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Influence of the explosive treatment on the mechanical properties and microstructure of copper

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ABSTRACT

The manuscript discusses mechanical properties and microstructure of copper before and after the explosive treatment. The aim of this research was to characterize and evaluate the influence of explosive treatment which is present during the manufacturing procedure of a new type of unidirectional cellular structure. For this purpose testing of tensile copper specimens before and after explosive treatment has been performed, accounting also for strain rate sensitivity. The experimental measurements have been supported by the 3D optical deformation measurement system and infrared thermography. The effect of the explosive treatment on coppers' microstructure has been analysed using the electron microscopy. The study shows that the explosive treatment significantly influences the global response of copper throughout the complete loading range. All specimens exhibit a positive strain rate sensitivity. The uniform distribution of principle strain in untreated specimens is replaced by strain localization which appears just after the start of the loading resulting in much lower failure strain. The observations of microstructure before and after explosive treatment revealed that explosive loading resulted in intensive fragmentation of grains that are enriched with sub-grain layered structure. Such grain size refinement is the main contributor to strengthening of the explosive treated copper.

1. Introduction

Copper is an attractive material for various engineering applications due to its mechanical and thermal properties, which are very well defined. A new type of cellular structure material [1–3] made of copper with unidirectional pores (UniPore) has been developed at Kumamoto University [4] in attempt to reduce the scatter of mechanical properties which is typical for conventional industrial cellular materials where the shape, size and distribution of cellular pores cannot be fully controlled. Although some recently developed fabrication methods of cellular metals result in more homogeneous pore structures [5–10], the new UniPore cellular structure exhibits more regular distribution of long unidirectional pores with constant pore size and wall thickness. The UniPore structure is manufactured by explosive compaction where copper thin-walled tubes are compressed together forming a cellular structure with straight unidirectional pores. The manufacturing procedure consists of the following steps (Fig. 1): (i) the outer pipe is tightly packed with thin-walled inner copper pipes of much smaller diameter, (ii) the inner pipes are filled with paraffin wax preventing their complete compaction at compressive blast loading, (iii) the structure is evenly coated with the explosive layer and placed in the centre of an explosive chamber, (iv) the explosive charge is detonated and high pressure blast loading causes compaction of the structure, where the outer and inner pipes walls are bonded together by diffusion and (v) the removal of paraffin wax by heat treatment. So far, specimens with the outer diameter of approx. 25 mm and 200 mm in length have been manufactured [2,4]. The porosity can be adjusted by the thickness of the inner walls (from 0.2 to 0.5 mm). The advantageous regular geometrical properties of the resulting UniPore structure together with its particular and unique mechanical [2] and thermal [11] properties provide many opportunities for its application in modern engineering and other structures.

The effects of high pressure due to explosive detonation on copper have been of some research interest since 1950s [12]. The copper hardening phenomena has been investigated [13–15] and the

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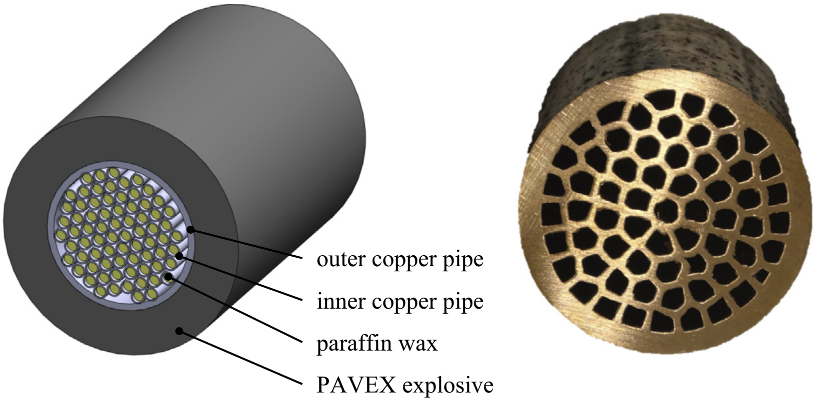

Fig. 1. Manufacturing setup (left) and the final UniPore copper product (right).

increase of hardness has been confirmed under higher pressure condition, caused by the dislocations and other micro-defects spread in the material. Remarkably higher shock hardening effect for oxygen-free high-conductivity copper than the effect of work hardening has been observed [12].

