JMEPEG (2008) 17:499–505
DOI: 10.1007/s11665-007-9166-4

1059-9495/$19.00

Microstructure and Properties of Copper Tube During Three-Roll Planetary Rolling

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(Submitted October 28, 2006; in revised form August 20, 2007)

During three-roll planetary rolling, the microstructure of copper tube with initial columnar grains develops into an equiaxed grain structure due to the large rolling deformation and high rolling temperature. The microstructure of copper tubes significantly influences formability and properties due to the three-roll planetary rolling operation. It is very important to understand the microstructural evolution for such special processing. It was found that dynamic recrystallization occurred at the concentrating deformation zone, followed by rapid grain expansion that gradually stabilized. Corresponding with the transformation of microstructure, the hardness of the tube billet reduced gradually away from the roller's concentrating deformation zone. The changing of roller velocity is responsible for the extreme evolution of the microstructure in the concentrating deformation zone. Therefore, the properties of copper tubes can be controlled by concentrating the deformation zone. This research can facilitate the application of planetary rolling to the manufacture of tubes for low formability materials.

Keywords copper tube billet, hardness, large deformation, microstructure evolution, three-roll planetary rolling

1. Introduction

Large deformation and high elongation characterize the microstructure of materials subjected to the three-roll planetary rolling mill (Planet Schräge Walzwerk, PSW), which is an advanced large deformation and continuous planetary machine. The three-roll planetary rolling operation can refine the microstructure of copper tubes, and improve the performance of applied products (Ref 1). The reasons are that the deformation is fast and concentrated, the temperature rises rapidly, and the microstructure evolves intensively. After the copper tube billet contacts the roller, large friction and three-dimensional compressive stress deform the copper tube substantially which changes the microstructure, and affects the properties of rolled copper tubes. Because of the severe friction and large deformation, the plastic work which mostly contributed to the heat energy of the copper tube increased the rolling temperature above the recrystallization temperature of the copper, transformed the microstructure and influenced the properties of final products.

The dynamic recrystallization (DRX) of pure copper tube was analyzed during the rolling process of a three-roll planetary mill, and both work-hardening and DRX softening happened as the hardness dropped when the recrystallization was complete (Ref 1). Shih et al. developed a finite model and studied the deformation behavior of steel materials in the three-roll planetary rolling operation (Ref 2-3). The bar rolling process was analyzed by means of the three-roll planetary mill and the numerical simulation, such as the equivalent stress and plastic strain distribution were obtained by Wu et al. (Ref 4). Several papers studied the deformation characteristics and the mechanism of DRX of copper. Gao et al. (Ref 5) discussed the DRX of copper polycrystals with different purities based on hot compression tests and obtained the hot deformation behaviors of copper characterized by multiple peaks or a single peak flow, and a new grain evolution by DRX at high strains. Montecinos et al. (Ref 6) investigated the rolling process of copper tubes and applied the cross-rolling process to reduce the thickness of copper tubes obtained by continuous casting. Manonukul et al. (Ref 7) analyzed the initiation of DRX under inhomogeneous stress states for pure copper and the motion of the recrystallization front with varying applied strain was found to be well predicted. Wusatowska-Sarnek et al. (Ref 8) investigated the nucleation and microtexture development under DRX of copper and discussed the mechanisms of dynamic nucleation of copper and the new DRX grains were evolved by bulging of serrated grain boundaries, which accompanied twinning at the back of the migrating boundary. Mao et al. (Ref 9) analyzed the formation of recrystallization cube textures for high purity face-centered cubic (fcc) materials such as copper. However, few works indicated that the copper tube billet's recrystallization zone was located in the zone of the roller's concentrating deformation area during three-roll planetary rolling, although the zone is critical to the performance of end products. The purpose of this study was to understand the microstructural evolution of rolled copper tube and to control the properties of the end products during three-roll planetary rolling. Therefore, the microstructural evolution of the copper tube was analyzed in this paper for the whole three-roll planetary rolling process, including macro and microstructural evolution. The behavior of microstructural evolution during the three-roll planetary rolling

