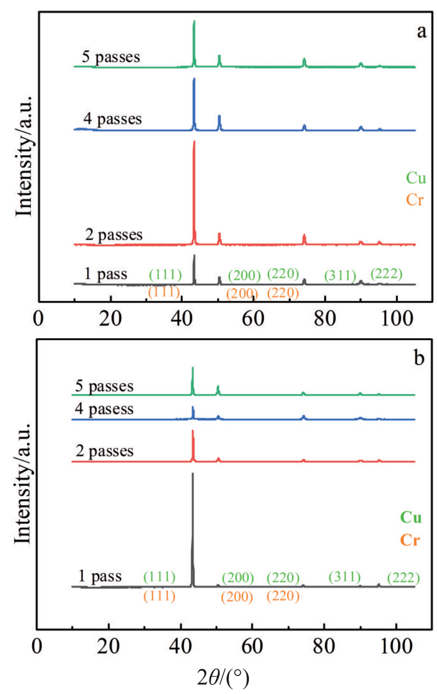

Fig.6 XRD patterns of Cu0.6Cr alloys after different passes of low-temperature ECAP with extended route before (a) and after (b) aging treatment at 450 °C for 1 h

hinder the dislocation movement. The intensity of the (111) diffraction peak obviously decreases, and the second-strongest diffraction peak changes from (220) to (200). The cross-slip occurs. The intensity of the primary and secondary diffraction peaks of the alloy decreases to a certain extent after 5 passes of ECAP deformation, because the grain refinement of the alloy is relatively complete, therefore hindering the slip.

Fig. 6b shows XRD patterns of Cu0.6Cr alloys after low-temperature ECAP with extended route and aging treatment at 450 °C for 1 h. It can be seen that main diffraction peak is the (111) crystal plane, and the secondary diffraction peak is the (200) crystal plane, due to the formation of dislocations in ECAP and precipitated phases in aging heat treatment. The fusion of sub-grains in the aging heat treatment affects the indices of crystal face, thereby decreasing the diffraction peak intensity of other crystal planes. The Cu0.6Cr alloy maintains a stable preferential orientation after ECAP and the reduction in dislocation density after aging treatment is the main reason for high conductivity[21]. Therefore, the directional distribution of Cu0.6Cr alloy structure in ECAP and aging heat treatment improves the uniformity and consistency of the structure. In conclusion, the preferential orientation and the decreased dislocation density in aging heat treatment jointly improve the alloy properties.

2.5 EDS analysis

Fig. 7 shows EDS results of Cu0.6Cr alloys after low-temperature ECAP with extended route and aging treatment at 450 °C for 1 h. The granular and rod-shaped precipitates are both composed of Cr. Different deformation passes have different grain refinement effects. After 1 pass of ECAP deformation, the Cu0.6Cr alloy has a small grain deformation and a small number of grain boundaries, indicating that there are few locations for the precipitation of the secondary phase. After aging treatment at 450 °C for 1 h, the granular Cr with a side length of 2~3 μm is precipitated between the two grains. The distribution of Cr precipitates after 2 passes of ECAP deformation and aging is basically the same as that after 1 pass of ECAP deformation. The granular precipitates are increased and mostly distributed in the grain boundaries after 2 passes of ECAP deformation and aging. Due to the large deformation in the Cu0.6Cr alloy after 4 passes of ECAP deformation and aging, the number of internal defects is increased. The precipitate can easily grow up with fast precipitation rate. Therefore, the rod-shaped precipitates with the length of about 8 μm appear between the willow-leaf-like crystal grains. The Cu0.6Cr alloy after 5 passes of ECAP

