Journal of University of Science and Technology Beijing
Volume 9, Number 5, October 2002, Page 343

Dynamic recrystallization of electroformed copper liners of shaped charges in high-strain-rate plastic deformation

Wenhuai Tian[1), *Hongye Gao*[1), *Ailing Fan*[1), *Xiaoou Shan*[1), *and Qi Sun*[2)

1) Department of Materials Physics and Chemistry, University of Science and Technology Beijing, Beijing 100083, China
2) Beijing 210 Institute, Beijing 100081, China(Received 2002-01-29)

Abstract: The microstructures in the electroformed copper liners of shaped charges after high-strain-rate plastic deformation were investigated by transmission electron microscopy (TEM). Meanwhile, the orientation distribution of the grains in the recovered slug was examined by the electron backscattering Kikuchi pattern (EBSP) technique. EBSP analysis illustrated that unlike the as-formed electroformed copper liners of shaped charges the grain orientations in the recovered slug are distributed along randomly all the directions after undergoing heavily strain deformation at high-strain rate. Optical microscopy shows a typical recrystallization structure, and TEM examination reveals dislocation cells existed in the thin foil specimen. These results indicate that dynamic recovery and recrystallization occur during this plastic deformation process, and the associated deformation temperature is considered to be higher than 0.6 times the melting point of copper.

Key words: electroformation; high-strain-rate deformation; dynamic recovery and recrystallization; transmission electron microscopy; electron backscattering diffraction

[*This work was financially supported by the National Natural Science Foundation of China (No.59971008).*]

The liner of shaped charge is used in the military as an armor penetrator. During deformation after explosive detonation, a metal liner of shaped charge forms an elongating jet. A copper jet about 1.5 mm in diameter, 0.5 m long, and traveling near $8\ \mathrm{km}\cdot\mathrm{s}^{-1}$ can form a 2 cm diameter hole in a mild steel target. This deformation procedure represents one of the most severe examples of plastic deformation, where strain varies from 500% to more than 1 000% at strain rates between $10^4\ \mathrm{s}^{-1}$ and $10^7\ \mathrm{s}^{-1}$.

The objective of this investigation is to examine the growth orientation of the grains in electroformed copper liners of shaped charges and the grain-orientation distribution in recovered slugs by determining the orientations of most grains in bulk specimens with EBSP. The microstructure of a single recovered copper slug was observed by optical microscopy and TEM. The scanning electron microscopy (SEM) equipped with EBSP analysis system was also used to provide a detailed overview of residual slug microstructures after high-strain-rate plastic deformation. Discussion on the deformation mechanism under such high strain at high-strain rate condition will be presented.

1 Experimental procedure

When undergoing a tremendous stress during the explosive process, the electroformed conical copper liners of shaped charges collapse and produce a jet to penetrate the target. This is a typical high strain and high strain rate deformation. The effective strain can reach 500% to 1 000% and the maximum strain rate can reach $10^7\ \mathrm{s}^{-1}$. **Figure 1** shows the deformation stages [1] involving the explosive shock loading of the metal liner (1) (at peak pressures ranging from about 30 GPa to 50 GPa); liner collapse (2); pressurization and release at the so-called stagnation region (3) (where the pressure can reach a peak value near 100 GPa); elongation (or stretching) of the metal jet (4); and jet breakup (5).

Figure 2 (a) shows schematically the recovered cop-

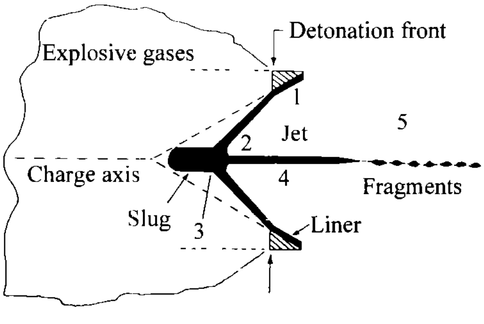

Figure 1 Schematic view of copper liner of shaped charge undergoing explosive detonation. The deformation is divided into stages 1-5.