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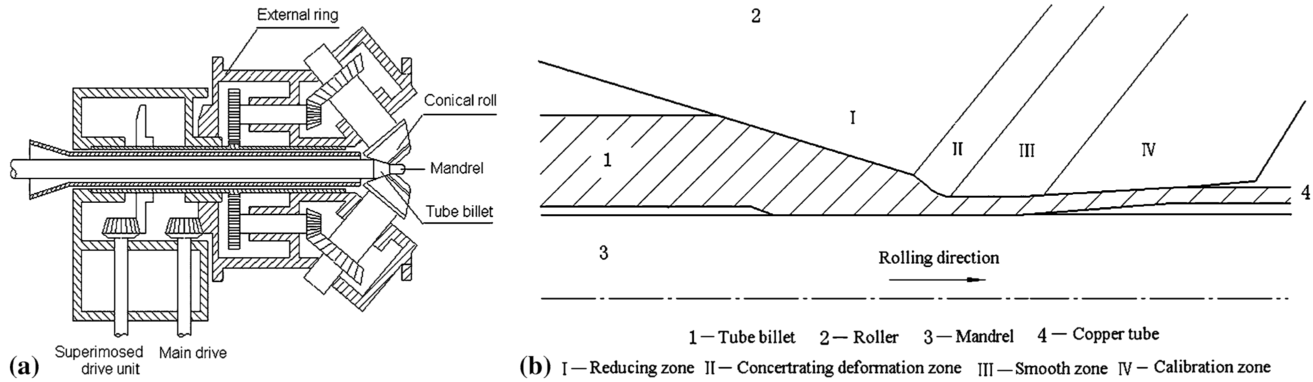

Fig. 1 (a) Cross section of three-roll planetary mill and (b) magnified view of the deformation zones of roller

process was further analyzed by measuring hardness and analyzing the velocity of the roller.

2. Experiments

The three-roll planetary rolling mill mainly consists of three uniform distributed conical rollers, the external ring and the mandrel as shown in Fig. 1a. The axes of the rollers have a certain inclined angle and an offset angle with the rolled copper tube, which make the copper tube generate plastic deformation and move forward as the rollers rotate. By the rotation of the roller, the copper tube billet is compressed and rotated around the mandrel to the forward direction. The magnified view of the deformation zones is shown in Fig. 1b. There are four deformation zones along the rolling direction, including the reducing zone, the concentrating deformation zone, which is the critical zone for microstructure evolution, the smooth zone and calibration zone. The profile of the roller is useful for deformation of copper tube billet in one rolling pass. The characteristics of three-roll planetary rolling include realization of a single pass with large deformation that drastically changes grain size, texture, and morphology.

The analysis material in this paper is TP2 (a type of copper deoxidized by the phosphorus element, ASTM: C12200) copper tube billet with chemical compositions of 0.002% Mn, 0.005% Ni, 0.005% Fe, 0.004% S, 0.039% P, 99.90% Cu (mass fraction).

To analyze grain structure in the four zones, the rolling process was stopped, and samples were water cooled to stabilize the microstructure of the copper tube. The macro-grain evolution in cross section and the micro-grain evolution in the longitudinal direction were analyzed to understand the microstructure evolution behavior in the rolling processing. Figure 2 shows the profile of rolled copper tube in the longitudinal direction. The macro- and microstructures were analyzed at points *a-c*.

The microstructures at points *e-f* in the positions away from the roller's concentrating deformation zone, were also obtained by micro-metallographic observation. With metallography from these positions, the regularity of microstructural evolution in three-roll planetary rolling can be observed. The initial wall thickness of copper tube billet t_o is 20.5 mm and the relative deformation is 0%. The relative deformations are calculated by the different values of wall thickness divided by the original wall thickness. The observational positions *a-f* and the relative deformation of samples are shown in Table 1.

