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Comparison of microstructures in electroformed and spin-formed copper liners of shaped charge undergone high-strain-rate deformation

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Abstract: The as-formed and post-deformed microstructures in both electroformed and spin-formed copper liners of shaped charge were studied by optical microscopy(OM), electron backscattering Kikuchi patterns(EBSP) technique and transmission electron microscopy(TEM). The deformation was carried out at an ultra-high strain rate. OM analysis shows that the initial grains of the electroformed copper liner are finer than those of the spin-formed copper liners. Meanwhile, EBSP analysis reveals that the fiber texture exists in the electroformed copper liners, whereas there is no texture observed in the spin-formed copper liners before deformation. Having undergone high-strain-rate deformation the grains in the recovered slugs, which are transformed from both the electroformed and spin-formed copper liners, all become small. TEM observations of the above two kinds of post-deformed specimens show the existence of cellular structures characterized by tangled dislocations and subgrain boundaries consisting of dislocation arrays. These experimental results indicate that dynamic recovery and recrystallization play an important role in the high-strain-rate deformation process.

Key words: microstructures; copper liners; high-strain-rate deformation; dynamic recovery and recrystallization

1 Introduction

Previous studies have investigated the effect of purity of liner materials[1−3] and other factors on the liner properties[4−5]. The formation technique of shaped charge liners has been described in Refs.[6−7]. Also some investigations focused on determining the influence of surface finish[8]. Experiments have shown that changes in the microstructures, especially in grain size, of the copper liners are related to the penetration depth attained during explosive detonation deformation. Notable reduction in grain size in liners was proven to improve penetration depth dramatically. Therefore, the grain size of liner materials, which mainly relies on the formation technology, is an important factor that affects the penetration depth of the liners.

In this study, we focus mainly on comparing the microstructures of copper shaped charges prepared by two kinds of forming technique, i.e., electroforming and spin-forming techniques, to make sure the influence of the different formation technology on the microstructures and subsequent penetration behavior of copper liners. Meanwhile, investigation and comparison of the plastically deformed microstructures attained at high strain rate in the recovered slug initiated from the two kinds of copper liners by transmission electron microscopy(TEM) and optical microscopy(OM) provide a detailed overview of residual microstructures and microstructure changes before and after explosive detonation deformation in order to understand deformation mechanism at high strain rates (10^3−10^7 s^{-1}).

2 Experimental

The processes of explosive detonation deformation and electro-forming were reported in Refs.[6−7]. The as-formed specimens with a size of 5 mm in length, 4 mm in width and 3 mm in thickness, were cut from the electro-formed and spin-formed copper liners of shaped

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charge, respectively. The post-deformed specimens with the same size of the as-formed specimens were cut along the longitudinal axis of the slugs that exhibit an irregular cylinder in shape after withdrawing from the steel target after finishing the explosive detonation. All surfaces of both as-formed and post-deformed specimens were mechanically polished with emery paper carefully and then were electropolished using 70% H_3PO_4+30% H_2O electrolyte at 293 K in order to remove the strain induced by mechanical polishing. All specimens were firstly examined by an optical microscope.

Crystallographic analyses of the grains in the as-formed specimens were carried out by SEM equipped with EBSP analysis system, Oxford Link-OPAL. In order to accurately determine the orientation of every grain in various directions, especially in the normal direction, the specimens were firstly examined by secondary-electron imaging so as to distinguish the grain boundary. This enabled illumination of the electron beam onto a single grain, from which the EBSP was initiated. More than 200 grains for each specimen were analyzed in this way. The pole figure and inverse pole figure were obtained at various crystal orientations.

Thin plates of about 0.3 mm in thickness were cut from the as-formed copper liners, with the plates disposed parallel to the surface of the liner. For the recovered slug, thin plates of the same thickness were cut along the longitudinal axis of the irregular cylinder. All thin foils for TEM observation were prepared by a mechanical thinning method using emery paper, and were then jet-polished by a standard double-jetting electro-polishing method using 70% H_3PO_4+30% H_2O or 20% HNO_3+80% CH_3OH electrolytes at ambient temperature. The electron microscope, which was used for microstructure observation, was model JEM−200CX equipped with a goniometer tilting stage and operated at 200 kV.

3 Results and discussion

3.1 Microstructure and texture of electroformed and spin-formed specimens before deformation

Fig.1 shows the optical metallographic observation of the electro-formed copper liners of shaped charge before deformation. It can be seen that the electro-formed specimen has mainly uniform equiaxial grains. Average grain size is about 2 μm. Fig.2 shows the optical metallographic observation of the spin-formed copper liners of shaped charge before deformation. The grains of the spin-formed specimen are elongated in the direction of the shear stress during spin-formation. The grain size is about 200 μm in long direction and about 20 μm in short direction that is much larger than that in electro-deformed liner. It is clear that the shape of the

