10 Effect of pulse current on micro-hardness and wear performance of cold-rolled T2 copper sheet

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Abstract

The effect of pulse current assisted rolling on the micro-hardness and wear properties of T2 copper sheet was studied. The micro-hardness of copper sheet with pulse current assisted rolling was measured, and the hardness values of the copper sheet at different deformation rates were obtained. The wear performance of rolled copper sheet was tested by friction and wear tester. The results show that compared with traditional cold rolling, with the increase of deformation rate, the micro-hardness of copper sheet with pulse current assisted rolling increased after an initial decrease. The micro-hardness reaches the minimum value((82.25 ± 2.5)HV0.1) when the rolling deformation rate reaches 65%. The specific wear rate of the copper sheet reached the maximum(0.00176 mm\textsuperscript{3}/N·m) when the deformation rate of the copper sheet was 65%. The copper sheet has a smaller specific wear rate by using pulse current assisted rolling, and the oxygen element of the wear debris has a lower content. This indicates that pulse current assisted rolling can improve the wear resistance and oxidation resistance of copper sheet.

1. Introduction

Cu has excellent electrical conductivity, thermal conductivity and ductility. It is widely used in heat transfer, petroleum, shipbuilding, electronics, aerospace, new energy and other fields. At the same time, it has a good application prospect in these fields\textsuperscript{[1–3]}. But copper belongs to the soft metal, and the copper sheet has poor wear resistance after forming\textsuperscript{[4]}. Therefore, the research on performance enhancement technology of copper sheet has great academic and commercial value\textsuperscript{[5, 6]}

In recent years, many scholars have conducted some researches on friction and wear during copper sheet forming and use. Gong F\textsuperscript{[7]} systematically studied the friction size effect during the micro-forming of T2 copper sheet, which revealed the influence of process parameters on the friction coefficient of different size T2 copper sheet samples under dry friction. Bai\textsuperscript{[8]} not only measured the friction coefficient of T2 copper sheet of different sizes under the condition of liquid lubrication, but also studied the influence of the contact conditions on the friction coefficient. The results show that the friction coefficient increases with decreasing sample size, and decreases slightly with increasing positive pressure and sliding speed. Jia et al\textsuperscript{[9]} studied the structure and properties of pure copper contact wire materials. The results showed that the pure copper contact wire began to soften when the temperature reached 200 °C, and its hardness decreased rapidly when it was higher than 200 °C. On this basis, the changes in the microstructure and cracks of materials caused by severe plastic deformation and process conditions of rolling have received widespread attention\textsuperscript{[10–12]}. The application of pulsed current-assisted rolling has simplified the production process and improved the microstructure and property\textsuperscript{[13, 14]}.
At present, there are few related researches on pulsed current-assisted rolling of copper sheet. For this reason, the copper sheet with pulse current assisted rolling has been studied in our lab. The evolution of micro-hardness and wear resistance with deformation rate of rolled copper sheet was studied.

2. Experimental procedure

The test material was 1.5 mm thick T2 copper sheet (99.91 wt%), and the chemical composition is shown in table 1. The copper sheet with a size of 160 mm × 30 mm × 1.5 mm was cold-rolled. The experiment was performed on a rolling mill with a roll diameter of 100 mm. A single pass and large deformation process was used in the experiment. The output pulse voltage, pulse width and frequency of the pulse power supply were 380 V, 40 Hz, 800 Hz, respectively. Micro-hardness testing was performed on the rolled copper sheet. Friction and wear experiments were performed on the rolled copper sheet to study its wear resistance.

