Characteristics of Electrolytic Copper Powder Compaction by Differential Speed Rolling*

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Differential speed rolling of electrolytic copper powder is conducted under conditions of carefully controlled powder feed volume. Roll speed ratios are changed in the range of 1.00 to 1.50 by choosing different combinations of roll diameters. The rolling load increases with an increase in the ratio of the powder feed volume to the strip speed. The strip thickness increases with an increase in the rolling load for each roll gap, regardless of the roll speed ratio. The relative density of the strip is greater than that achieved using conventional powder rolling.

Key Words: Powder Metallurgy, Plastic Working, Differential Speed Rolling, Electrolytic Copper Powder, Rolling Load, Relative Density, Strip Thickness

1. Introduction

There have been many studies on conventional powder rolling. Dube⁽¹⁾ has reviewed most of these. It has been shown that the characteristics of the rolled strip are dependent on various factors, such as powder characteristics, feed rate of the powder, roll peripheral speed, friction condition at the roll/powder interfaces, initial roll gap and rigidity of the rolling mill. The characteristics of compaction for conventional powder rolling were analyzed by Shima and Yamada⁽²⁾ using the upper bound method and the influences of the initial roll gap, powder feed volume and speed of compacting powder on the strip thickness, relative density and rolling load were discussed.

Utilizing positive shearing force in the compacting powder could be considered to improve relative strip density and joining forces among the powder particles. When differential speed rolling is applied to

powder rolling, the neutral points referring to the two rolls are located at different positions, and the frictional forces act in the opposite direction on the surfaces between the points. It may be expected that the stress state in the compacting zone will change compared with that in conventional powder rolling. Therefore, the effects of the roll speed ratio on the strip property and rolling property should be considered. In our previous study⁽³⁾, we conducted differential speed rolling under an unstable powder feed volume and found that powder accumulates above the roll surface. Therefore, the results obtained could be discussed from a certain condition of the unstable powder feed volume.

In this study, a green strip is fabricated from electrolytic copper powder by applying differential speed rolling. The roll speed ratios are varied with the change in roll diameters under the condition that the number of revolutions of the two rolls is arranged equally. The powder feed volume is closely controlled using a specially designed hopper. The effects of the roll speed ratio, initial roll gap, powder feed volume and powder compacting speed on the strip thickness, relative density, rolling load and forward slip are

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examined and compared with those in conventional powder rolling.

2. Phenomena of Powder Rolling

A schematic representation of conventional powder rolling is shown in Fig. 1. β is the gripping angle, i.e. the angle between the roll surface plane at the beginning of compaction of the powder and the line through the centers of the rolls. ρ is the relative density and t is the thickness of the strip formed. V_s is the strip speed at the roll exit. Q and Q_F express the compacted quantity and the powder feed volume per unit width, respectively.

By using ρ , t and V_s , the compacted quantity Q is given by

$$Q = \rho \cdot t \cdot V_s \quad (1)$$

The powder feed volume Q_F is given by Eq. (2), since Q_F is equal to Q .

$$Q_F = Q = \rho \cdot t \cdot V_s \quad (2)$$

When Q_F is increased under a constant V_s , either ρ or t becomes larger. In addition when the peripheral speeds of the rolls are increased under a constant Q_F , V_s becomes larger and either ρ or t becomes smaller. When the rolling load increases with an increase in Q_F , t becomes larger because t is the sum of the mill spring and the initial roll gap. When Q_F is increased under a constant V_s , the gripping angle β becomes

Fig. 1 Schematic representation of conventional powder rolling

Fig. 2 Schematic diagram of the experimental rolling mill and signal processing

larger. A Q_F that is just equal to Q causes t and ρ to vary according to changes in Q_F . The magnitude of β depends on the conditions of the roll surface and the powder. Therefore, an upper limit for β exists. The value of this upper limit is expressed as the maximum gripping angle $\beta_{\max}$. When the powder is supplied on the roll surface beyond $\beta_{\max}$, the powder accumulates above the roll surfaces, and is not be compacted. This suggests that a maximum value of t or ρ exists for each initial roll gap or each roll speed ratio when the powder feed volume is strictly controlled.