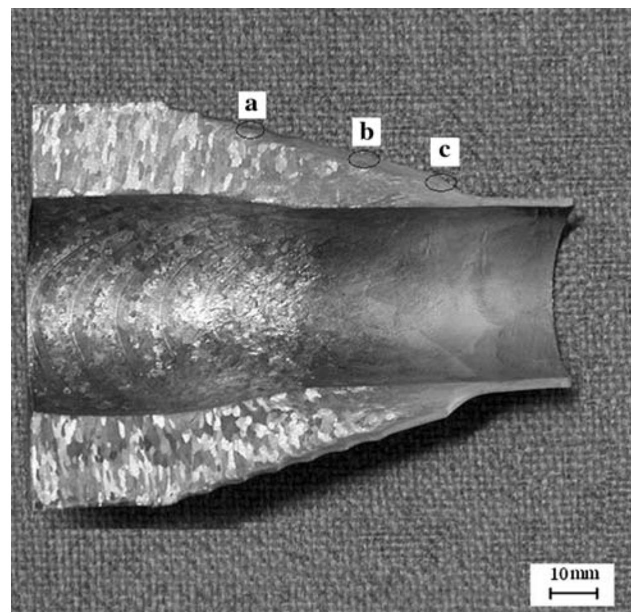

Fig. 2 Macrostructure of rolled copper tube in longitudinal direction

For macro-metallographic observation, such as the cross sections A-C at points *a-c*, samples were cut, cleaned, ground, polished, and etched with 50% nitric acid. For micro-metallographic observation, such as the points *a-f*, the regularity of structural evolution of the copper tube can be observed for the three-roll planetary rolling process, to understand its influence on grain distribution and grain size of the rolled copper tube. The etchant ratio for micro-metallographic observation is nitric acid: phosphorous acid: glacial acetic acid = 1:1:1.

3. Results and Discussion

3.1 Microstructure Evolution

The microstructure of the copper tube billet after the horizontal continuous casting process contains columnar grains and equiaxed grains; due to the high thermal conductivity of

Table 1 Observational positions and relative deformation of samples

Observational positions of samples	Wall thickness of copper tube t, mm	Relative deformations, %, $((1-t/t_o)*100\%)$
a (Entering position of reducing zone)	18.5	9.76
b (Middle of reducing zone)	15.0	26.83
c (Position of concentrating deformation zone)	6.5	68.29
d (Position of rolling out 50 mm)	2.3	88.78
e (Position of rolling out 100 mm)	2.3	88.78
f (Position of rolling finished)	2.3	88.78

