Structural change and improvement of the mechanical properties of a lotus-type porous copper by wire-brushing

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Abstract. The surface of lotus-type porous copper plates that had cylindrical open pores in the thickness direction (porosity 50.4%, average pore diameter 144.4 µm) were processed by wire-brushing. Open pores on the surface of the lotus copper are closed by a newly formed nonporous thin layer. Electron backscatter diffraction patterns of the processed plate cross section show that the deformed surface consists of ultra-fine grains and that a nonporous layer was formed on the deformation of the surface layer. The Vickers hardness of the wire-brushed lotus copper is higher than that of the wire-brushed non-porous copper. The Vickers hardness increases with the increase in the rate of revolution of the wire-brush due to grain refinement. The increment of the ultimate tensile strength of lotus copper by wire-brushing is larger than of non-porous copper. The increment of ultimate tensile strength of the lotus copper reaches maximum when the newly deformed layer closes all the pores on the surface. These results show that wire-brushing is an effective process for the improvement of mechanical properties for lotus metals.

1. Introduction

Porous metals have been actively studied in recent years because of their promising properties such as light-weight, vibration and acoustic energy damping, and impact energy absorption [1]. However, for many kinds of porous metals the specific strength decreases with increasing porosity because spherical pores cause stress concentrations. On the other hand, lotus-type porous metals with long cylindrical pores aligned in one direction have superior mechanical properties compared with porous metals with spherical pores. The specific strength does not decrease with increasing porosity in the pore growth direction [2]. Therefore, lotus metals are expected to be used as light-weight structural materials.

However, as lotus metals are fabricated by solidification processes, their as-cast microstructure have lower strength than that of commonly used structural materials, which is usually produced by plastic forming. It is, therefore, desirable to deform the metallic matrix of lotus metals without causing a severe change in the porous structure during plastic deformation.

It was reported that the Vickers hardness of lotus copper increases by ECAE (equal-channel angular extrusion) with a remnant porous structure [3], which showed the effect of severe plastic deformation on the improvement of lotus metal strength. Recently, the wire-brushing process is also
considered to be an effective method for use in the severe plastic deformation of bulk metals. It was reported that wire-brushed nonporous metals have fine-grained surfaces [4,5]. This process is expected to provide severe plastic deformation to the metallic matrix of lotus metals without destroying the porous structures.

For these reasons, lotus copper plates were processed by wire-brushing. The effects of angular velocity of the wire-brush on mechanical properties such as the Vickers hardness and the ultimate tensile strength were investigated. An improvement of mechanical properties is discussed considering the structural change in the lotus copper plates.

2. Experimental

2.1. Fabrication of lotus copper
A lotus copper ingot was fabricated by the mould casting technique [2]. Copper ingots were melted in a pressurized hydrogen atmosphere of 0.5 MPa. Inside the chamber, the melt was poured into a mould and was solidified unidirectionally. Because of the solubility gap of hydrogen between solid and liquid phases the pores evolved in the solidification direction. The fabrication process of the lotus copper ingot resulted in pore alignment in the direction of the cylinder’s axis. The lotus copper had a porosity of 50% and an average pore diameter of 144 µm.

2.2. Samples for the tensile test
The cylindrical lotus copper ingot was sliced into disks of 2.1 mm in thickness and 100 mm in diameter. The pores were orientated in the direction of the thickness and open pores were visible on the surface. Tensile test samples were cut and had a length of 80 mm (25 mm for the test part) and a width of 10 mm (6.5 mm for the test part). Some samples were not processed and were used as reference materials for tests of the mechanical properties.

2.3. Wire-brushing
A schematic illustration of the wire-brushing process used in this study is shown in Fig. 1. A lotus copper plate in the shape of the tensile specimen was fixed on a table. On the surface of the plate, a rotating stainless steel wire cup brush (grade CN-16, length of the wires was 18 mm and the diameter 0.3 mm, the cup diameter was 70 mm) was transferred in the direction of the sample’s width. The rate of revolution of the wire-brush was set at 2500, 3750 or 5000 rpm. The transference velocity was set so that the revolutions per unit length, were constant at 100 mm⁻¹. The wire-brush was rotated clockwise as observed from the upper side and the axis of the wire-brush was tilted 7 degrees from the vertical during movement. Only half of the circumferential part of the wires hit the sample.

