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Effects of microstructure on the deformation behavior, mechanical properties and residual stress of cold-rolled HAl77-2 aluminum brass tube

Yongda Mo[a], Yanbin Jiang[a,b,*], Xinhua Liu[a,b], Jianxin Xie[a,b]

[a] *Key Laboratory for Advanced Materials Processing of Ministry of Education, University of Science and Technology Beijing, Beijing 100083, China*
[b] *Beijing Laboratory of Metallic Materials and Processing for Modern Transportation, University of Science and Technology Beijing, Beijing 100083, China*

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ABSTRACT

HAl77-2 aluminum brass (UNS C68700) tubes with equiaxed grain (EG) structure and with an axial-oriented columnar grain (CG) structure were prepared by the traditional horizontal continuous casting (cooling mold casting) and heating-cooling combined mold horizontal continuous casting, respectively. The tubes were cold rolled, and the influences of microstructure on the deformation behavior, mechanical properties and residual stress of the cold-rolled tubes were investigated. It was found that visible cracks formed on the surface of the cold-rolled EG tube when the accumulative rolling reduction reached 80%, while the good surface quality cold-rolled CG tube without any cracks can be obtained when the accumulative reduction exceeded 95%. During cold rolling, intersecting planar dislocations, deformation twins and shear bands were successively developed in the EG tube. On the other hand, the planar dislocations, deformation twins and shear bands were almost parallelly distributed in the CG tube. The formation mechanisms of the different deformation microstructures were discussed. At 70% reduction, the circumferential and axial residual stresses of the CG tube were 201 MPa and 175 MPa, respectively, which were significantly lower than those (281 MPa and 238 MPa) of the EG tube. The uniform deformation and low residual stress in the CG tube contributed to the better cold-rolled performance and higher elongation than the EG tube.

1. Introduction

HAl77-2 aluminum brass (UNS C68700) alloy, as the material of condenser and heat exchanger tube, has been widely used in thermal power, petrochemical industry, desalination and other fields due to its high strength, good thermal conductivity and excellent corrosion resistance (Trostmann and Morin, 2010). During cold deformation, however, the alloy shows a high work hardening rate and its ductility drops remarkably. Therefore, repeated intermediate annealing and pickling are required during cold working of the alloy tube, resulting in some problems, such as long process, low product yield and high cost. In addition, high residual stress which is produced by cold deformation may cause cracks in brass alloy during further deformation (Wu et al., 1994) or stress corrosion (Ulaganathan and Newman, 2014). Improving the cold workability of the alloy and reducing the residual stress induced by cold deformation are effective methods to solve the above problems.

Hirsch et al. (1988) indicate that deformation twins and shear bands can be easily formed in the cold-rolled brass alloy due to its low stacking-fault energy (SFE). Because of the orientation dependence of deformation twinning (Christian and Mahajan, 1995), the possibility to develop deformation twin and the number of twins are different in the grains of equiaxed grain structure with random grain orientation, leading to significantly inhomogeneous deformation in these grains. Duggan et al. (1978) have reported that the shear strain is mainly concentrated in the shear band at large cold-rolled reduction, which also results in inhomogeneous deformation in the brass alloy. According to Rossini et al. (2012), the inhomogeneous deformation induces the increase of the residual stress, which reduces the formability, dimensional accuracy and service performance of the alloy.

Mo et al. (2014) show that the columnar grain HAl77-2 brass with strong <001> texture is deformed by homogeneous dislocation planar slip, and numerous uniform low-angle sub-grain boundaries form, when subjects to tensile deformation at room temperature.

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* Corresponding author at: Key Laboratory for Advanced Materials Processing of Ministry of Education, University of Science and Technology Beijing, Beijing 100083, China.

E-mail addresses: jiangyanbin@tsinghua.org.cn, jybin811@163.com (Y. Jiang).

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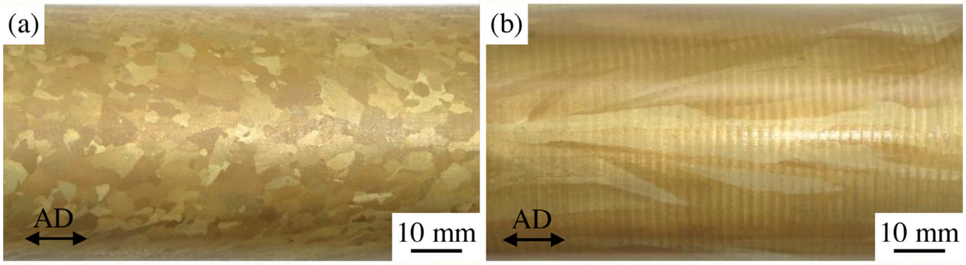

Fig. 1. External surface macrostructure of the as-cast tubes: (a) EG tube; (b) CG tube. (AD: axial direction).

Table 1
Processing parameters of HAl77-2 tubes fabricated by different methods.

