Rare Metal Materials and Engineering
Volume 50, Issue 12, December 2021
Available online at www.rmme.ac.cn

Science Press

Cite this article as: Pei Jiuyang, Zhao Ying, Fan Zhixin, et al. Microstructure and Property Evolution of Weld Seam in Copper Tube During Continuous Extrusion Process[J]. Rare Metal Materials and Engineering, 2021, 50(12): 4251-4255.

ARTICLE

Microstructure and Property Evolution of Weld Seam in Copper Tube During Continuous Extrusion Process

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Abstract: The formation of weld seams in the rectangular section of continuously extruded copper tubes with unequal wall thickness was investigated via optical microscopy (OM), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and universal electronic tensile testing machine. Results show that the weld seams are formed by the confluence of two fine grain belts with a grain size of 13.1~53.4 μm. As the continuous extrusion proceeds, the fine grains gradually grow to the similar grain size (100~200 μm) of the base material. Secondary grain refinement occurs as the fine grains pass through the compression zone of the die. Afterward, micropores in the welded interface disappear. Dynamic recrystallization occurs during continuous extrusion welding. The interface between the two metal is broken through dislocation migration, and new grains form. The bonding strength of the weld seams dramatically increases along the flow direction of the metal. The bonding strength increases from 63 MPa in the initial confluence area to 212 MPa at the outlet of the die, which achieves 98.1% of that of the weld seam-free zone. The number and size of dimples in the fracture of the weld seams gradually and simultaneously increase. The elongation increases from 0.5% to 35%, reaching 70% of that of the weld seam-free zone.

Key words: copper tube; continuous extrusion; extrusion weld seam; microstructural evolution; weld strength

The development of the large water-cooled generator industry and the launch of national big science projects, such as the large particle accelerator, have compounded the demand for long high-quality conductive copper tubes[1]. As a newly developed plastic processing method, continuous extrusion has been widely used in copper, aluminum wire, and cable manufacturing; this new method has rendered many traditional process obsolete[2,3]. The copper products fabricated via continuous extrusion are all solid profiles, and the commercial production of copper tubes has not been achieved yet.

Continuous extrusion is highly efficient, energy saving, environmentally friendly, and straightforward. These properties make continuous extrusion a perfect technology for the production of profiled copper tubes[4]. However, the lifespan of dies and the bonding strength of extrusion weld seams are the technical bottlenecks that restrict the industrial applications of this technology. Research on the continuous extrusion of copper tubes has been conducted. Yan et al[5] analyzed the formation process of continuously extruded copper tubes and considered the yield of abutment and mandrel under great stress as the main problems in the production. Xu et al[6] examined the microstructures of continuously extruded copper tubes and found that weld seams form inside the tubes because of the insufficient temperature in the welding chamber. Guo et al[7] investigated the formation process of continuously extruded copper tubes and tested the bonding strength of weld seams. They found that the bonding strength can achieve up to 98% of that of the base metal. Research on the continuous extrusion of copper tubes is mainly focused on copper tube formation and performance testing. The microstructural and property evolution of weld seams in copper tubes during continuous extrusion is rarely reported.

In hot extrusion process, the microstructure and mechanical

Received date: December 20, 2020
Foundation item: National Natural Science Foundation of China (51705062, 51505056, 51675074)
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properties of weld seam were investigated. Valberg et al[8] studied the influence of height of welding chamber, sectional dimension of profile, and volume of welding chamber on the welding quality, and found out the defects of weld seam such as no-welding and holes. Donti et al[9] investigated the quality of welds and found that when the die design and the extrusion process are optimized, the strength of weld seam will become equal to that of the base metal. Yu et al[10] studied the grain structure, special grain boundary and micro-texture along the welding path of an aluminum alloy profile. They found that along the welding path, the fine equiaxed grains around the welding line are elongated along extrusion direction under the combined action of shearing and compression, and then some strip-shaped coarse grains evolve into the fine equiaxed grains by means of dynamic recrystallization. Li et al[11] analyzed the effect of dynamic recrystallization (DRX) on the microstructure of 6063 aluminum alloy profile during porthole die extrusion. They found that the grain size in the welding zone is larger than that in the matrix zone due to lower DRX fraction. Xue et al[12] analyzed the effect of the extrusion temperature on microstructure of the welding zone, and they found that the percentage of the low angle boundaries of welding zone is the highest and the relative frequency of low angle boundaries keeps at 65% with the rise of extrusion temperature. However, the evolution of weld seam in continuous extrusion is rarely reported.