Corresponding author: Wenhuai Tian **E-mail**: wen huaitian@sina.com

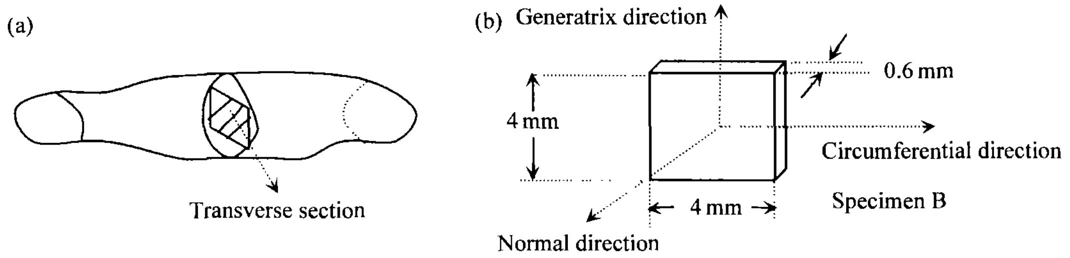

Figure 2 Schematic illustration showing the geometry of (a) recovered copper slug and (b) specimen cut from the recovered copper slug by EBSP technique.

per slug which was extracted from the steel target after undergoing high-strain-rate plastic deformation. The shape of the recovered copper slug exhibits as an irregular cylinder. The recovered slug was firstly subjected to optical microscopy examinations. Figure 2 (b) shows the shape and the size of the specimen to be used for grains orientation examination by EBSP technique. The specimen was cut from the recovered copper slug and the normal direction of the specimen is corresponding to long axis of the slug. In this study, the two directions which are perpendicular to the long axis of the irregular cylinder were referred as generatrix direction and circumferential direction.

Crystallographic analyses of the grains in the recovered slug were carried out by SEM equipped with EBSP analysis systems, Oxford Link-OPAL. To accurately determine the orientation of every grain, especially the normal direction of every grain the specimen was first carefully examined by the use of secondary-electron imaging in order to recognize the grain boundaries. This allowed the 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 such a way. The pole figure and the inverse pole figure were obtained at various crystal orientations and the most preferential growth direction of the grains was determined by the use of computation software.

Thin plates of about 0.3 mm thickness were cut along the long axis of the irregular cylinder. All the thin foils for TEM were prepared by standard double-jetting electro-polishing method using a 20% nitric acid, 80% methanol electrolyte (volume fraction) at 273 K. The electron microscope was JEM-200CX equipped with a goniometer tilting stage and operating at 200 kV.

2 Results and discussion

2.1 EBSP analyses

After plastic deformation of the electroformed copper liners of shaped charges at ultra-high strain rate by explosive detonation, the recovered copper slug withdrawn from the target was examined for the consequent microstructure and microtexture, by SEM, TEM, and EBSP. **Figure 3** is the (001) pole figure containing 200 measured grains along the normal direction. It can be seen that the data are distributed randomly on the pole figure. **Figures 4** (a)-(c) show the inverse pole figures for all the 200 analyzed grains in the specimen cut from the recovered slug along the normal direction (a), generatrix direction (b) and circumferential direction (c) of the recovered copper slug, respectively. The figures show that all the analyzed grains in the specimen in all the three major directions are randomly distributed. This observation clearly indicates that the fibrous texture which exists in as-electroformed copper liners of shaped charges [2] disappears after high-strain plastic deformation at high strain rate.