Under the condition of normal temperature without lubrication, the friction and wear test used the CFT-I multifunctional material surface comprehensive performance tester. The ball-surface contact mode was used during the experiments. The size of the friction specimen (copper disc) was 25 mm, and the size of its counterpart (GCr15 steel ball) was 6 mm. Reciprocating friction was used in friction and wear experiments. The entire wear test was run for 20 min using reciprocating friction. A 12N normal load was applied to the copper disc. The track radius and speed of reciprocating motion were 5 mm and 500 r min⁻¹, respectively. The micro-hardness of copper sheet was measured with the head pressures of 0.98 N by vickers hardness machine (THV-5MD) for 10 s. VHX-2000 super depth of field 3D microscope system was used to observe the contour of the worn surface. ZEISS FSEM scanning electron microscope (SEM) was used to detect the morphology of wear debris and scratches at 20 KV. The chemical composition of the wear debris was analyzed by energy spectrometer (EDS) attached to the electron microscope.

3. Results and discussion

3.1. Effect of deformation rate on micro-hardness under different rolling processes

The traditional cold rolling process and the pulse current assisted rolling based on the traditional cold rolling process were compared. The changes of micro-hardness with deformation rate under different rolling processes were shown in figure 1.

Figure 1 shows the curve of micro-hardness of rolled copper sheet with deformation rate under different rolling processes. It can be seen from the figure that the micro-hardness of copper sheet without pulse current assisted rolling increases with the increasing deformation rate. When pulsed current-assisted rolling was applied, the mean micro-hardness of copper sheet was $(128.77 \pm 2.5)$HV0.1 at 55% deformation rate, higher than that of the traditional cold rolling process.
than that of copper sheet without pulsed current assisted rolling \((104.83 \pm 2.5)\)HV0.1. With the increase of deformation rate, the micro-hardness of copper sheet increased after an initial decrease. When the deformation rate was 65%, the micro-hardness of the copper sheet reached the minimum value \((82.25 \pm 2.5)\)HV0.1. The results showed that pulse current assisted rolling has a softening effect on copper sheet. It was due to the joule heat generated by the pulse current, which causes an instantaneous rise in the temperature of the copper sheet. In pulsed current assisted rolling, a large number of electrons with a certain drift velocity collide with the atoms when the current passes through the copper sheet. Joule heat energy was generated in a moment under the impact of electron flow collision. The heating rate of metal can reach \(10^6 ^\circ \text{C}/\text{S}^{-1}\) order of magnitude. Such high-speed heating can be regarded as a short-time insulation heating process. The average temperature rise of joule heat caused by electron movement can be expressed as [15]:

\[
\Delta T = (c \rho S^2)^{-1} \int_0^\infty \gamma I^2 dt
\]

\(S\): cross-sectional area of the sample; \(I\): peak pulse current; \(t\): corresponding pulse time; \(c\), \(\rho\) and \(\gamma\): specific heat, the density and the electrical resistivity of the material, respectively.

When the deformation rate is between 55% and 65%, the cross-sectional area of the copper sheet decreased gradually with the increase of the rolling deformation rate. When the output voltage is constant, the current density through the copper sheet increases during the rolling process, and the metal temperature rise generated by joule heat also increases. The instantaneous temperature rise of the copper sheet increases during rolling, causing an increase in the average grain size of the metal copper (As shown in figures 2(a)–(c)). The micro-hardness and grain size of the metal generally meet the hall-petch formula [16, 17]:

\[
H = H_0 + kD^{-1/2}
\]

\(H\): measured value of micro-hardness; \(H_0\): intrinsic value of micro-hardness; \(k\): parameter related to the material; \(D\): average grain size.

It can be seen from formula (2) that the grain size is inversely proportional to the micro-hardness of the metal. The average grain size of copper sheet increases due to the instantaneous temperature rise during the rolling process. The increase of grain size causes the decrease of micro-hardness.

**Figure 2.** Microstructure of copper sheet under different rolling processes, (a) pulse 55% deformation rate, (b) pulse 60% deformation rate, (c) pulse 65% deformation rate, (d) pulse 70% deformation rate.