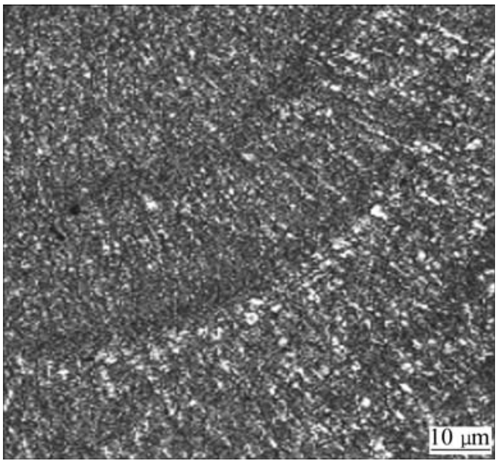

Fig.1 Optical metallographic view of electro-formed copper liners of shaped charge

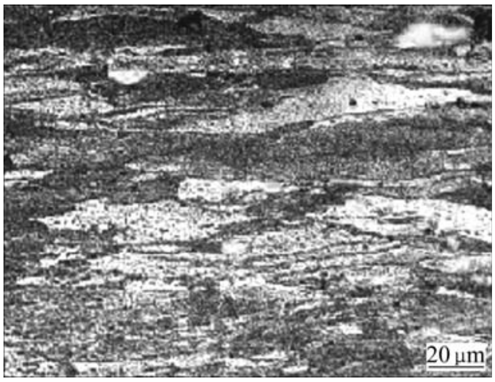

Fig.2 Optical metallographic view of spin-formed copper liners of shaped charge

grains in the two types of liners is also different. The explosive detonation behavior of the electro-formed copper liners of shaped charge is improved because of its finer grains[9−10].

Along the normal directions of the copper liner of shaped charge, the distribution of crystallographic orientations were investigated by EBSP technique. Fig.3 shows {110} pole figure and inverse pole figure of the electro-formed copper liner of shaped charge before deformation, containing 200 measured grains lying on a line along the normal direction of the cone. Fig.3(a) shows that spots are distributed on two ringed areas with definite width and concentrated on [110] direction. Fig.3(b) indicates that the orientation of the grains normal to the copper liner of shaped charge concentrates on the [101] corner. It is clear that the grains are oriented preferentially in the normal direction, and the specimen has <110> fiber texture.

Fig.4 shows the {110} pole figure and inverse pole figure of the spin-formed copper liner of shaped charge, containing 200 measured grains lying a line along normal direction of the cone. There is not distinct spot concentration and ring observed on the pole figure, nor

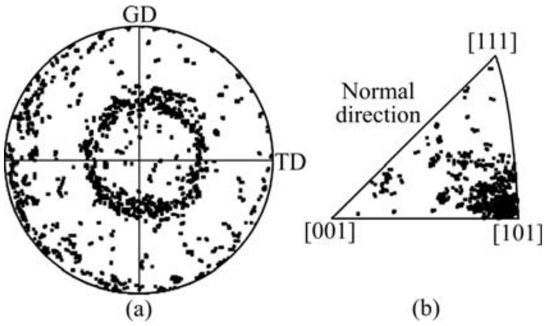

Fig.3 {110} pole figure (a) and inverse pole figure (b) of electro-formed copper liner of shaped charge before deformation

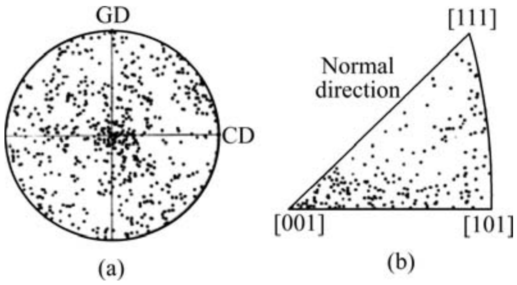

Fig.4 {110} pole figure (a) and inverse pole figure (b) of spin-formed copper liner of shaped charge before deformation

inverse pole figure. The fact that spots, which show the orientation of the grains, distribute randomly on the pole figure and inverse pole figure, indicates that there is not grains oriented preferentially in the normal direction. That is, the spin-formed copper liner of shaped charge has not almost any texture.

3.2 Microstructure and dislocation cell of electro-formed and spin-formed specimens after deformation

After the copper liners have undergone explosive detonation deformation, the slugs were withdrawn from the steel target and the ending microstructure in the recovered copper slug was examined. Fig.5 shows the optical metallographic view of the recovered slug initiated from electro-formed copper liner. It can be seen that the grains are equiaxial and the grain size has almost the same order as that before deformation. This result is consistent with the previous study[11]. Fig.6 shows the optical metallographic view of the recovered slug initiated from spin-formed copper liner. It is clear that the grains become dramatically fine and equiaxial as comparing with the elongated grains before deformation. By comparing Fig.5 with Fig.6, it is clear that their microstructures are very similar except that the equiaxed grain size of the electro-formed slug is finer than that of the spin-formed slug. MURR et al[12] have investigated the beginning grain size in forged and sputtered metal