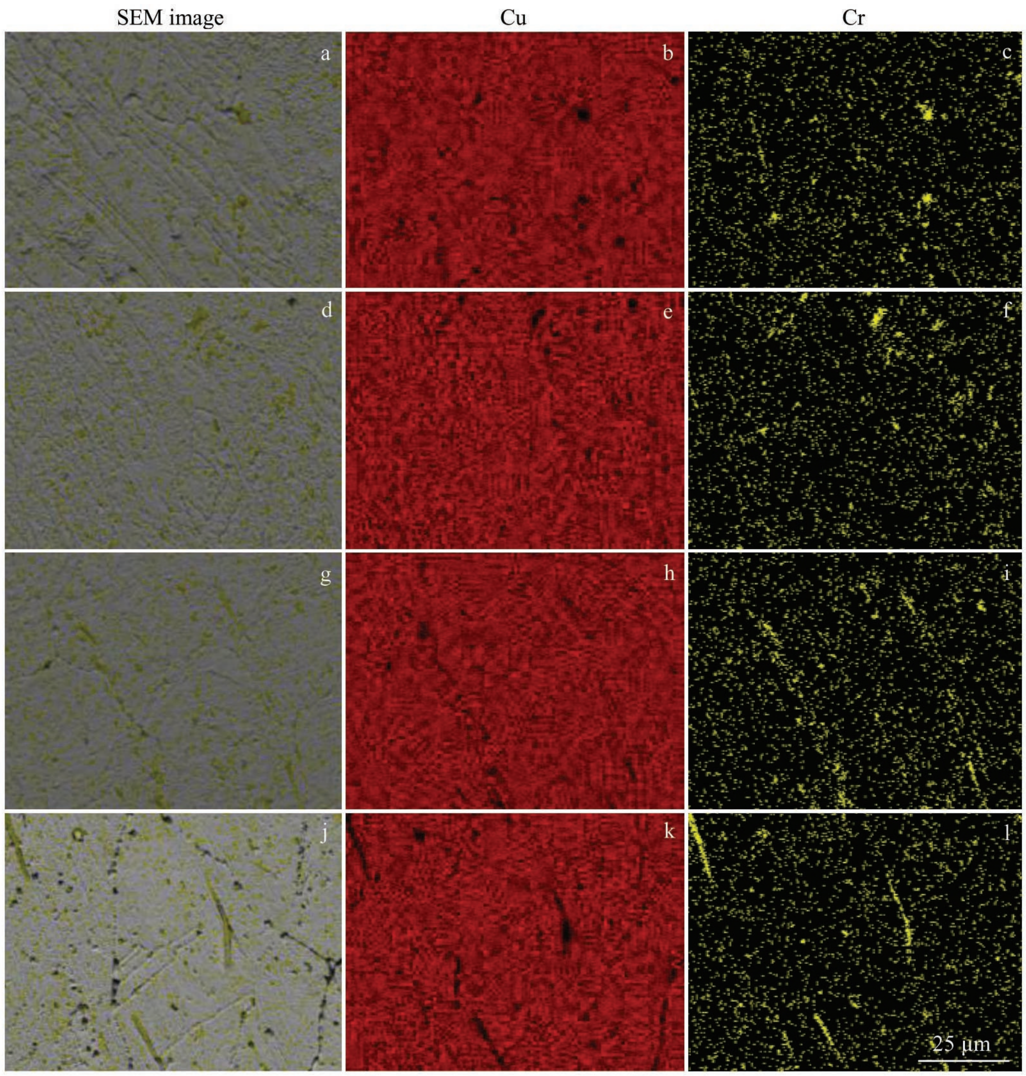

Fig.7 EDS results of Cu0.6Cr alloys after 1 pass (a~c), 2 passes (d~f), 4 passes (g~i), and 5 passes (j~l) of low-temperature ECAP with extended route and aging treatment at 450 °C for 1 h

deformation and aging provides more locations for the precipitates due to the grain fragmentation, and the precipitation rate of the secondary phase is fast due to the high storage energy after deformation. The number and the size of precipitated phases in the alloy after 5 passes of ECAP deformation and aging are significantly increased.