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**Mater. Res. Express 7 (2020) 066512 H Song et al**
Qin et al. [18] studied the nucleation rate of disordered medium under pulse current. The effect of pulse current causes the change of nucleation barrier [19]:

\[
\Delta G_A = (\Delta G_0 + \Delta G_E) = \Delta G_0 + K_1 \cdot j^2 \cdot \xi^2 \cdot V
\]

Where \( \xi = (\sigma_n - \sigma_p) \cdot (\sigma_n - 2\sigma_p)^{-1} \); \( \Delta G_E \): nucleation thermodynamic barrier when pulse current is not applied; \( \Delta G_E \): nucleation thermodynamic barrier after applying pulse current; \( K_1 \): parameter related to the material; \( j \): pulse current density; \( \sigma_n \): conductivity of the disordered medium; \( \sigma_n \): nucleus conductivity; \( V \): volume of the nucleus. For copper crystals, \( \sigma_n > \sigma_p \), then \( \xi > 0 \). Therefore, the pulse current makes the copper sheet easier to reach the nucleation potential barrier during the rolling process.

From the above theoretical analysis, it can be seen that when the deformation rate reaches 70%, the mean micro-hardness of copper sheet was \((104.91 \pm 2.5)\) HV0.1, and its hardness value increased significantly. In pulsed current assisted rolling, copper sheet can nucleated at a lower deformation rate, and its nucleation rate increased. The increase of the nucleation in copper sheet limited the growth of the nucleation and leaded to the reduction of the grain size (As shown in figure 2(d)). At the same time, the existence of pulse current duty cycle interrupted the grains growth process continuously and caused the change of grains growth direction, which limited the grains growth. Along with the reduction of grain size, the higher micro-hardness values can be obtained.

3.2. Effect of deformation rate on wear resistance under different rolling process

At room temperature and without lubrication, the friction and wear test of copper sheet was carried out by means of material surface comprehensive performance tester. The influence of deformation rate on friction coefficient under different rolling processes is shown in figure 3.

As shown in figure 3, the friction coefficient of copper sheet without pulse current assisted rolling gradually decreased with the increase of deformation rate. It is because the friction coefficient decreases as the hardness of copper sheet increased. After pulse assisted rolling, the friction coefficient of copper sheet first increased and then decreased with the increase of deformation rate. The friction coefficient of copper sheet was slightly smaller than that of copper sheet without pulse assisted rolling.

The wear resistance of copper sheet was compared and analyzed by observing the profile and parameters of wear marks with a super depth of field microscope. Figure 4 shows the contour of wear marks measured by a super depth of field microscope. Figure 5 shows the change curve of wear marks with deformation rate.

As shown in figures 4 and 5, the wear mark height of copper sheet without pulse current assisted rolling decreased with the increase of deformation rate. The wear mark width does not change much. The wear mark height of copper sheet with pulse current assisted rolling first increased and then decreased with the increase of deformation rate. The maximum value was reached at 65% deformation rate, and the maximum height of wear marks was 33.03 \( \mu \)m. The cross section area of wear marks and the average weight loss of rolled copper sheet without pulse current decrease with the increase of deformation rate. The cross section area of wear marks and the average weight loss of copper sheet with pulse current assisted rolling first increased and then decreased with the increase of deformation rate. The maximum cross section area and average weight loss reached the maximum under 65% deformation rate, which were 21132.57 \( \mu \)m² and 0.940 mg, respectively.

The specific wear rate of copper sheet without pulse current assisted rolling decreased with the increase of deformation rate (figure 6). The specific wear rate of the copper sheet, which was assisted by the rolling of the pulse current, first increased and then decreased with the increase of deformation rate. At the rolling
deformation rate of 65%, the specific wear rate reaches the maximum (0.00176 mm³/N · m). The specific wear rate of copper sheet rolled with pulse current was lower than that of copper sheet rolled without pulse current. This indicates that pulse current assisted rolling can improve the wear resistance of copper sheet.