In this study, the microstructural and property evolution of weld seams in section of 20 mm×29 mm of copper tubes with 3 mm in thickness were investigated. The copper tubes were fabricated via the dual rod continuous extrusion method (Fig. 1) under extrusion wheel speed of 5 r/min at 500 °C of chamber preheating, to reveal the microscopic mechanism of weld-seam formation during continuous extrusion of copper tubes. The results can be used to address the problem of low-quality welds formed in copper tubes during continuous extrusion.

1 Experiment

1.1 Experimental materials

Two oxygen-free copper rods (99.96wt%) fabricated by up-pulling method with the diameter of 12.5 mm were adopted in the experiment. The rods were pickled and dried prior to the conduction of experiment. Rectangular copper tubes (Fig. 2) were continuously extruded using a TLJ400 continuous extrusion machine, and the extruded product was cooled by water. The diameter of extrusion wheel was 400 mm and the rotational speed was 5 r/min. The cavity preheating temperature was 500 °C. The extrusion wheel was emergently stopped, and the copper tubes were removed from the welding chamber after quenching to maintain their deformation state.

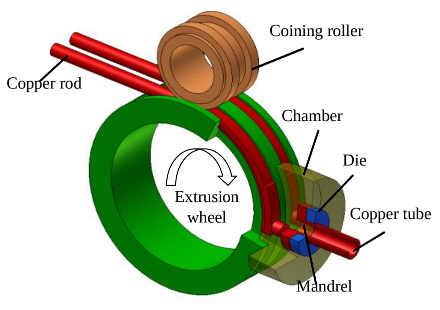

Fig.1 Principle of copper tube continuous extrusion using double billets

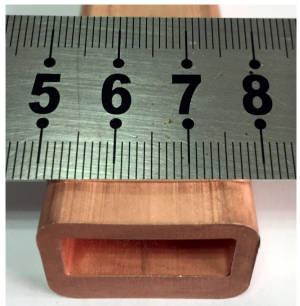

Fig.2 Continuous extruded rectangular copper tube

1.2 Specimen preparation

The copper in the welded area was cut into several specimens. The specimens were located at 10%, 40%, 70%, and 100% of weld chamber height along the metal flow direction, and they were denoted by A~D, respectively (Fig.3). The surface perpendicular to metal flow direction on the specimens was observed for metallographic analysis.

The specimens were polished and then corroded with $FeNO_3$ alcohol solution (2 g $FeNO_3$+50 mL anhydrous ethanol). The microstructures of the weld seams were examined using an OLYMPUS BX41M metallographic microscope. The samples were stretched at room temperature at a stretching speed of 1 mm/min using an AG-IC100kN precision electronic universal tensile testing machine. The microstructures of the weld seams were analyzed using a JEM-2100F transmission electron microscope (TEM). Fracture morphology was examined using a SUPRA55 field emission scanning electron microscope (SEM).

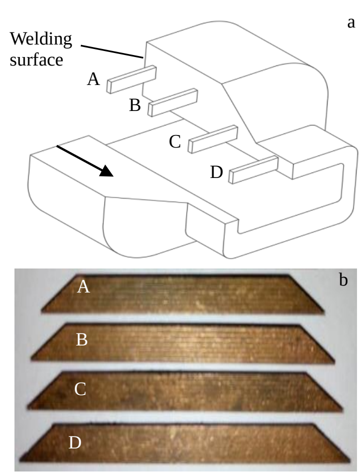

Fig.3 Sampling diagram (a) and specimens at different locations (b)

2 Results and Discussion

2.1 Microstructural evolution of the weld seams

The metallographic images of the formation process of the weld seams in copper tubes during continuous extrusion are shown in Fig. 4a~4d (corresponding positions are denoted as A~D, respectively).