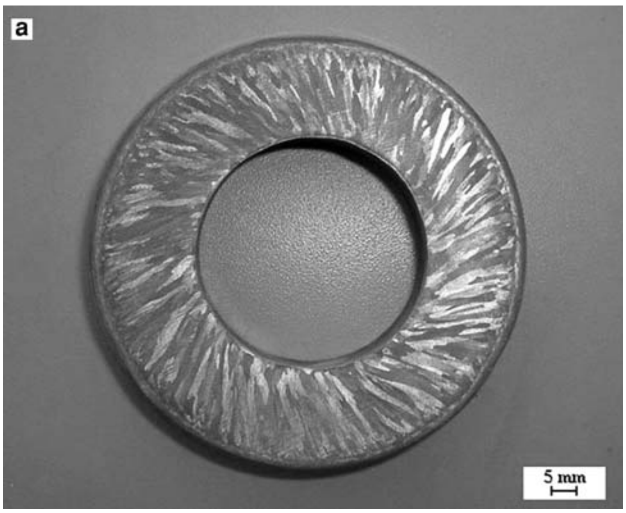

Fig. 3 Macroscopic grain in cross section of point *a*

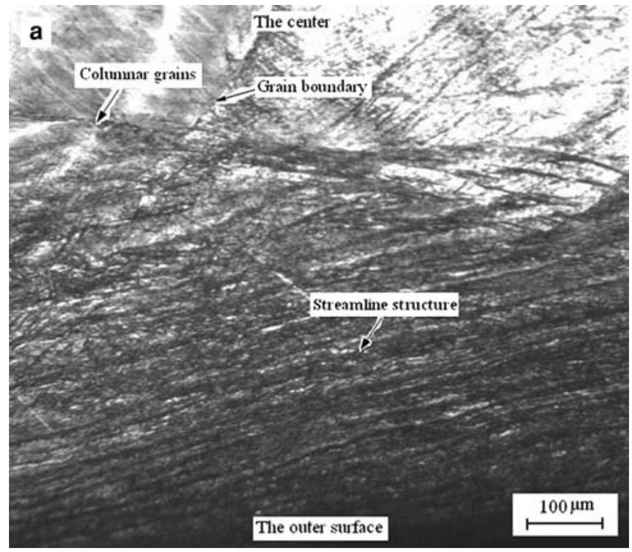

Fig. 4 Microscopic grain in position *a*

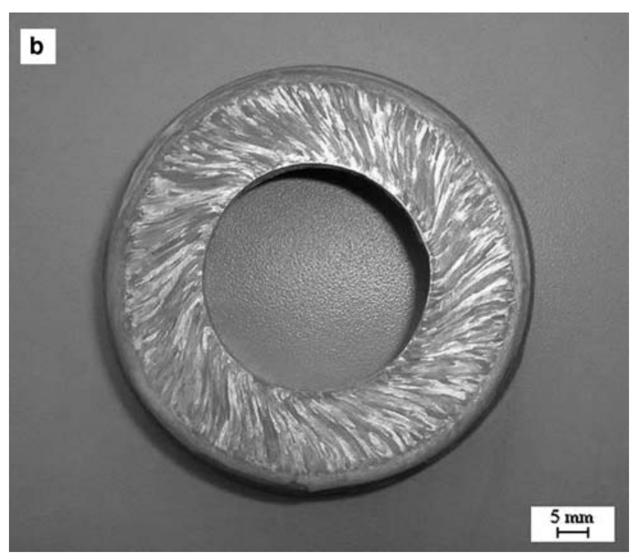

Fig. 5 Macroscopic grain in cross section of point *b*

copper and the rapid cooling rate as well as to the characteristics of flash solidification and directional crystallization (Ref 10). There are small amounts of equiaxed grains in the outer surface of the copper tube billet due to the high cooling rate. The more uniform the texture of the copper tube billets, the more uniform the microstructure and properties of three-roll planetary rolling copper tubes.

Figure 3 shows the macrostructure in cross section at point *a*, from which the distribution of macroscopic grains can be observed where the copper tube billet entered into the roller's reducing zone. The columnar grains experience the twist deflection due to the friction force of the roller's reducing zone, which generates strong shear stress. The equiaxed grains in the outer surface of the copper tube billet are refined into the streamline structure, which can be observed in the outer surface of the copper tube billet. The microstructure in position *a* is shown in Fig. 4. Under the intense shear stress from the rollers, the equiaxed grains in the outer surface and the outer parts of the columnar grains are refined into some smaller grains, which form a streamline structure in the outer surface of copper tube billet.

Figure 5 shows the macrostructure in the cross section at point *b*, which shows the grain morphology when the copper tube billet is nipped into the middle of the roller's reducing zone. With development of rolling process, the deformation temperature increases continuously and the friction force intensities. The twist deformation of columnar grains is more obvious, which reveals the characteristics of the billet's revolution and is one of characters of three-roll planetary rolling. With the increasing deformation temperature of the rolled copper tube billet, the outer parts of columnar grains are more refined. The microstructure of the outer surface of the copper tube billet in position *b* is shown in Fig. 6. It can be