Preparation method	T_M/°C	T_H/°C	$Q_1/(L\,h^{-1})$	$Q_2/(L\,h^{-1})$	$V/(mm\,min^{-1})$
Cooling mold casting	1100	–	400	400	110
HCCM casting	1100	1080	600	400	90

Note: T_M—melting temperature; T_H—mold heating temperature; Q_1—primary cooling water flow; Q_2—second cooling water flow; V—drawing speed.

The alloy shows an excellent plasticity with the elongation of more than 80%. Therefore, it is possible to achieve a large cold-rolled deformation of the columnar grain alloy tube. In the present work, HAl77-2 aluminum brass tubes with equiaxed grain structure and with strong axial-oriented (<001> orientation) columnar grain structure were prepared by the traditional horizontal continuous casting (cooling mold casting) and heating-cooling combined mold (HCCM) horizontal continuous casting (invented by Xie et al., 2011a), respectively. The influences of solidification microstructure on the deformation behavior, mechanical properties and residual stress of the tubes and the corresponding mechanism were studied.

2. Experimental methods

2.1. Preparation of the tube blank

HAl77-2 aluminum brass tube blanks with equiaxed grains and with strong axial-oriented columnar grains were prepared by the cooling mold casting and HCCM continuous casting, respectively. The outside diameter and thickness of the tubes were 50 mm and 5 mm, respectively. Chemical analysis results showed that the tube had the chemical compositions (in wt.%) of 77.0 Cu, 2.1 Al, 0.05 Pb, 0.05 Fe, and the balance Zn. The processing parameters of the tube produced by different casting methods are listed in Table 1.

The tube fabricated by cooling mold casting showed the equiaxed grain macrostructure on the external surface, as shown in Fig. 1a. On the other hand, the tube prepared by HCCM casting exhibited the axial (<001>) orientation columnar grains, and had smooth internal and external surfaces without any defects (internal and external surface roughnesses were 2.6 μm and 3.4 μm, respectively), as can be seen from Fig. 1b. For simplicity, the tubes produced by cooling mold casting and HCCM casting were named as equiaxed grain (EG) tube and columnar grain (CG) tube thereinafter, respectively.

2.2. Cold rolling of the tubes

The tubes were directly cold rolled by a three-roller pilger mill without preliminary surface milling and intermediate annealing. The cold rolling reduction (ε) of the tube was denoted by the change percentage of cross-sectional area before and after rolling. Cross-sectional dimensions (outside diameter × thickness) and the accumulative reduction of the rolled tubes are listed in Table 2.

2.3. Microstructure analysis

The longitudinal section samples were cut from the as-cast tubes and the rolled tubes. The samples were mechanically grinded, polished and etched by a solution of $FeCl_3$ 10 g + HCl 30 mL + H_2O 120 mL for metallographic observation, which was performed using a LV150 optical microscope (OM). Samples for electron backscattered diffraction (EBSD) analysis were electropolished in a chemical solution of 100 mL H_3PO_4 + 100 mL C_2H_5OH + 50 mL $CH_3CH_2CH_2OH$ + 250 mL H_2O. The microstructure and crystallographic orientation of the samples were detected by EBSD using SUPRA 55 scanning electron microscope (SEM) with a TSL-EBSD detector. For the transmission electron microscope (TEM) samples, longitudinal section samples with a thickness of 0.5 mm were cut from the tubes. The samples were grinded to 30–50 μm and thinned to perforation using twin jet electro-polishing in a solution of 100 mL HNO_3 and 200 mL CH_3OH, at −30 °C with an electric current of 45 mA. Microstructures of the samples were observed by TEM equipment FEI Tecnai F20.

2.4. Mechanical property and residual stress tests

The tensile samples were cut from the tubes by electrical discharge machining according to GB/T 228-2010 Standard (metallic materials—tensile testing—method of test at room temperature, 2010). Tensile tests were carried out by MTS material test machine at a strain rate of $1 \times 10^{-3}\,s^{-1}$ at room temperature. Three samples of each condition were tested and the average values were taken as the test results.

Residual stresses of the cold-rolled tubes were measured using the hole-drilling strain-gauge method. Due to the hole drilled on the surface of the tubes, the residual stresses were relieved. The corresponding relieved strains were measured using the electric resistance rosette strain gages (BX120-1CG) and displayed on a Sigmar ASM3.0 strain indicator. Fig. 2 shows a rosette strain gages bonded on the tube for residual stress measurement and the schematic view of the rosette strain gages.

Residual stresses are determined by three measured strains, ε_1, ε_2 and ε_3 ($\mu\varepsilon$) (Fig. 2b) based on the elastic mechanics. The principal residual stresses (σ_1 and σ_2, MPa) in the tubes can be calculated by the following equations (Anawa and Olabi, 2008):

$$\sigma_1 = \frac{E}{4A}(\varepsilon_1 + \varepsilon_3) + \frac{E}{4B}\sqrt{(\varepsilon_1 - \varepsilon_3)^2 + (2\varepsilon_2 - \varepsilon_1 - \varepsilon_3)^2} \qquad (1)$$