2.6 Property variation after different aging heat treatments

The optimal aging temperature was also investigated for the Cu0.6Cr alloy after 1 pass of ECAP deformation with extended route and aging treatment at 400, 425, 450, 475, and 500 °C for 1 h. The tensile strength and hardness of the Cu0.6Cr alloy aged at 450 °C for 1 h are maximum of 506 and 1614.1 MPa, respectively, as shown in Table 1. Due to the aging treatment at high temperatures, the dislocation density of the alloy after ECAP is decreased. The alloy conductivity is closely related to the content of solid solution elements and the number of defects in the matrix. The higher the content of solid solution element, the more the lattice distortion in the matrix, the more obvious the hindrance for the movement of free electrons, and thereby the lower the alloy conductivity. With increasing the aging temperature, the desolubilization rate of solid solution alloying elements is increased, resulting in better conductivity.

Usually, the tensile strength is positively correlated with the hardness and negatively correlated with the conductivity[22]. The optimal aging temperature was considered under the weighting coefficient of 0.5, as follows:

$$K=0.5H+0.5C \tag{1}$$

where K is coefficient for comprehensive property evaluation, H is the Vickers hardness, and C is the conductivity. The larger the K value, the better the comprehensive property. The corresponding properties of Cu0.6Cr alloys after ECAP with extended route and aging treatment at different temperatures are shown in Table 1.

It can be seen from Table 1 that 450 °C is the optimal aging temperature. Therefore, the effects of the number of passes of ECAP deformation with extended route and the aging duration at 450 °C on the properties of Cu0.6Cr alloy were further investigated.

Fig.8 shows the properties of Cu0.6Cr alloys after different passes of ECAP deformation and aging treatment at 450 °C for different durations, and the fracture characteristic of the alloys is also analyzed, as shown in Fig.9. It can be seen that

Table 1 Properties of Cu0.6Cr alloys after 1 pass of ECAP deformation with extended route and aging treatment at different temperatures for 1 h

Aging temperature/°C	400	425	450	475	500
Tensile strength/MPa	478	487	506	485	450
Hardness, HV/MPa	1430.8	1554.3	1614.1	1486.7	1461.2
Conductivity/%IACS	79.2	80.9	81.6	82.4	83.5
K	112.60	119.75	123.15	117.05	116.30