Position A is located at the initial confluence of two copper strands. The grains are recrystallized, which can be divided into three distinct areas (Fig.4a). The middle area is the coarse-grain region with the maximum grain size of 223 μm. The middle area is the dead zone in the initial convergence area. The copper tubes stay for long duration in the dead zone of the chamber, resulting in abnormal grain growth. The two sides are fine-grain zones with grain size of 13.1~53.4 μm, which are formed in extrusion wheel grooves before entering the welding chamber. The raw materials undergo severe shear deformation and frication in the extrusion wheel grooves. The original grains are severely broken and evolve into fine grains and then flow into the welding chamber.

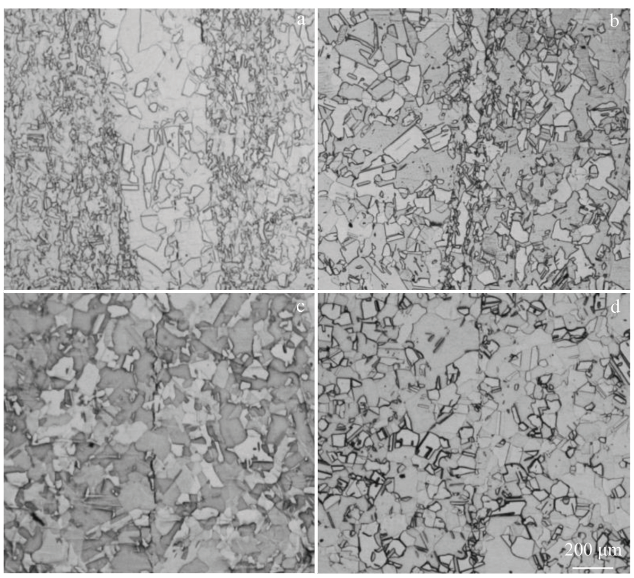

Fig.4 Microstructure evolution of weld seam in continuously extruded copper tube at different positions marked in Fig.3a: (a) position A , (b) position B, (c) position C, and (d) position D

Fig.4b shows that the grains on both sides of the fine-grain zones substantially grow. The widths of the fine-grain zones are narrowed, 18.6~86.1 μm in size. The width of the coarse-grain zone evidently decreases, and the two fine-grain belts are gradually converged. Fig.4c shows that the two fine-grain belts completely disappear. The grains in position C dramatically grow compared with those in position B. The unwelded micropores form a discontinuous weld line[13,14], at which the grain size in most regions is 51.2~104.7 μm. Fig.4d shows that the grain size in position D becomes smaller than that in position C. The micropores and weld lines disappear, and the two metal strands achieve metallurgical bonding[15-17].

TEM images at different positions in the welding area are shown in Fig. 5. When the metal strands enter the welding chamber, numerous dislocations pile up and walls form (Fig. 5a and 5b) because the copper tubes are subjected to severe shear deformation in the wheel grooves, resulting in the piling up of numerous dislocations. When the copper tubes enter the welding chamber, the temperature inside is low and thus the dislocation configuration is relatively stable. Dislocation cells and subgrains form in the welding area (Fig. 5c and 5d) because of the accumulation of deformation energy and the increase in deformation temperature. The recrystallization core forms in the position with no or low distortion. Then dynamic recrystallization occurs by devouring a matrix with high distortion energy[18-20].

2.2 Bonding strength evolution of the weld seams

The bonding strength at different positions in the welding chamber and its relative value to the tensile strength (225 MPa) of the metal in the weld seam-free area are shown in Fig. 6. The bonding strength increases from 63 MPa at the entrance to 212 MPa at the exit. The bonding strength, especially at position B (40%), substantially increases to 149 MPa, which is 2.36 times higher than that at position A (10%). This result is because of the microstructural evolution of the weld seams (Fig. 4 and Fig. 5). A dead zone of metal flow is developed at position A, and a large velocity difference appears between the plastic flow zone and the dead zone. Hence, the metal is only mechanically occluded with a low bonding strength. At position B, the actual contact area of the two metal strands dramatically increases. Dynamic recrystallization and grain growth then simultaneously occur.