Figure 4. Wear mark profile of copper sheet with different rolling technology: (a) 55% deformation rate, (b) pulse 55% deformation rate, (c) 60% deformation rate, (d) pulse 60% deformation rate, (e) 65% deformation rate, (f) pulse 65% deformation rate, (g) 70% deformation rate, (h) pulse 70% deformation rate.
3.3. The effect of deformation rate on wear marks under different rolling processes

Figures 7(a), (c), (e), and (g) show the worn surfaces of copper sheet rolled without pulse current. It can be seen from the figure that there are fine particles on the copper surface. Furrows parallel to the direction of load movement and dense cracks perpendicular to the direction of load movement on the wear surface make the lamellar separation layer smaller. It is characterized by abrasive wear and surface fatigue wear. Figures 7(b), (d), (f) and (h) show the worn surfaces of copper sheet rolled by pulse current. It can be seen from the figure that there are also fine particles on the worn surface of copper. Furrows parallel to the direction of load movement and a few cracks perpendicular to the direction of load movement on the wear surface make the lamellar separation layer larger. Compared with the wear surface of the copper sheet rolled without pulse current assisted...
Figure 7. SEM image of surface wear of copper sheet. (a) No pulse 55% deformation rate, (b) pulse 55% deformation rate, (c) No pulse 60% deformation rate, (d) pulse 60% deformation rate, (e) No pulse 65% deformation rate, (f) pulse 65% deformation rate, (g) No pulse 70% deformation rate, (h) pulse 70% deformation rate.
rolling, the wear surface of the copper sheet rolled with pulse current assisted rolling was relatively less after wear experiments. This is because when the ball crosses the copper surface, every point on the contact surface carries a circular load. Plastic deformation occurred under the repeated action of the load. Plastic deformation extended along the stress field of the material to a certain depth, where a large number of dislocations occurred within the metal. The formation and aggregation of vacancies was caused by dislocation slip. Micro-cracks were often formed in these areas. During the micro-crack propagation process, the interconnection of multiple micro-cracks inside the copper sheet formed the main crack. These crack edges present jagged arrangement, which is typical of toughness crack expansion [20]. When the crack extended to a certain critical length, a lamellar separation layer was formed between the crack and the copper sheet surface. Under the action of friction, the thin sheet breaks up into fine particles, which surface oxidizes under the condition of contact with oxygen, forming copper oxide particles. These lamellar separation layers break up into fine particles under load. The surface of these particles oxidizes under contact with oxygen, forming copper oxide particles. During sliding, particles and adhesive particles between the steel ball and the copper sheet cause abrasive wear on the copper sheet.

Figure 8. Element percentages of wear debris and wear debris of copper sheet without pulse current assisted rolling: (a), (b) 55% deformation rate, (c), (d) 60% deformation rate, (e), (f) 65% deformation rate, (g), (h) 70% deformation rate, (i), (j) surface of unworn copper sheet.
surface. Abrasive wear gives the copper a parallel but uneven furrow surface. Pulsed current assisted rolling of copper sheet can enhance the migration of atoms. At the same time, it reduced the intensity of dislocation movement obstacles, but the mobility of dislocations was improved. The pulse current increased the nucleation rate of the copper sheet, while the nucleation increased the dislocation consumption. It also greatly reduced the dislocation density in the copper sheet. Based on Frank-Read (F-R for short) dislocation source mechanism, the proliferation of original dislocations has led to the generation of new dislocations \[21\]. Therefore, the original dislocation density has a certain effect on the increment of dislocation after surface wear. The surface dislocation density of the copper sheet was low after the application of pulse current assisted rolling, which further reduced the formation of vacancies. The reduction of vacancy formation slows down the initiation of crack. Therefore, the crack was reduced on the worn surface of copper sheet due to the action of pulse current.

The micro-hardness of copper sheet by pulse current assisted rolling first decreased and then increased with the increase of the deformation rate (as shown in figure 1). At 55% deformation rate, the micro-hardness of the copper sheet was the highest, and the brittleness was also relatively large. More cracks were more easily formed due to the increasing brittleness. At 65% deformation rate, the micro-hardness of the copper sheet was the smallest, so its plasticity was better. Cracks occur less frequently during wear, as shown in figure 7(f). At 70% deformation rate, the micro-hardness of the copper sheet was increased, and the brittleness was also improved. The number of cracks on the surface of the copper sheet increased during the wear process. It shows that the wear surface crack of copper sheet was relatively less and the wear resistance of copper sheet was relatively higher under the condition of 65% deformation rate.