![Figure 1. Schematic illustration of the wire-brushing process of a lotus copper plate.](image)

2.4. Evaluation of the processed samples
The Vickers hardness was measured on the processed surface of the lotus copper plates by a hardness tester (AKASHI MVK-III). The testing force was 5~10 N and the testing time was 20 s. Ten points on
the same sample were tested and statistical processing was made. The tensile tests were carried out using a universal testing machine (INSTRON 5582). The crosshead speed was set at 2 mm min⁻¹. From the obtained stress-strain curve, the ultimate tensile strength was measured. The tensile tests were performed four times for each processing condition and statistical processing was done.

Mechanical properties of nonporous copper plates, before and after the wire-brushing, were also measured as reference data.

The surface of the processed lotus copper was observed with a digital microscope (KEYENCE VHX-200). The microstructure of processed lotus copper plate cross sections was observed with a FE-SEM JEOL 9800 and EBSD analyzer Tex SEM Labo. Inc. MSC-2200.

3. Results and discussion

Figure 2 shows the Vickers hardness of the lotus copper surface and the nonporous copper surface versus the angular velocity of the wire-brush. For both cases, the Vickers hardness increased after the wire-brushing process. The Vickers hardness of lotus copper after wire-brushing at a rate of revolution of 5000 rpm was higher than that of the nonporous copper. The Vickers hardness values of the lotus copper and the nonporous copper before wire-brushing (0 rpm) were similar. These results suggest that the deformation behaviour of the lotus and the nonporous copper are different as explained below.

In the case of the lotus copper, the Vickers hardness increases with an increase in the rate of revolution. For severe plastic deformation, it is known that an increase in strain causes an increase of Vickers hardness. Higher strain is obtained by a higher angular velocity of the wire-brush because of its higher kinetic energy.

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\Delta \sigma_{\text{UTS}} / \sigma_{\text{UTS}} = (\sigma_{\text{UTS}} \text{ of the wire-brushed sample} - \sigma_{\text{UTS}} \text{ of the as-cast sample}) / (\sigma_{\text{UTS}} \text{ of the as-cast sample}) \quad (1)
\]

For the nonporous sample, there is no significant change in the strain-stress curves between wire-brushed and as-cast samples, as can be seen in previous work [4,5]. The reason is that the grain refinement in a layer of only several tens of μm in thickness does not affect the mechanical properties of a bulk sample of several mm in thickness. On the other hand, there is an increase in all the samples of the lotus copper. Furthermore, the change in tensile strength is dependent on the angular velocity. The strength increases up to 3750 rpm and then decreases. This trend is different to that of the Vickers hardness.

Figure 2. The Vickers hardness on the surface of the lotus copper and the nonporous copper at different rates of revolution.
Figure 3. Changes in the ultimate tensile strength ($\Delta \sigma_{UTS}$) of the wire–brushed samples.

To investigate the increase of the tensile strength by wire-brushing and the angular velocity dependence of the tensile strength the surface and the cross sections of the processed lotus copper plate were observed and the grain size was analyzed.

Surfaces of the processed samples were changed by a change in the rate of revolution. At 2500 rpm, many pores were closed and large pores remained after wire-brushing. At 3750 rpm almost all the pores were closed. However, large pores were opened again at 5000 rpm.

The cross section of the processed sample showed that the thickness of the layer, which covers the top of the pores is 80~100 µm. EBSD mapping showed that the grain size is smaller than 80 nm in the top part of this layer, several hundred nm in the middle and a few µm in the bottom. The deformed layer on the metallic part near the pores was around 50 µm in thickness, while that on the metallic part, apart from the pore, was 20µm in thickness. This is similar to the results of wire-brushed nonporous metals [4,5].

These results suggest that metallic parts near the pores can be deformed easily toward the pore side. In the case of lotus copper, a layer of fine grains was generated because of the large strain of the metal near the pores. The strain increases with increasing angular velocity of the wire-brush and then some part of surface was removed at a higher velocity which decreases strength.

4. Summary

A severe plastic deformation by a wire-brushing process increased the hardness and the strength of lotus copper by the formation of a nonporous skin layer with fine-grained crystals that closed the top of the pores. This process forms a sandwich structure consisting of a lotus metal plate with two fine-grained nonporous layers. The effect of angular velocity of the wire-brush on the hardness of the surface and the tensile strength of the processed lotus copper was investigated by considering the structural change.

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