During explosive compaction of UniPore structure the base material (copper) is exposed to extremely high pressure within a very short time frame, which causes intensive dynamic plastic deformation of copper at high strain rates. Severe plastic deformation is accompanied by intensive fragmentation of grains; the formation of disoriented nanostructural fragments with accumulation of complex system of dislocation and disclination type defects at inner interfaces [16]. The state of the copper microstructure after explosive treatment can be therefore referred to as "the metastable state", which strongly influences its mechanical properties. Namely, the metastable state of material with higher Gibbs free energy depends on thermodynamic stability of the microstructure and is closely connected with concentration of its constitutive elements (phases, defects in the crystal lattice, grain boundaries). Increasing concentration of defects in the crystal lattice decreases thermodynamic stability of the microstructure. Depending on the external influential parameters, specific reactions and changes take place in such metastable system, which cannot be predicted or anticipated by known equilibrium transformations. Consequently, new phases and microstructures, which cannot be found in the equilibrium phase diagram, come into existence. While the properties of materials are mainly dependent on the microstructure, it is possible to attain new special properties for engineering materials by inducing the highly metastable states. At the same time, the metastable microstructure influences also the mechanism of reactions and plastic deformation in materials. Therefore, characterization of the microstructure metastable state formed during various processing technologies continuously engages the curiosity of scientists.

To better understand the macroscopic mechanical properties of the UniPore cellular structure and the effect of explosive treatment on pure copper, a set of tensile specimens made of copper before and after the explosive treatment has been subjected to quasi-static and dynamic loading. A detailed deformation analysis has been performed using the 3D optical deformation measurement system GOM ARAMIS [17] capable of tracing surface particles during the deformation process [18–20]. The effect of the explosive treatment on copper and its microstructure has been analysed by using the electron microscopy. As plastic yielding is accompanied by significant heat energy dissipation, the infrared (IR) thermography technique was also used to trace strain localization and propagation of localization bands and plastification fronts [21,22]. The high-speed IR camera enabled capturing thermographic images during dynamic loading conditions (loading velocity of approx. 300 mm/s) with short loading periods where influence of heat dissipation is minor.

2. Sample preparation

Six copper plate specimens measuring 100 × 200 × 3 mm were used for subsequent mechanical and microstructural characterization of pure copper before and after explosive treatment, with three of them subjected to explosive treatment.

The experimental set-up of explosive treatment is shown in Fig. 2. The main components are the flyer plate made of copper and the anvil (thick steel block). Four small distance spacers have been placed at corners of the flyer plate to achieve desired displacement and deformation of the copper plate. To avoid metallic bonding (welding) between the flyer plate and the anvil a thin polymer film has been placed on the anvil [23].

The powder explosive PAVEX (Table 1) has been used for each explosive treatment experiment, where the explosive was detonated with the electric detonator [24]. Both were supplied by Kayaku, Japan, Co., Ltd, and are used also for the explosive compaction of the UniPore structure.

To determine the maximum pressure to which the flyer plate has been exposed, the dynamic bending angle β and the flyer plate velocity V_p have to be calculated first. The dynamic bending angle for a powder type explosive can be predicted with the Deribas' equation [24,25]:

$$\beta = \left(\sqrt{\frac{k+1}{k-1}} - 1\right) \cdot \frac{\pi}{2} \cdot \frac{r}{r + 2.71 + 0.184 \cdot t_e/s}, \tag{1}$$

where $t_e = 30$ mm is the explosive layer thickness, $s = 5$ mm is the stand-off distance between the copper plate and the anvil and $r = 0.616$ is the loading ratio (mass of explosive per unit mass of flyer plate) and the parameter $k = 2.21$ for the explosive thickness $t_e = 30$ mm [24]. The dynamic bending angle evaluated with Eq. (1) is equal to $\beta = 7.87°$.

The flyer plate velocity can be estimated with the well-known equation [12,25]:

$$V_p = 2 \cdot V_d \sin(\beta/2), \tag{2}$$

where V_d is the explosive detonation velocity (Table 2). The flyer plate velocity is thus estimated to be $V_p = 313$ m/s.

The pressure at the moment of collision between the copper flyer plate and the steel base is defined by the following relations [12]:

$$P_{steel} = \rho_{steel}(C_{steel} + S_{steel}U_p)U_p, \tag{3}$$