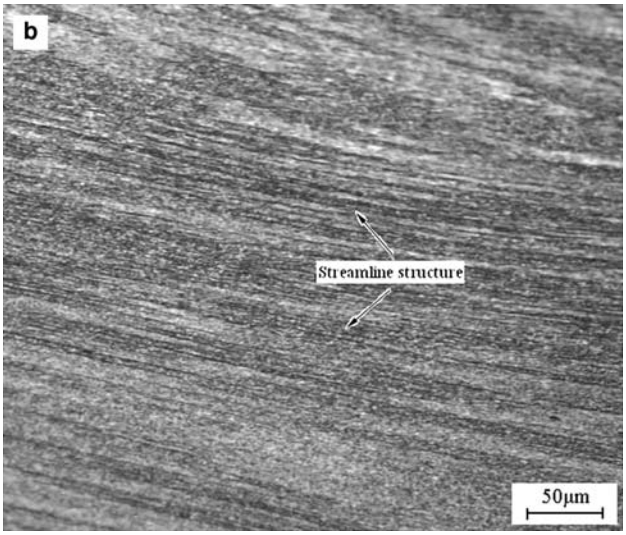

Fig. 6 Microscopic grain in position *b*

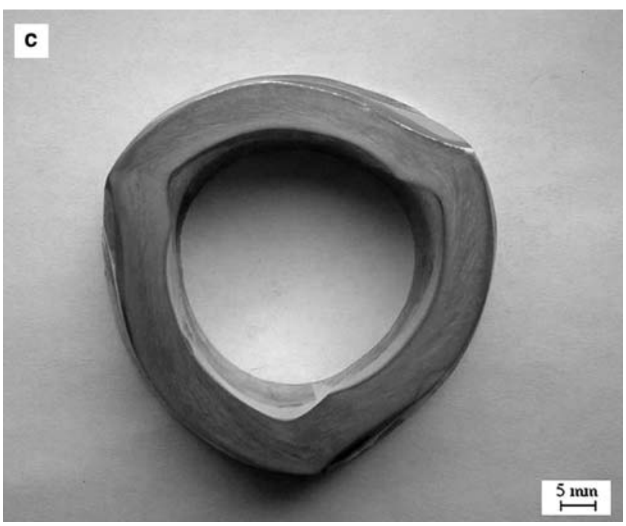

Fig. 7 Macroscopic grain in cross section of point *c*

observed that as deformation precedes the extent of refinement of columnar grains increases. As the increase of the temperature with further grain refinement occurs, laying a foundation for recrystallization. However, the deformation temperature is lower than the material's recrystallization temperature in this region, so the fine grains appear without evidence of DRX.

The macrostructure of the copper tube billet in the cross section of position *c* is indicated in Fig. 7, where the copper tube billet is in the concentrating deformation zone of the roller. The profile of the copper tube billet approaches a trianglular shape, which is a significant characteristic feature of tube billet deformation in three-roll planetary rolling. In this region, the inner surface of the columnar grain is broken by the friction force between the mandrel and the copper tube billet. Therefore, the fine grains in the outer and inner surfaces of the copper tube billet are converged and the torsional columnar grains in the middle almost disappear and cannot be seen in Fig. 7, which consist almost entirely of the streamline structure.

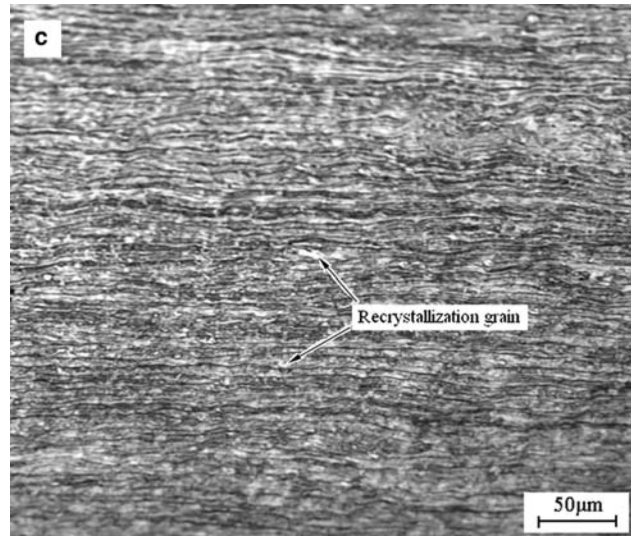

Fig. 8 Microscopic grain in position *c*

This suggests that the grains in this zone are quite refined. At the same time, the temperature of rolled copper tube there has exceeded the recrystallization temperature of the copper. Thus, the nuclei of DRX are generated in this region.

The microstructure of the copper tube in position *c* is illustrated in Fig. 8. The microstructure displays that, in the concentrating deformation zone, the deformation is severe, the columnar grains are refined, and the temperature rises above the recrystallization temperature of copper. These satisfy the forming conditions of the recrystallization nuclei and then generate fine recrystallized grains. However, the copper tube is in the zone of concentrating deformation, the deformation is severe and the deformation rate is the highest. Therefore, the rolled grains are mostly of the streamline structure along the rolling direction. The streamline structure is made up of many small DRX grains. The forming condition of the DRX is that copper has low stacking fault energy with wide extended dislocation and dislocations cannot disappear by interactive slipping and climbing, so the recovery mechanism is limited in the deformation. Therefore, when the energy of dislocation is high enough in the deformation zone, DRX can occur under the specialized stress and deformation conditions.