3.4. The effect of deformation rate on the oxidation of wear debris under different rolling processes

Figures 8(a), (c), (e) and (g) show the SEM image of copper sheet wear debris without pulse current applied to assist rolling. Figures 8(b), (d), (f) and (h) show the element percentages corresponding to the wear debris of copper sheet under each rolling deformation rate. It can be seen from the diagram that with the increase of deformation rate, the diameter of wear debris gradually decreased. The oxygen content of the wear debris was significantly higher than that on the surface of unworn copper sheet (figure 8 (j)).
Figures 9(a), (c), (e) and (g) show the SEM image of copper sheet wear debris with pulse current applied to assist rolling. Figures 9(b), (d), (f) and (h) show the element percentages corresponding to the wear debris of copper sheet under each rolling deformation rate. It can be seen from the diagram that with the increase of deformation rate, the diameter of wear debris first increased and then decreased. The micro-hardness of copper sheet by pulse current assisted rolling first decreased and then increased with the increase of the deformation rate (as shown in figure 1). At 55% deformation rate, the micro-hardness of the copper sheet was the highest, and the brittleness was also relatively large. Smaller wear debris were more easily formed due to this increase in brittleness at the same wear time. Therefore, the wear debris has a smaller diameter. With the increase of deformation rate, the micro-hardness of the copper sheet was reduced, and the brittleness was reduced. It is difficult to break the wear debris during the wear process, which leads to the relatively large diameter of the wear debris. At 70% deformation rate, the micro-hardness and brittleness of copper sheet were increased, which results in a smaller diameter of the wear debris. The wear debris diameter was the largest at 65% deformation. The oxygen content of the wear debris was significantly higher than that on the surface of unworn copper sheet (figure 9(j)). Cracks perpendicular to the direction of load movement appear on the worn surface during dry
During the reciprocating friction process, the temperature of the copper sheet surface increased, and the fresh metal exposed at the crack edges was rapidly oxidized. When the crack reaches a certain limit, it formed a lamellar separation layer. When the steel ball continued to reciprocate friction on the lamellar separation layer, the outer surface was oxidized again. As the load continues to be applied to the lamellar separation layer, cracks occur again on the surface of the lamellar separation layer. The constant reciprocating friction caused the decreasing size of the lamellar separation layer until it became the wear debris shown in figure 9. Due to the small size of the wear debris, the wear debris tend to gather in the pits on the surface of the wear marks under the effect of external load. Compared with figure 8, it can be found that the oxygen element content in the wear debris decreased. It is because pulsed current-assisted rolling increased the nucleation rate of the copper sheet, which inhibits the continued growth of the formed grains. Therefore, the microstructure of copper sheet rolled under the action of pulse current was more continuous and dense, which effectively reduced the oxidation rate from the surface of the oxide film to the interior of the metal during the oxidation process. This indicates that the oxidation resistance of copper sheet after pulse current assisted rolling has been improved to some extent.

4. Conclusions

Because of the joule effect in the process of pulsed current assisted rolling, the micro-hardness of copper sheet first decreased and then increased with the increase of deformation rate. When the deformation rate was 65%, the micro-hardness of the copper sheet reached the minimum value ((82.25 ± 2.5) HV0.1).

With the application of pulse current to assist the rolled copper sheet, its specific wear rate first increased and then decreased with the increase of deformation rate. At the rolling deformation rate of 65%, the specific wear rate reaches the maximum (0.00176 mm³/N·m). The specific wear rate of copper sheet rolled with pulse current was lower than that without pulse current. This indicates that pulse current assisted rolling can improve the wear resistance of copper sheet.

With the application of pulse current to assist the rolled copper sheet, the diameter of the wear debris first increased and then decreased with the increase of the deformation rate. The content of oxygen in the wear debris
was lower than that in the copper sheet without pulse current assisted rolling. This indicates that the oxidation resistance of copper sheet after pulse current assisted rolling has been improved to some extent.

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