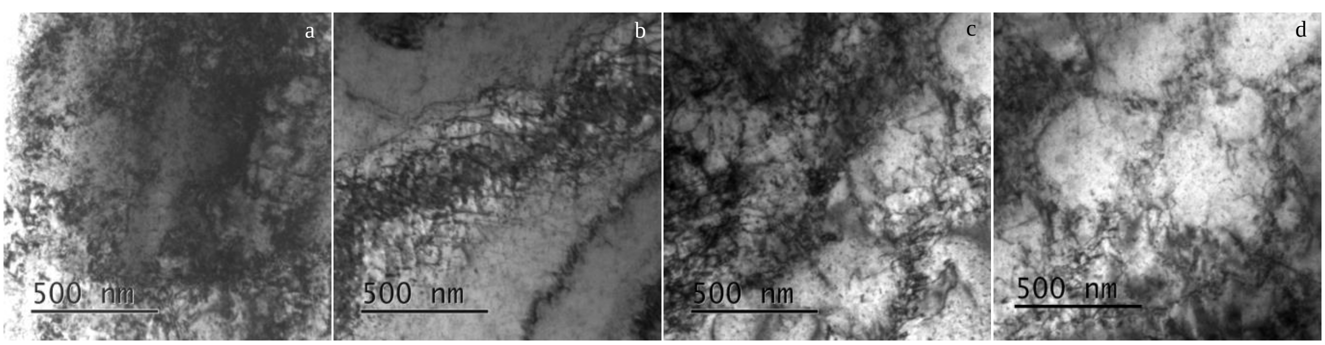

Fig.5 TEM microstructures of weld zone at different positions marked in Fig.3a: (a) position A , (b) position B , (c) position C , and (d) position D

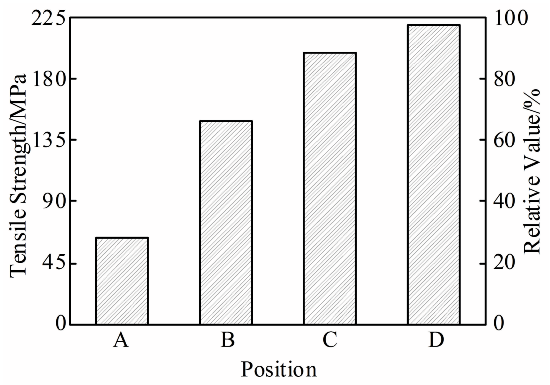

Fig.6 Tensile strength of weld seam at different positions

Consequently, the bonding strength substantially increases, reaching 67.6% of that of the weld seam-free zone. At position C, the grains in the welding area noticeably grow, and the fine grains disappear as the residence time of the metal in the cavity is prolonged and the deformation temperature is increased. However, a few still unwelded micropores remain, and the bonding strength further increases to 200 MPa and reaches 92.6% of that of the weld seam-free zone. At position D, the unwelded micropores completely disappear while secondary grain refinement occurs after the grains pass through the compression zone of the die. Thus, the two metal strands achieve metallurgical bonding[19], and the tensile strength reaches 98.1% of that of the weld seam-free zone. The bonding strength of the weld seam of the final product is 215 MPa, reaching 99.1% of that of the weld seam-free zone (217 MPa).

2.3 Plasticity evolution of the weld seams

The elongation of the samples at different positions are obtained via room-temperature stretch tests, as listed in Table 1. The corresponding fracture morphologies are shown in Fig. 7. Almost no dimples form in the fracture of sample A. The fractures are brittle with an elongation of only 0.5%. This is because there are many microvoids at the welding interfaces of the metal and most of the grains in the welding zones are separated along the bonding interfaces[21,22]. Numerous fine isoaxial dimples appear in the fractures of samples B and C; the fractures are ductile and their elongation increases to 15% and 22.5%, respectively. The fracture morphology of sample D is a large structure with obvious tearing edges. Its elongation increases to 35%, reaching 70% of that of the weld seam-free area. The elongation of the weld seam of final product is 35.6%, reaching 74.9% of that of the weld seam-free zone (47.5%).