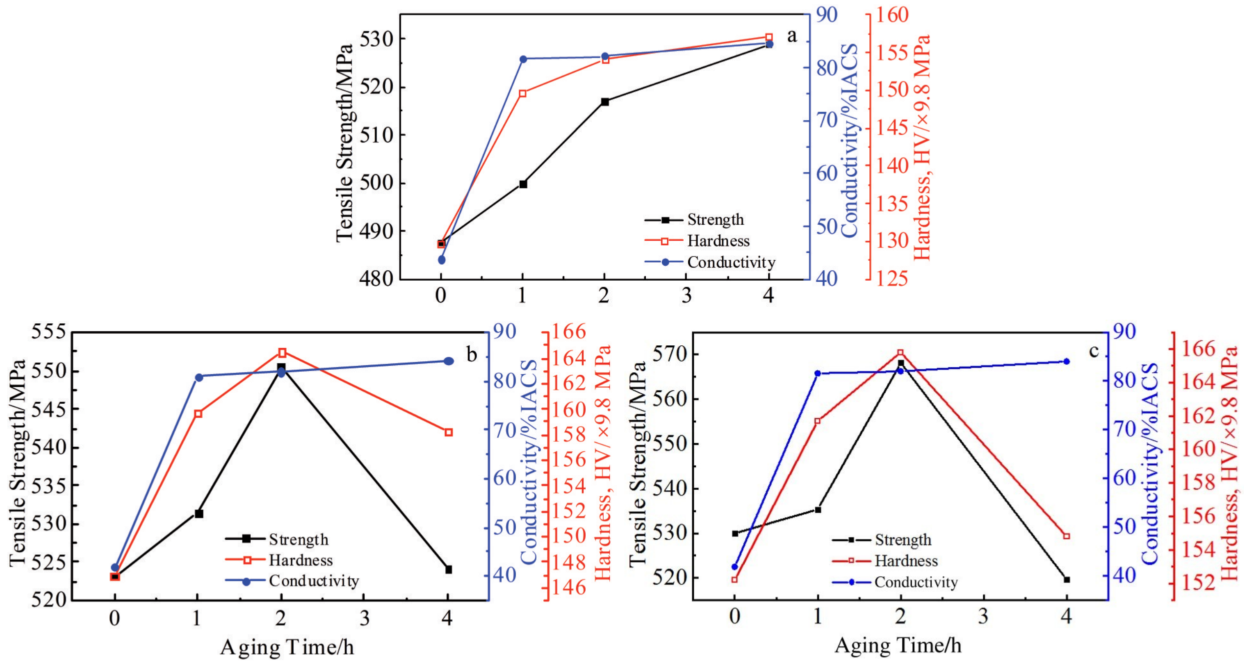

Fig.8 Properties of Cu0.6Cr alloys after 2 passes (a), 4 passes (b), and 5 passes (c) of ECAP deformation with extended route and aging treatment at 450 °C for different durations

