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Deformation behavior of explosive detonation in electroformed nickel liner of shaped charge with nano-sized grains

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Abstract: Nickel liner of shaped charge with nano-sized grains was prepared by electroforming technique and the ultra-high-strain-rate deformation was performed by explosive detonation. The as-electroformed and post-deformed microstructures of electroformed nickel liner of shaped charge were observed by optical metallography (OM), scanning electron microscopy (SEM) and transmission electron microscopy (TEM) and the orientation distribution of the grains was analyzed by electron backscattering pattern (EBSP) technique. Both melting phenomenon in the jet fragment and recovery and recrystallization in the slug after ultra-high-strain-rate deformation were observed. The research evidence shows that dynamic recovery and recrystallization play an important role in ultra-high-strain-rate deformation for electroformed nickel liner of shaped charge with nano-sized grain.
Key words: nano-sized electroformed nickel; ultra-high-strain-rate deformation; electroformation; microtexture; dynamic recovery and recrystallization; detonation

1 Introduction

As a key part of the armor penetrator, the preparation of liner of shaped charge is very important. Specially, the grain size of liner of shaped charge has a dramatic effect on the penetration depth of the liner[1]. The smaller the grain size, the greater the cumulative length and the better the performance of penetration. Electroformation technique is a useful method for preparing liner materials due to the controlled microstructure[2]. Electroformed nickel was selected as a potential material applied for liner of shaped charge because of its high density and sound velocity and good corrosion resistance[3].

After explosive detonation, a conical metal liner forms an elongated jet that represents one of the most severe examples of plastic deformation where strains vary from 500% to more than 1 000% at strain rates between 10^4 and 10^7 s^{-1}. Copper and tantalum shaped charges were researched extensively[4−8] and dynamic recovery and recrystallization played a significant role in the deformation process. There was a systematic relationship between the starting grain size in the liner (D_0) and the ratio of starting/ending (jet) grain size (D_0/D_s)[9]. Knowledge of the physical state of the jet is crucial in determining its apparent ductility in relation to its breakup at the high strain rate. The temperature issue, in connection with the detonating shaped charge, is still an unsettled question.

In the present work, the electroformed nickel liner of shaped charge with nano-sized grains was prepared by electroforming technique and undergone a plastic deformation by explosive detonation. The microstructures of recovered slug were observed by transmission electron microscopy (TEM) for comparison with the un-deformed nickel liner of shaped charge. Optical metallography (OM) and scanning electron microscopy (SEM) were also employed to provide a detailed overview of residual microstructures of slug and the changes in microstructures before and after high-strain deformation at the ultra-high strain rate. Electron backscattering pattern (EBSP) technique was employed to examine the distribution of grain-orientation in the recovered slug. The deformation mechanism and temperature distribution over the whole section of the slug under such high strain rate deformation were presented.

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2 Experimental

The electroformed nickel liner of shaped charge, named as specimen A in the present study, was prepared by direct current electroforming technique. Fig.1 shows the schematic representation of the experimental set-up used for electroformation of nickel liners of shaped charges. Specimen A was prepared by using electrolytic bath of 240 g/L nickel sulfate, 45 g/L nickel chloride, 30 g/L boric acid, and additive of saccharin 2.5 g/L, at pH value of 4, temperature of 293 K, and current density of 2 A/dm^2. The anode was prepared from pure nickel sheets after appropriate cleaning. A core mold of conical shape as a cathode was made from stainless steel and was used as the substrate of electroformation. The surface of the core mold was mechanically polished carefully so as to enable easy separation from an electroformed nickel liner of shaped charge which is hollow cone in shape and has a thickness of about 3 mm.