The microstructural and mechanical property evolution of the weld seams demonstrate that dynamic recrystallization and

Table 1 Elongation of weld seam at different positions (%)

Position	A	B	C	D
Elongation	0.5	15	22.5	35
Relative value	1	30	45	70

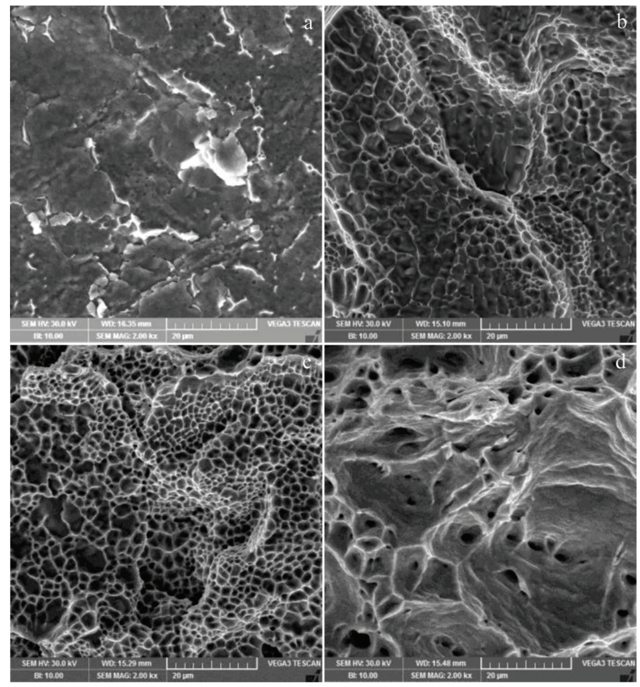

Fig.7 Fracture morphologies of the weld seam at different positions: (a) position A, (b) position B, (c) position C, and (d) position D

micropore closing mechanisms play a major role in continuous extrusion welding of copper tubes. A large amount of lattice distortion energy is accumulated because of the intense friction and shear deformation in the wheel grooves. This energy promotes the dynamic recrystallization process. On the one hand, the existence of the compression zone in the die increases metal flow resistance, thereby increasing the pressure in the welding chamber and promoting micropore closure[23]. On the other hand, continuous deformation at high temperatures promotes the continuous process of dynamic recrystallization, and new grain boundaries formed during recrystallization breaks through the original interface between the two metal strands, thereby achieving metallurgical bonding.

3 Conclusions

1) During the double rod continuous extrusion process, when the speed of the extrusion wheel is 5 r/min and the cavity preheating temperature is 500 °C, the bonding strength of the copper tube welds increases from 63 MPa in the initial confluence area to 212 MPa at the outlet of the die, and the elongation increases from 0.5% to 35%. The bonding strength of the welds of the final product reaches 99.1% of that of the weld seam-free zone, and the elongation reaches 74.9% of that of the weld seam-free zone.

2) The weld seams are formed by the confluence of two fine grain belts, whose grain size is 13.1~53.4 μm. As continuous extrusion proceeds, the fine grains in the welding

area rapidly grow. Secondary grain refinement occurs after the grains pass through the compression zone of the die, and the micropores in the welded interface disappear.

3) The copper billets experiences strong shear deformation in the grooves, and numerous dislocations sre entangled in the welding chamber. As the deformation temperature and continuous deformation increase, dynamic recrystallization occurs. The interface between the two metal strands breaks through dislocation migration, and new grains form, which allows the welding between the metals to achieve metallurgical bonding.

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铜管连续挤压焊缝形成过程的组织和性能演变

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摘 要：利用光学显微镜（OM），扫描电镜（SEM），透射电镜（TEM）和万能电子拉伸试验机对矩形不等壁厚铜管连续挤压焊缝的形成过程进行了研究。结果表明：铜管连续挤压焊缝由2条细晶带汇合而成，晶粒尺寸在13.1~53.4 μm之间，随着挤压的进行，细小晶粒逐渐长大到与基体晶粒尺寸相同，分布在100~200 μm之间，经过模具的压缩区后，发生二次晶粒细化，焊合界面上的微孔消失；挤压焊合过程中发生了动态再结晶，通过位错迁移突破两股金属之间的界面，形成新的晶粒；沿金属的流动方向，焊缝结合强度不断提高，由初始汇合区的63 MPa升高到模具出口处的212 MPa，达到无焊缝区域抗拉强度的98.1%；焊缝断口内的韧窝数量逐渐增多、尺寸增大，延伸率由0.5%升高到35%，达到无焊缝区域的70%。

关键词：铜管；连续挤压；挤压焊缝；组织演变；焊合强度

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