Figure 9 shows the microstructure of the rolled copper tube, about 50 mm away from the roller. It can be seen that the DRX grains will grow rapidly after the copper tube is rolled at high temperature, and some streamline appearance formed in the rolling process disappears gradually. The microstructure of the copper tube rolled out about 100 mm is shown in Fig. 10, where the DRX grains coarsened more those in Fig. 9 with less apparent processing streamline structure. The microstructure of the roll-finished copper tube is shown in Fig. 11. After the rolling process is complete, the DRX grains are distributed homogeneously, little apparent processing streamline structure, and the average grain size is 29.5 μm. It can be seen from Fig. 11 that the DRX grains are equiaxed, and the subgrain structure divided by the tangled dislocations can also be seen. The reason is that during growth of the nuclei, the deformation also continues in the process of DRX, causing strain in the new grains, and subgrain structures with tangled dislocations appear (Ref 11). Twin crystal will easily form above the recrystallization

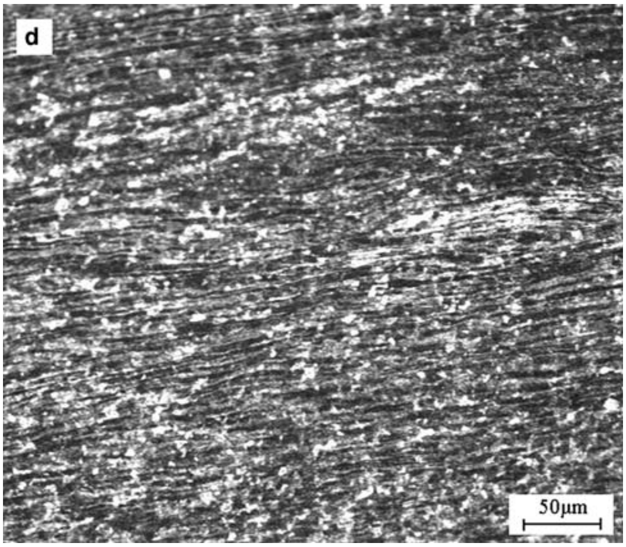

Fig. 9 Microscopic grain in position *d*

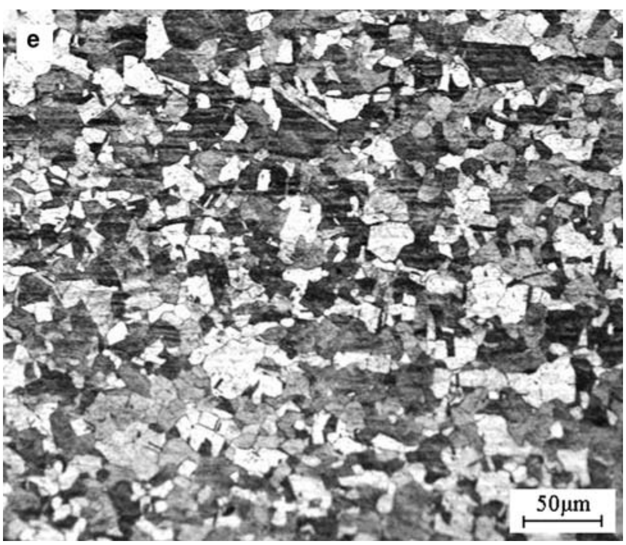

Fig. 10 Microscopic grain in position *e*

temperature because of the low stacking fault energy of copper, which can be seen from the microstructure of rolled copper tube in Fig. 11.

Therefore, the microstructural evolution behavior of copper tubes due to the large deformation of three-roll planetary rolling is concluded as follows. The microstructure at the early stage of the rolling is mainly columnar grains, with grain size range from 1 to 20 mm. As the deformation continues, the grains at the outer surface of the copper tube billet in contact with the roller are refined, which generates a streamline structure formed with refined grains along the processing direction. At this point, the grains in the inner surface and the center portion of the copper tube billet remain mainly torsional columnar grains. This phenomenon gradually becomes severe and the length of the columnar grains reduces. When the copper tube billet reaches the concentrating deformation zone, the refined grains are generated both of the outer surface in contact with the roller and the inner surface contact with the mandrel which form the