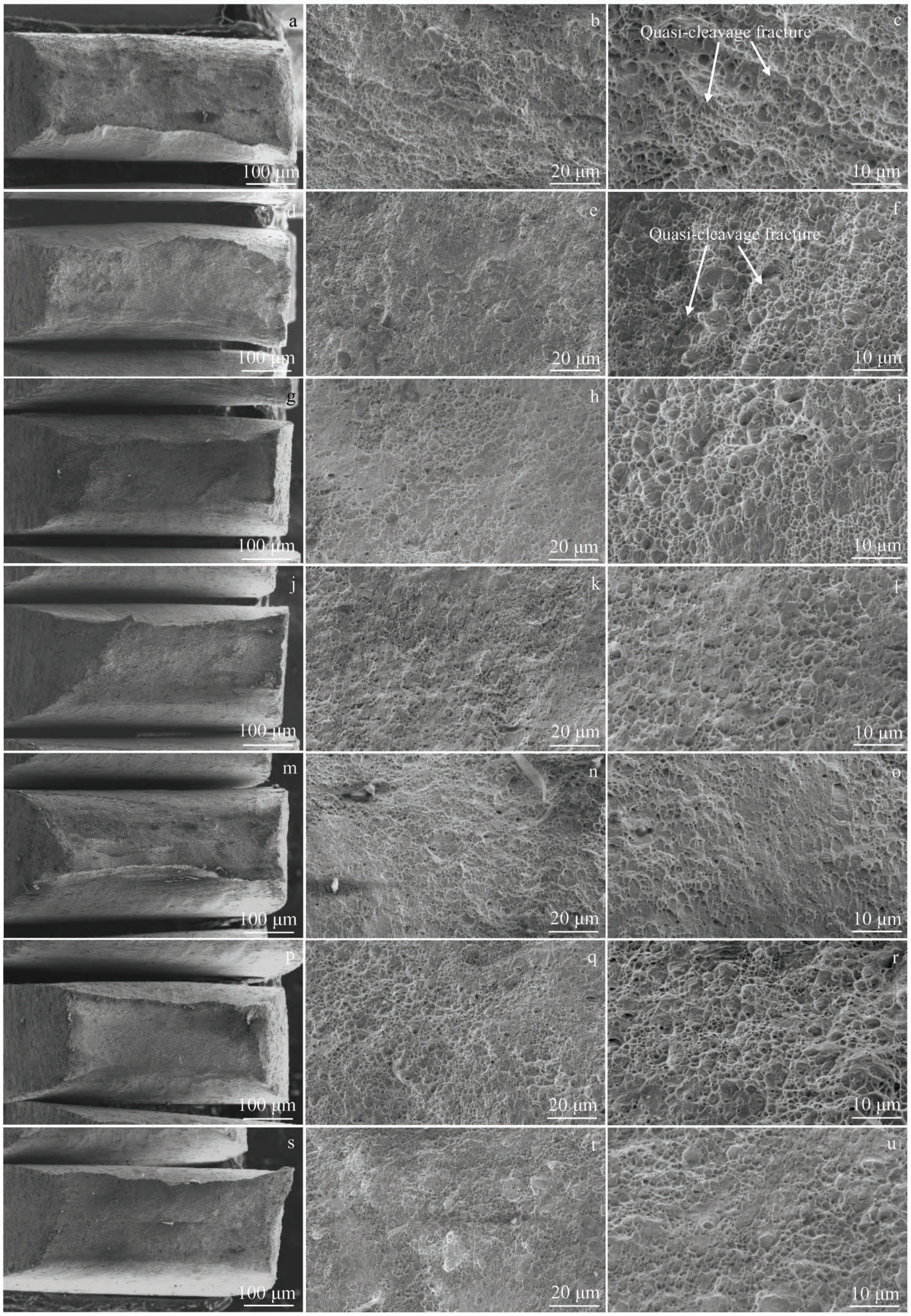

Fig.9 Fracture morphologies of Cu0.6Cr alloys after different low-temperature ECAP with extended route and aging treatments: (a~c) 1 pass of ECAP+450° C/1 h; (d~f) 2 passes of ECAP+450° C/1 h; (g~i) 4 passes of ECAP+450° C/1 h; (j~l) 5 passes of ECAP+450° C/1 h; (m~o) 2 passes of ECAP+450° C/2 h; (p~r) 4 passes of ECAP+450° C/2 h; (s~u) 5 passes of ECAP+450° C/2 h

when the aging duration is 1~2 h, the alloys deformed after different passes achieve higher tensile strength and hardness. The tensile strength of the alloys after 2, 4, and 5 passes of ECAP deformation with extended route and aging at 450 °C for 2 h is 517.0, 550.6, and 568.1 MPa, and the hardness is 1510.2, 1612.1, and 1624.8 MPa, respectively. After aging at 450 °C for 4 h, the tensile strength of the alloys after 4 and 5 passes of ECAP deformation with extended route is 524.1 and

519.6 MPa, and the hardness is 1551.3 and 1517.0 MPa, respectively. It is found that for the alloys after 1 and 2 passes of ECAP deformation, the alloy properties are continuously increased with prolonging the duration of aging treatment at 450 °C from 0 h to 4 h, whereas for the alloys after 4 and 5 passes of ECAP deformation, the alloy properties are increased firstly with aging duration of 0~2 h and then decreased when the aging duration exceeds 2 h. This phenomenon indicates that the Cu0.6Cr alloys after different passes of ECAP have different internal storage energies, significantly affecting the mechanical properties. During the initial aging heat treatment, the content of solid-dissolved alloying elements in the grains is higher than that at grain boundaries, leading to the precipitation of the alloying elements at grain boundaries. However, the number of grain boundaries and defects in alloys after 4 and 5 passes of ECAP deformation, namely high-pass alloy, is much greater than that in the alloys after 1 and 2 passes of ECAP deformation, namely low-pass alloy. Therefore, the high-pass alloys have more secondary phase precipitation locations during the aging process. The contents of alloying elements in grains and at grain boundaries gradually tend to balance with prolonging the aging duration. Before the end of the recovery stage, the tensile strength and hardness increase. However, the storage energy of the high-pass alloys is greater than that of low-pass alloys, indicating that the recovery rate of high-pass alloys is faster than that of low-pass alloys. The recovery stage ends after aging for 2 h, resulting in the obvious reduction in tensile strength and hardness at the beginning of recrystallization stage (Fig.8b and 8c).

The alloy conductivity is increased throughout the aging process. After aging at 450 °C for 4 h, the conductivity of the alloy after 2 passes of ECAP deformation with extended route reaches the maximum of 84.6%IACS, which is increased by 93.2%, compared with that before aging treatment. Meanwhile, the strength and hardness also reach the maximum. The strength and hardness of the high-pass alloys reach the maximum after aging at 450 °C for 2 h, and the conductivity is 82.0%IACS. The conductivity is increased rapidly with prolonging the duration of aging treatment from 0 h to 1 h, and then it is increased slightly with further prolonging the aging duration. Because the decomposition rate of supersaturated solid solution in the early aging stage is fast, the desolubilization rate of solid solution elements is also fast, resulting in the rapid increase in conductivity. The content of solid solution elements in the alloy continues to decrease during subsequent aging treatment, and the number of solid solution atoms is significantly reduced. The precipitation rate of the secondary phase is obviously slower, and the conductivity rise is slight.