3. Experimental Procedures

3.1 Powder and experimental apparatus

An electrolytic copper powder with irregular shaped particles is used. The average particle diameter is $106 \mu\text{m}$ and the range is $45 - 180 \mu\text{m}$. Electrolytic copper powder is considered to be superior in terms of compressibility because of its large specific surface (surface area per unit mass). A schematic diagram of the experimental rolling mill and signal processing is shown in Fig. 2. The rolling mill is a two-high mill of the inclined type. The roll speed ratios are varied by changing the diameters of the rolls under the same roll revolutions. The rolling load is measured with a load cell installed on a bearing supporting the rolls. A non-contact-type turn indicator is used to count the number of spindle revolutions. Peripheral roll speeds are calculated from the roll diameter and the number of roll revolutions. A schematic diagram of the hopper and rolling arrangements for differential speed rolling is shown in Fig. 3. V_H and V_L are the peripheral speeds of the higher speed roll and the lower speed

Fig. 3 Schematic diagram of the hopper and rolling arrangements for differential speed rolling. V_H and V_L are the peripheral speeds of the higher speed roll and the lower speed roll, respectively. V_s is the strip speed and the R_g roll gap

roll, respectively. V_s is the strip speed and R_g is the roll gap. The powder feed volume Q_F is strictly controlled by regulating the rate of falling of powder in the hopper. A guide plate is installed across the inside of the hopper, and the compacted strip is 20 mm in width.

3.2 Strip and rolling property

The compacted strip is evaluated by its thickness and relative density, and the rolling property by the rolling load and forward slip. The relative density ρ is obtained by dividing the apparent density of the compacted strip by the true density of copper. The rolling load P per unit width is employed. The forward slip represents the relative slip between the roll surface and the compacted strip surface. The forward slip f in conventional powder rolling is given by Eq. (3) using V_s and the peripheral speed of the rolls V_R .

$$f = (V_s - V_R) / V_R \quad (3)$$

f is different for the higher and lower speed rolls when differential speed rolling is used. The forward slip f_H of the higher speed roll and the forward slip f_L of the lower speed roll are given in Eqs. (4) and (5), respectively.

$$f_H = (V_s - V_H) / V_H \quad (4)$$

$$f_L = (V_s - V_L) / V_L \quad (5)$$

f_H and f_L are calculated using marks on the strip transferred from the roll surfaces at a specific arc length.

3.3 Experimental conditions

The roll speed ratio is defined by Eq. (6).

$$\alpha = V_H / V_L \quad (6)$$

α is set at 1.00, 1.20, 1.33 and 1.50. The combinations of roll diameters for each α are given in Table 1. An α of 1.00 represents conventional rolling. Other conditions are summarized in Table 2. The initial roll gaps are varied from 0.05 to 0.25 mm in 0.05 mm increments. The initial roll gap is written as roll gap R_s hereafter. The peripheral speeds of the higher speed roll are changed from 10 to 40 mm·s⁻¹. The roll surface is finished at 0.28 μ m in the centerline average height. Rolling is conducted without a lubricant.

The strip speed V_s is calculated from f_H or f_L and the peripheral roll speeds. Q/V is used to generalize the feed volume Q_F and the strip speed V_s . Q/V is represented by Eq. (7) obtained from Eq. (2).

$$Q_F / V_s = \rho \cdot t \quad (7)$$

Q/V is varied by selecting Q_F and V_s . Q/V reaches its maximum value at $\beta_{\max}$ under each roll gap R_s . The Q/V value at which powder begins to accumulate on the roll surface is expressed as $(Q/V)_{\max}$.

4. Experimental Results and Discussions

4.1 Forward slip

Variations of the forward slip f_H and f_L with roll

Table 1 Roll speed ratio, diameters of higher speed roll and lower speed roll

Roll speed ratio α	1.00	1.20	1.33	1.50
Dia. of higher speed roll mm	50.0	54.5	57.0	60.0
Dia. of lower speed roll mm	50.0	45.5	43.0	40.0

Table 2 Roll gap, peripheral speed of higher roll and roll surface roughness

Roll gap R_g mm	0.05, 0.10, 0.15, 0.20, 0.25
Periph. speed of higher roll V_H mm·s ⁻¹	10 ~ 40
Roughness of roll surface R_a μ m	0.28
Lubrication	Without lubricant