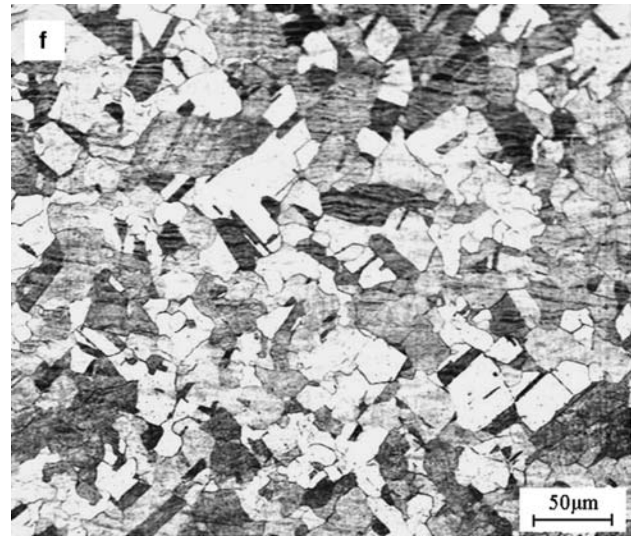

Fig. 11 Microscopic grain in position *f*

streamline structure. The streamline structure of the outer and the inner surface converge, which generates new recrystallized equiaxed grain nuclei under the high rolling temperature. After rolling for a short distance, the recrystallized grains coarsen rapidly and simultaneously the streamline structure decreases. After rolling is finished, the recrystallized structure is distributed uniformly. The properties of the rolled copper tube are influenced by microstructure. Through controlled cooling of the copper tube just after the concentrating deformation zone, the growth rate of recrystallized grains can be adjusted to obtain desired mechanical properties of the copper tube.

The comparison of microstructure and properties between copper tube billet and rolled copper tube is illustrated in Table 2.

The initial copper tube billet has a cast microstructure composed of columnar grains and equiaxed grains in the outer surface. For the microstructure of rolled copper tube under three-roll planetary rolling, the microstructure is homogenous with equiaxed recrystallized grains. The processing microstructure generated by three-roll planetary rolling is consistent and homogenous, which can improve the properties of the copper products. After the three-roll planetary rolling process, both the tensile strength and the elongation percentage increase remarkably, which indicates the virtue of such three-roll planetary rolling in improving the properties of rolled workpieces.

3.2 Effect of the Roller Velocity on Microstructure Evolution

The microstructure evolution behavior of the copper tube billet during three-roll planetary rolling can be explained by analyzing the velocity field of the roller at the contact points. The velocity field in contact point of the roller is shown in Fig. 12. It can be seen that the velocities in normal, axial and tangential directions of the roller's contact point are large in the reducing zone, such as position *a* to position *b*. This means that the copper tube billet is undergoing the compressive deformation in the radial direction which moving forward with the action of rotation simultaneously. In the concentrating deformation zone, starting from position *c*, velocity in the normal direction of the contact points increases to the maximum value,

Table 2 Comparison of microstructure and properties between copper tube billet and rolled copper tube

Comparison items		Copper tube billet	Rolled copper tube by PSW
Microstructure		Casting microstructure: columnar grains and equiaxed grains in the outer surface	Processing microstructure: homogenous equiaxed recrystallization grains
Mechanical properties	Tensile strength σ_b, MPa	162.3-175.5	213.2-224.5
	Elongation percentage δ, %	30.0-45.2	46.2-51.8