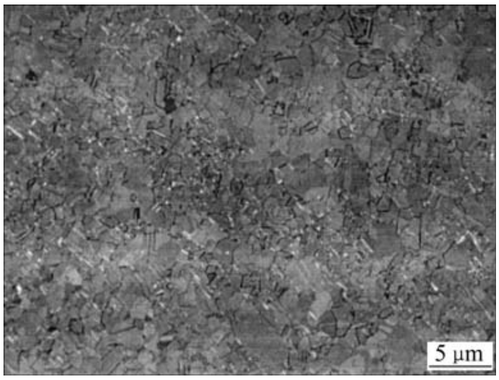

Fig.5 Optical metallographic view of electro-formed copper liners of shaped charges after deformation

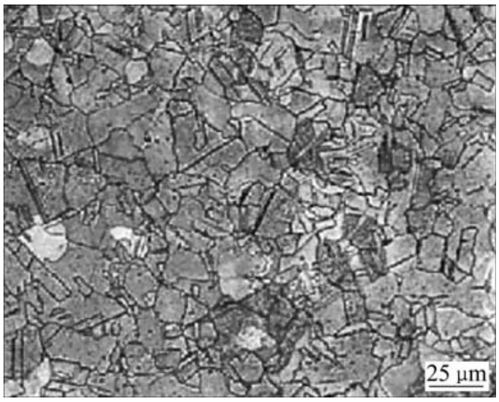

Fig.6 Optical metallographic view of spin-formed copper liners of shaped charges after deformation

liners of shaped charges and the ending microstructure of recovered jet fragment and slug. They point out there is a systematic change between the starting grain size in the liner(D_0) and the ratio of ending/starting grain size (D_0/D_s). They found that at sufficiently small starting liner grain size, the steady-state grain size in the elongating jet and slug would approach some constant value. This value appears to be around 1 μm. They indicated that dynamic recovery and recrystallization played a significant role in the deformation process, especially since the associated process temperature was considered to be $>0.6\ T_M$ (T_M is the melting point of the metal). The present study also gives evidence that the shape and size of the grains in spin-formed liner of shaped charge have changed after undergoing the explosive detonation deformation. That is, the grains in the liner materials have re-adjusted during explosive detonation deformation.

Fig.7 shows the TEM bright field image taken from the recovered slug after explosive detonation deformation, which was initiated from electroformed copper liner. The substructures and subcells around which a dislocation cell wall is formed can be observed. Cell structure is formed by tangled dislocations, and sub-

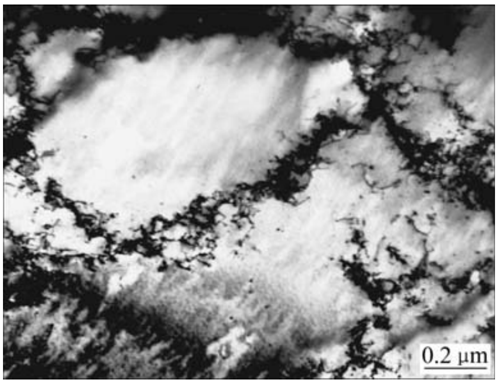

Fig.7 TEM bright-field image showing cell dislocation in electro-formed copper liner of shaped charge after deformation

grain boundaries are constituted by aligned dislocation. But inside the grains no dislocations can be observed. This observation result indicates that a typical dynamic recovery and recrystallization occur during plastic deformation process at high strain rate.

Fig.8 shows the TEM bright field image taken from the recovered slug after explosive detonation deformation, which was initiated from spin-formed copper liner. The microstructure is extraordinarily similar to that as shown in Fig.7. These results reveal that dynamic recovery and recrystallization play an important role in deformation process at high strain rate, whatever in electro-formed or in spin-formed copper liners of shaped charge.

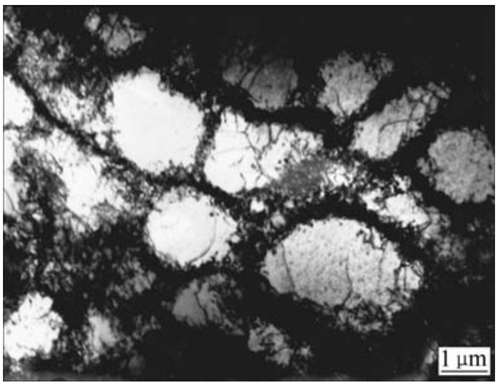

Fig.8 TEM bright-field image showing cell dislocation in spin-formed copper liner of shaped charge after deformation

4 Conclusions

1) The grain size of electro-formed copper liners of shaped charges is finer than that of the spin-formed copper liners of shaped charges. The shape of the grains in spin-formed liner of shaped charge is elongated in the direction of shear stress while that in electro-formed liners of shaped charge is equiaxial. In electro-formed copper liner of shaped charge, there exists a <110> fiber texture that is normal to the surface of the copper liners, whereas no texture is observed in the spin-formed copper liners of shaped charge.

2) After undergoing high-strain deformation at an ultra-high strain rate (10^7 s^{-1}), the grains of the electro-formed and spin-formed recover copper slugs, all become equiaxed in shape. This result indicates that the grains have re-nucleated and re-grown during explosive detonation deformation.

3) The dynamic recovery and recrystallization play a significant role in deformation process at high strain rate during explosive detonation deformation.

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