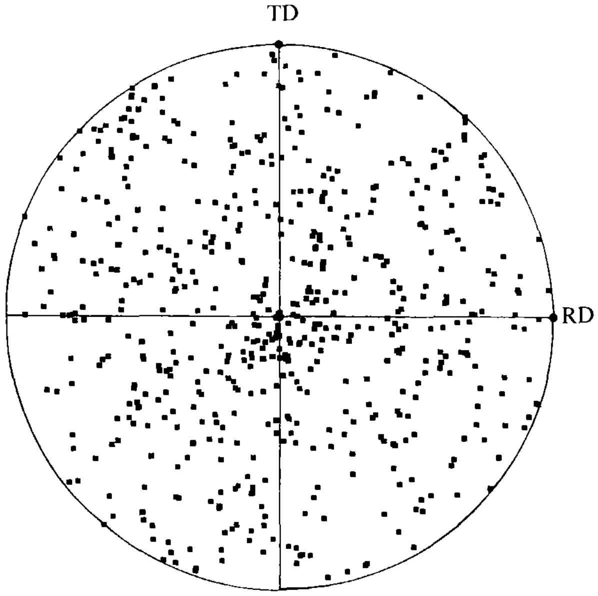

Figure 3 (001) pole figure containing 200 grains along the normal direction of the specimen cut from the recovered copper slug after ultra-high-strain-rate deformation.

2.2 Optical microscopy observations

Figure 5 is the optical metallographic view of the recovered copper slug. It can see that the grains are equiaxed and the grain size has almost the same order as that before deformation [2]. Murr *et al.* [3] investigated the beginning grain size in forged and sputtered metal liners of shaped charges and the ending microstructure

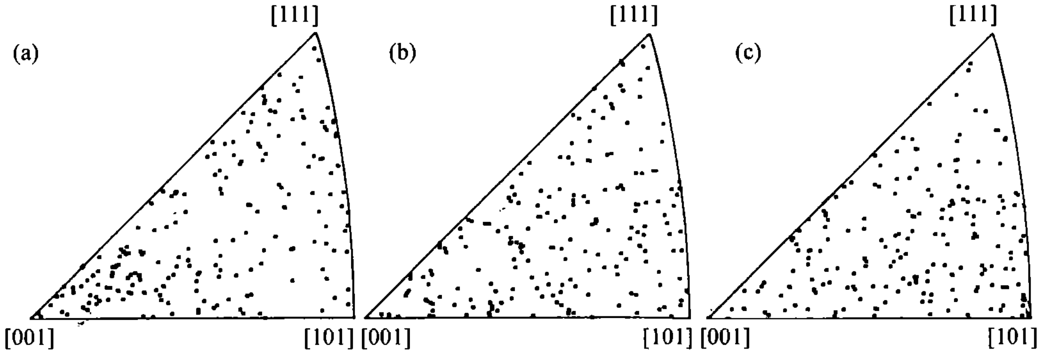

Figure 4 Inverse pole figures of 200 grains in the (a) normal direction, (b) generatrix direction and (c) circumferential direction of the recovered copper slug.

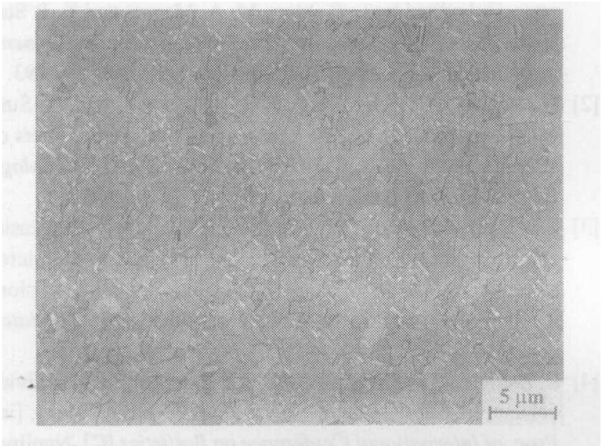

Figure 5 Optical metallographic image taken from the recovered copper slug.

of recovered jet fragment and slug. They pointed out there is a systematic relationship between the starting grain size in the liner (D_0) and the ratio of starting/ending 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 shell approach some constant value. This value appears to be around 1 μm. They indicated that dynamic recovery and recrystallization play a significant role in the deformation process, especially since the associated process temperatures were considered to be $>0.6T_M$ (T_M is the melting point of the metal). The present observation result by optical microscopy clearly shows a typical recovery and recrystallization structure.