Fig. 4 Variation of forward slips f_H of the higher speed roll and forward slip f_L of the lower speed roll with roll speed ratio α

speed ratio α are shown in Fig. 4. f_H and f_L are almost zero for an α value of 1.0, that is, conventional rolling. f_H decreases whereas f_L increases with increasing α in differential speed rolling. From Eqs. (4) and (5) the relation among V_H , V_L and V_s for conventional rolling leads to Eq. (8).

$$V_H = V_L = V_s \quad (8)$$

Equation (8) states that the neutral point position is at the roll exit because the peripheral roll speeds are equal to the strip speed at this point. In differential speed rolling f_H takes a negative value and f_L a positive. Accordingly, the relation among V_H , V_L and V_s results in Eq. (9).

$$V_H > V_s > V_L \quad (9)$$

From Eq. (9), the concept of differential speed rolling is graphically shown in Fig. 5. F_r is the frictional force and N the position of the neutral point. The

Fig. 5 Concept of differential speed rolling, where F_r is the frictional force, N is the position of the neutral point and A is the zone subject to opposite frictional forces

shaded area A refers to the zone that is subject to opposite frictional forces acting on the strip surfaces. The neutral point of the higher speed roll does not appear due to the relation, $V_H > V_s$. The neutral point of the lower speed roll is shifted toward the direction of the roll entrance. The frictional forces acting on the strip surfaces assume mutually opposite directions. The resulting stress state is different from that in conventional rolling.

4.2 Rolling load and Q/V

The relations among Q/V , the rolling load P and the roll gap R_g for α values of 1.00, 1.20 and 1.50 are shown in Figs. 6 (a), (b) and (c). From Fig. 6 (a), the magnitudes of P in each R_g increase with increasing Q/V , and if Q/V is held constant, P decreases with an increase in R_g . It is found from Figs. 6 (b) and (c) that the relationships have a similar tendency to exhibit that observed in Fig. 6 (a), however, the magnitudes of Q/V and P decrease with an increase in α compared with those for an α of 1.00.

Figures 7 (a) and (b) show typical relations among the rolling load P , Q/V and roll speed ratio α for roll gaps R_g of 0.05 and 0.25 mm. The maximum $(Q/V)_{\max}$ is presented in Fig. 7 (a) for α values of 1.00 and 1.20. When Q/V is constant, the magnitude of P for each α becomes smaller than that in conventional rolling. It is evident that the difference between these P loads increases with an increase in Q/V . Let us suppose that friction occurring at the surface between the roll surface and the powder is described by Coulomb friction, then we can obtain the magnitude of the frictional force that is proportional to the magnitude of P . Accordingly, when either Q/V or P increases, the influence of α on P is considered to increase. P in Fig. 7 (b) is small when compared with P in Fig. 7 (a), thus the difference between these values of P for conventional rolling and differential

Fig. 6 (a), (b) and (c) Relations among Q/V , rolling load P and roll gap R_g for roll speed ratios α of 1.00, 1.20 and 1.50

speed rolling is found to be very small. It should be noted that $(Q/V)_{\max}$ in Fig. 7 (b) decreases with an increase in α .

4.3 Thickness and rolling load

The effect of the rolling load P on the thickness t achieved by changing the roll gap R_g is shown in Fig. 8. Dotted lines are the approximate curves for each R_g . It can be concluded that each t increases linearly

Fig. 7 (a) and (b) Relations among rolling load P , Q/V and roll speed ratio of α for roll gaps R_s of 0.05 and 0.25 mm

Fig. 8 Effect of rolling load P on thickness t achieved by changing the roll gap R_g and the roll speed ratio α

with increases in P , regardless of the magnitude of α .

4.4 Relative density and rolling load

Figure 9 shows the dependence of the rolling load P on the relative density ρ for varying roll gaps with an α of 1.20. The approximate curve for conventional

Fig. 9 Dependence of rolling load P on relative density ρ for different roll gaps R_g with roll speed ratio of α 1.20

Fig. 10 Variation of relative density ρ with rolling load P for each roll gap R_g with roll speed ratio α of 1.50

rolling is given by the dotted line. ρ increases with increasing P for each R_g . The values of ρ in differential speed rolling are equal to or lower than those of conventional rolling within the low rolling load at larger R_g . On the other hand, the values of ρ in differential speed rolling are larger than those of conventional rolling with the higher rolling load, regardless of R_g . For example, ρ in conventional rolling is approximately 0.87 at a P value of $0.6 \text{ kN}\cdot\text{mm}^{-1}$, however the relative density ρ for an α of 1.20 is approximately 0.92. In other words, when a strip with a certain relative density is produced, the rolling load in the differential speed rolling is fairly small compared with that in conventional rolling. The increase in the relative density by changing the roll speed ratio in differential speed rolling is significant, especially with a higher rolling load. Figure 10 shows the variation of relative density ρ with rolling load P for each roll gap R_g with a roll speed ratio α of 1.50.