2.7 Fracture analysis

The fracture morphologies of Cu0.6Cr alloys after different passes of low-temperature ECAP with extended route and aging treatment at 450 °C for different durations are shown in Fig.9. The fracture necking of the low-pass alloys is obvious in the early aging stage, and numerous dimples can be observed. The obviously torn prismatic pattern, namely quasi-cleavage fracture, can be found in the low-pass alloys, indicating the better plasticity. After aging for 1 h, the dimples of the high-pass alloy are large and shallow, and the necking fracture is reduced. The alloy elongation is low. After aging at 450 °C for 2 h, the secondary phases in the alloy are obviously precipitated. The low-pass alloys have a lower recovery rate than the high-pass alloys do. The fracture morphologies of the high-pass alloys after aging for 2 h are basically the same, presenting numerous deep dimples. Because the high-pass Cu0.6Cr alloys have a high degree of grain refinement after deformation, more defects can be used for the precipitation of the secondary phases. The precipitates are increased after aging treatment, and the internal defects or the secondary phases of the grains are the crack source. Therefore, the fracture is related to the microporous aggregation, and the plastic deformation of the Cu0.6Cr alloy gradually recovers.

3 Conclusions

1) After 1 pass of low-temperature equal channel angular pressing (ECAP) with extended route, a large number of deformation twins appear in Cu0.6Cr alloy. The Cu0.6Cr alloy after 2 passes of ECAP deformation has deformation bands with the intersection angle of 45°. The staggered distribution between the deformation bands results in the complete grain refinement. The deformation strengthening and fine grain strengthening jointly improve the Cu0.6Cr alloy property. The tensile strength and hardness of Cu0.6Cr alloy after 5 passes of ECAP deformation are 530.00 and 1491.6 MPa, respectively. The conductivity is decreased after ECAP process.

2) The number and the size of Cr precipitated in high-pass alloys are obviously larger than those in the low-pass alloys. The Cr phases in the low-pass alloys are granular with 1~3 μm in size, whereas those in the high-pass alloys are rod-shaped with the length of 5~10 μm. Cr phase is dispersed in the grain boundaries and inside the grains, therefore effectively strengthening the alloys.

3) The tensile strength, hardness, and conductivity of the Cu0.6Cr alloy after 5 passes of ECAP deformation with extended route and aging treatment at 450 °C for 2 h are 568.1 MPa, 1624.8 MPa, and 82.0%IACS, respectively. The alloy properties after aging heat treatment are better than those before aging heat treatment.

4) With increasing the number of extrusion passes, the tensile strength and hardness of the alloy are increased significantly, but the electrical conductivity is decreased. Proper aging heat treatment after ECAP can obtain optimal comprehensive properties of the Cu0.6Cr alloys.

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扩展路径低温ECAP及时效热处理对Cu0.6Cr合金的组织和性能影响

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摘 要：采用光学显微镜和X射线衍射仪对Cu0.6Cr合金经低温扩展路径等通道转角挤压（ECAP）后的组织演变规律进行了研究。采用扫描电子显微镜和能谱仪研究了Cu0.6Cr合金经不同时效热处理条件后的晶粒大小、析出相分布规律和断裂特征。并且分别测试了合金经低温ECAP和低温ECAP+时效热处理后的抗拉伸强度、硬度和导电率。结果表明，Cu0.6Cr合金经低温ECAP变形后形成明显细化且相互交割的纤维组织，并且合金在变形中始终保持（111）面的择优取向。时效热处理的合金变形量越大，析出相的数目和尺寸就越大，第二相析出速率也越快。5道次合金经450 ℃时效2 h后的抗拉伸强度为568.1 MPa，维氏硬度为1624.8 MPa，导电率为82%IACS。
关键词：扩展路径；低温ECAP；时效热处理；微观组织；性能变化；Cu0.6Cr合金

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