2.3 TEM observations

Figures 6 (a) and (b) show the TEM bright-field image and the electron diffraction pattern, respectively, taken from the specimen cut from the recovered slug. The substructures and sub-cells around which a dislocation cell wall is formed can be observed. Cell structure formed by tangled dislocations. Sub-grain boundary is constructed by dislocations lined up at the boundary. But inside the grain no dislocation can be observed. These results indicate that the grains in the electroformed copper liners of shaped charges have re-nucleated and re-grown during explosive detonation deformation. Zernow [4] and Zernow and Lowry [5] observed a similar structure in a recovered jet fragment and slug. Besides the dislocation cells, voids and porosity have also been observed in the thin foil specimen. Kiritani *et al.* [6,7] found that a large amount of vacancy clusters are observed in heavily deformed thin metal foil. The formation mechanism of voids is on the way of continuous study.

Comparison of the microstructure between the starting copper liners of shaped charges [2] and the ending copper slugs clearly shows that recovery and recrystallization indeed played an important role in high

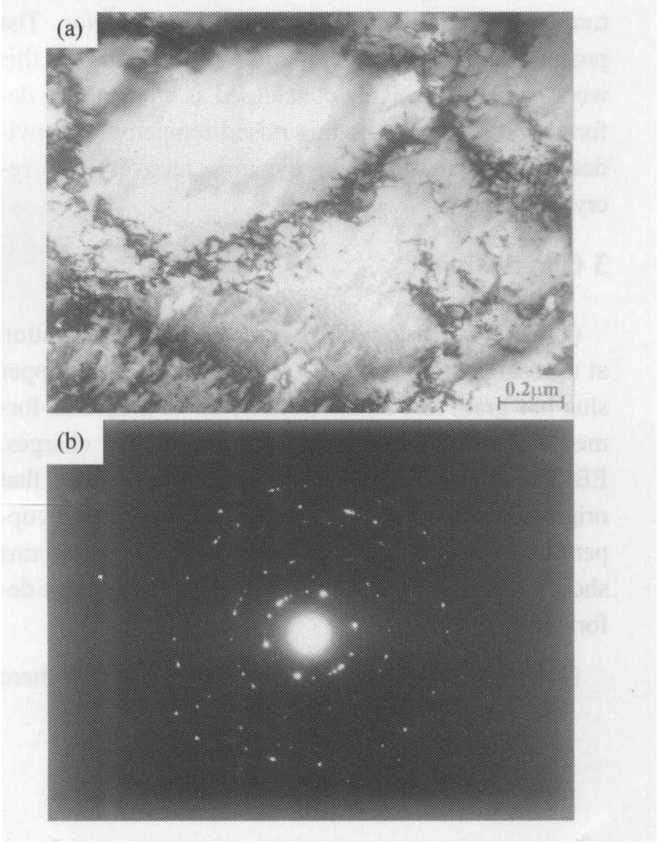

Figure 6 (a) TEM bright-field image showing the cell dislocation in the recovered copper slug and (b) the corresponding electron diffraction pattern.

strain deformation at ultra-high strain rate. The fact that fibrous texture existing in starting liners disappears after deformation also indicates that the re-partitioning and re-arrangement of the grains in the liners have occurred during the explosive detonation. Murr *et al.* [3] have compared the beginning microstructure of forged and sputtered metal liners of shaped charges with the recovered jet fragments and slugs, and pointed out that dynamic recrystallization dominates the plastic deformation at high strain rate. Zernow and Lowry [5] have estimated that the temperature in a copper jet exceeds 0.7 times the melting point of copper. This evidence predicts that, in present case, the temperature reached during plastic deformation at ultra-high strain rate exceeded the dynamic recovery and recrystalli zation temperature of copper, although the actual temperature would be very difficult to and must be measured directly by a special method. An extreme important fact was that the copper jet remains in the solid state while the material is being deformed plastically.