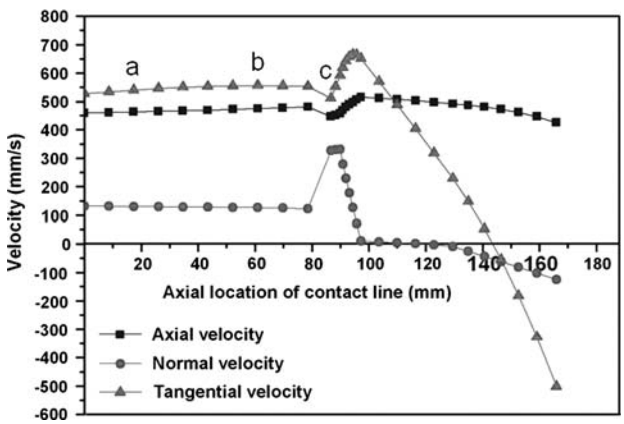

Fig. 12 Velocity field in contact point of the roller

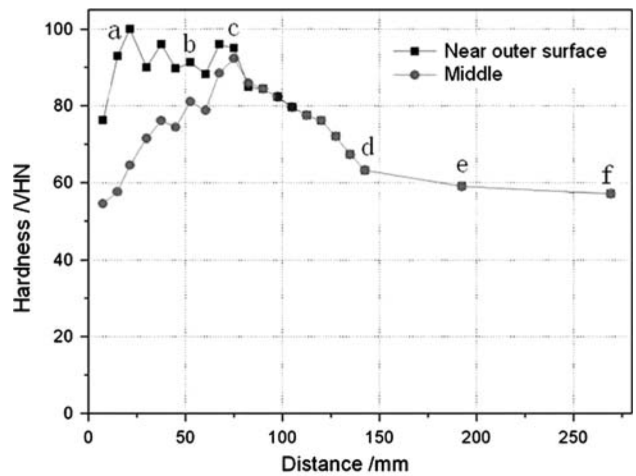

Fig. 13 Hardness evolution curves in longitudinal direction of copper tube billet

which is the most important characteristic of three-roll planetary rolling. The rolling method can be used to produce tubes with low formability materials. After this zone, the velocity in normal and tangential directions decreases quickly and the velocity in the axial direction decreases slightly. Thus, the copper tube billet experiences severe compressive and shear deformation which leads to the accumulation of deformation energy while raising the temperature of rolled copper tube higher than the recrystallization temperature of copper. Therefore, significant DRX nuclei are generated because of the large mount of deformation energy and high deformation temperature. The large deformation value and high deformation velocity make the temperature of rolled copper tube increase quickly, which reach the forming condition of DRX of copper and is one of characteristics of three-roll planetary rolling.

3.3 Hardness Evolution of Rolled Copper Tube

Hardness of the copper tube billet was measured along the axial direction using the Vickers hardness scale as shown in Fig. 13. Square symbols indicate hardness near the outer surface and circular symbols represent the hardness in the middle of copper tube section. Due to the work hardening, it can be seen that the hardness of the center of copper tube billet is increasing (Ref 12). Under the high friction force between the roller and copper tube billet, work hardening in the outer surface of the copper tube billet is greater than in the center; thus the hardness near the outer surface is higher than in the center of copper tube billet. In the concentrating deformation zone, as shown at point *c* in Fig. 13, the hardness of rolled copper tube is uniform through the thickness and there after decreases quickly. This suggests that the effect of DRX softening is more dominant than the work hardening. After the copper tube passed the concentrating deformation zone, there is nearly no difference in hardness along the wall thickness direction of the copper tube. In addition, due to the increasing of the copper tube temperature, the DRX softening caused a rapid decrease of the hardness. The hardness decreased until DRX was complete. Dynamic recrystallization softening is greater than the work hardening after the concentrating deformation zone, where the DRX is developing rapidly and subsequently, the hardness of the tube billet decreased gradually. The DRX grains grow up rapidly once the copper tube billet leaves the concentrating deformation zone.

4. Conclusions

The microstructure and properties of copper tubes were analyzed for the three-roll planetary rolling process. The test results can be used to analyze the behavior of microstructure evolution of the workpiece in the rolling process of similar mills. The conclusions are as follows:

(1) The microstructure of the copper tube changes from columnar grains to the equiaxed grains during three-roll planetary rolling. Dynamic recrystallization occurs at the concentrating deformation zone and coarsening of the DRX grains occurs after leaving the concentrating deformation zone. Therefore, the grain size can be optimized by controlling the cooling rate after rolling out of the concentrating deformation zone.
(2) The temperature of a copper tube can increase above the recrystallization temperature due to larger deformation

and higher deformation rate according to calculated velocity field in the contact area between the roller and the workpiece. This is one of the main characteristics of three-roll planetary rolling.

(3) The hardness of different zones has been analyzed. Hardness values decreased after the copper tube billet left the concentrating deformation zone. This suggests that softening is more dominant than work hardening after this zone. The observed microstructure has a good agreement with the experimental hardness results. This research can facilitate the application of planetary rolling process to the manufacture of tubes for low formability materials.

Acknowledgments

The Natural Science Foundation of China (Project No. 50474059) and the National Key Projects of China (Project No. 2002BA327C) are thanked for their support in the research field of the casting and rolling of copper tubes.

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