Fig. 11 (a)~(d) Strip surface appearance, where (a) corresponds to conventional rolling, and (b), (c) and (d) correspond to differential speed rolling for roll speed ratio α of 1.33

Fig. 12 (a) and (b) Sectional microphotographs of a strip formed using a roll gap R_g of 0.10 mm and rolling load P of approximately $0.6\text{ kN}\cdot\text{mm}^{-1}$

The dotted line is the approximate curve for conventional rolling. ρ in differential speed rolling is small compared with that found in conventional rolling for comparatively small magnitudes of P . The rolling load showing this tendency was found to be approximately $0.3\text{ kN}\cdot\text{mm}^{-1}$ for an α value of 1.33, however, this rolling load increases to approximately $0.4\text{ kN}\cdot\text{mm}^{-1}$ for an α value of 1.50. We find that the rolling load P increases with increasing α when the relative density caused by the effect of differential speed rolling is larger than the values of ρ in conventional rolling.

4.5 Strip surface appearance

The strip surface is shown in Figs. 11 (a)~(d). Figure 11 (a) corresponds to conventional rolling, while (b), (c) and (d) correspond to differential speed rolling with an α of 1.33. P for each strip is

shown below these images. In these figures, black parts represent the shiny surface and the white parts the rough surface. It is evident from Figs. 11 (b) and (c) that the strip surface in differential speed rolling is lustrous due to the large slip occurring between the roll surface and the compacted strip surface compared with (a) in conventional rolling. It was generally found that there was an upper limit to the relative density of the compacted material in each compacting process. The upper limit of ρ is approximately 0.95 regardless of the magnitude of α . The split in the rolling direction is observed on the strip surface given in (c) resulting from rolling subjected to an excessive rolling load under the upper limit of ρ . On the other hand, when the rolling load is decreased, the relative density becomes lower due to insufficient compaction. The appearance of minute cracks in the strip surface in Fig. 11 (d) is attributable to a fairly small rolling load in differential speed rolling.

4.6 Sectional microphotography of the compacted strip

Figures 12 (a), (b) and (c) show sectional microphotographs of the compacted strip with an R_g value of 0.10 mm and a P value of approximately $0.6\text{ kN}\cdot\text{mm}^{-1}$. Figure 12 (a) corresponds to an α of 1.00, to (b) an α of 1.20 and to (c) an α of 1.33. The black parts represent the areas of low relative density in these figures. It is likely that the powder particles in the strip compacted by differential speed rolling are subjected to large shearing deformation, and that this shearing deformation contributes to the large relative density.

4.7 Strip appearance

From Eq.(9) and the strength of the strip produced, the strip with a higher relative density rolled by a higher load was curved toward the lower roll speed side, and was produced with a certain curvature. However, the strip with a lower relative density was fabricated as a plate due to the moment of force caused by the strip's own weight.

5. Conclusions

Differential speed rolling was applied to powder rolling, and electrolytic copper powder was used as the metal powder. The roll speed ratio was arranged by changing the combinations of roll diameters with constant roll revolutions. The effects of the process parameters such as roll speed ratio, initial roll gap and powder feed volume on the rolling load, forward slip, strip thickness and relative density were examined under carefully controlled powder feed volume conditions.

The main results obtained are as follows:

- 1) The rolling load increases with increasing

Q/V , that is, the ratio of the powder feed volume to the strip speed.

2) The strip thickness increases with an increase in the rolling load for each roll gap, regardless of the roll speed ratio.

3) The relative density of the strip compacted by differential speed rolling is large compared with that of conventional rolling under the same rolling load.

4) When the roll speed ratio is relatively large under the ranges of the small rolling load, the relative density achieved by differential speed rolling is small compared with that of conventional rolling.

5) The upper limit value of the strip relative density is found to be 0.95, regardless of roll speed ratio.

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