Ryazanov *et al.* [8] investigated the effect of shock-wave propagation in metals on point defect producing by Thomas-Fermi-Dirac microscopical model. Andrade *et al.* [9] investigated the relationship between strain and temperature, which can be reached during high-strain rate ($10^4\ s^{-1}$) deformation under an adiabatic condition for copper. The maximum reached temperature can raise up to 1 000 K under this condition. The process of explosive detonation deformation in this work can be reasonably considered as an adiabatic deformation. Apparently, this raised temperature provides a good condition for dynamic recovery and recrystallization.

3 Conclusions

(1) After undergoing high-strain plastic deformation at ultra-high strain rate ($10^7\ s^{-1}$), the recovered copper slug has grain size of the same order as that in as-formed electroformed copper liners of shaped charges. EBSP analysis revealed that the micro-texture that originally existed in the as-formed electroformed copper liners of shaped charges disappeared; *i.e.*, the grains show a random orientation distribution, after plastic deformation.

(2) Optical microscopy observations revealed there exists a typical recrystallization structure. TEM observations showed that dislocation cells exist in the thin foil. These experimental results indicate that dynamic recovery and recrystallization play a significant role in ultra-high-strain-rate plastic deformation.

Acknowledgment

The authors wish to express thanks to Mrs. Jianqi Xu and Mr. Shilian Hu for their experimental assistance.

References

[1] F. I. Grace, Shaped charge jetting of metals at very high strain rates, [in] edited by L. E. Murr, M. A. Meyers and K. P. Staudhammer, *Shock-Wave and High-Strain-Rate Phenomena in Materials* [C], Marcel Dekker, New York, 1992, p. 493.

[2] W.H. Tian, H.Y. Gao, A.L. Fan, X.O. Shan, and Q. Sun, Microstructure and texture of electroformed copper liners of shaped charges [J], *J. University of Science and Technology Beijing*, 30 (2002) in press.

[3] L.E. Murr, C.S. Niou, J.C. Sanchez, H.K. Shih, L. Duplessis, and S. Pappu, Comparison of beginning and ending microstructure in mMetal shaped charges as a means to explore mechanisms for plastic deformation at high rates [J], *Mater Sci.*, 30 (1995), p.2747.

[4] L. Zernow, Metallurgical, XRD and SEM studies of individual shaped-charge jet particle captured by soft recovery, [in] *Proc. of International Conference on Ballistics* [C], Nanjing, China, 1988, p.89.

[5] L. Zernow and L. Lowry, High-strain-rate deformation ofcopper in shaped charges jets, [in] edited by L. E. Murr, M. A. Meyers and K. P. Staudhammer, *Shock-Wave and High-Strain Rate Phenomena in Materials* [C], Marcel Dekker, New York, 1992, p.46.

[6] M. Kiritani, Y. Satoh, Y. Kizuka, K. Arakawa, Y. Ogasawara, S. Arai, and Y. Shimomura, Anomalous production of vacancy clusters and the possibility of plastic deformation of crystalline metals without dislocations [J], *Philos. Mag. Lett.*, 79 (1999), p.797.

[7] M. Kiritani, K. Yasunaga, Y. Matsukawa, and M. Komatsu, Plastic deformation of metal thin films without involving dislocations and anomalous production of point defects [J], *Radiation Effects & Defects in Solids*, 157 (2002) p.3.

[8] A.I. Ryazanov, V.V. Dremov, and M. Kiritani, Molecular dynamic simulation of high speed deformation effect on microstructure change in thermal heated metals [J], *Radiation Effects & Defects in Solids*, 157 (2002), p.209.

[9] U. Andrade, M.A. Meyers, K.S. Vecchic, and A.H. Chokshi, Dynamic recrystallization in high-strain, high-strain-rate plastic deformation of copper [J], *Acta Metall. Mater*, 42 (1994), p.3183.