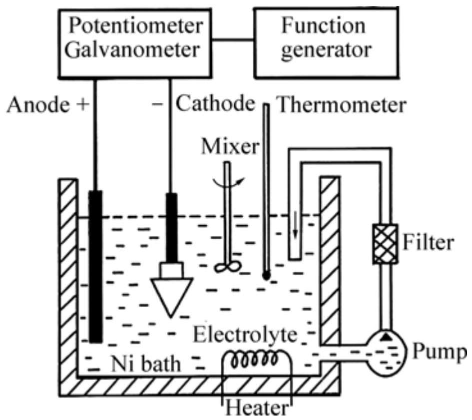

Fig.1 Schematic view of experimental set-up used for electroformation of nickel liner of shaped charge

The electroformed conical nickel liner of shaped charge underwent a plastic deformation by explosive detonation. A shock wave produced by highly explosive gas collapses the nickel liner, which eventually forms jet fragments and a slug. Fig.2(a) shows the schematic illustration of the geometry of the nickel liner of shaped charge. The cone angle of liner is 50˚ and the diameter is 50 mm. In the present study, the direction normal to the outside surface of the hollow cone is referred as the normal direction (ND), whereas the direction along the circumference of the conical nickel liner is referred as the circumferential direction (CD). Fig.2(b) shows the photo of nickel slug, which is withdrawn from the steel target after undergoing a plastic deformation by explosive detonation. It is clear that the recovered slug exhibits a shape of irregular cylinder. Fig.2(c) schematically shows the schematic illustration of the recovered nickel slug by transverse section and longitudinal section. In this study, the recovered slug was refereed as specimen B. All surfaces of specimens cut from the nickel liner of shaped charge and slug as shown in Figs.2(a) and (b) were mechanically polished carefully and then electropolished using 60% H_2SO_4+ 40% H_2O electrolyte at 293K in order to remove the strain induced by mechanical polishing. The microstructures in both the as-electroformed conical liner and the recovered slug were examined under an optical microscope. The texture in the as-electroformed nickel liner of shaped charge was determined by conventional pole figure measurements in an automated X-ray texture goniometer. Crystallographic analyses of the grains in the slug were carried out by an SEM equipped with EBSP analysis systems of Oxford Link-OPAL. In order to accurately determine the orientation of every grain, the specimen was first carefully examined by secondary-electron imaging so as to distinguish the grain boundaries. This enabled illumination of the electron beam onto a single grain, from which EBSP analysis was initiated. More than 200 for each specimen were analyzed in this way. The most preferential growth direction of the grains was determined by using the special computation software.

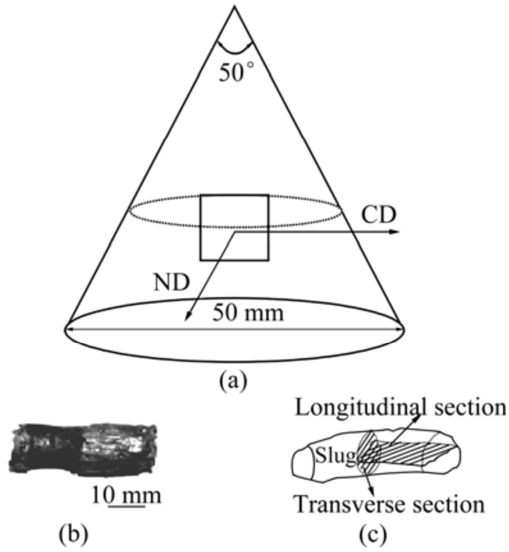

Fig.2 Schematic illustration of nickel liner of shaped charge (a), photo of nickel slug (b) and schematic illustration of recovered nickel slug by transverse section and longitudinal section (c)

3 Results and discussion

3.1 Microstructure of as-electroformed nickel liner of shaped charge

Fig.3 shows the second electron image of specimen A showing the ultra-fine-sized structures in the electroformed nickel liner of shaped charge. It is clear that the deposits are composed of colony structures having a size of about 700 nm in diameter. Inside the colony area, many grains with a nanocrystalline structure can be observed. WEIL and COOK[10] reported that the colony structures were observed in samples from baths containing thiourea and aniline. FISCHER[11] concluded that the incorporation of organic additives into the plating bath resulted in the inhibition of pyramidal growth, a concomitant reduction in surface roughness and increase in surface brightness. More recently, NAKAMURA et al[12] observed morphological transitions from large crystals to a colony-like morphology in nickel electrodeposited from the Watts bath containing saccharin.

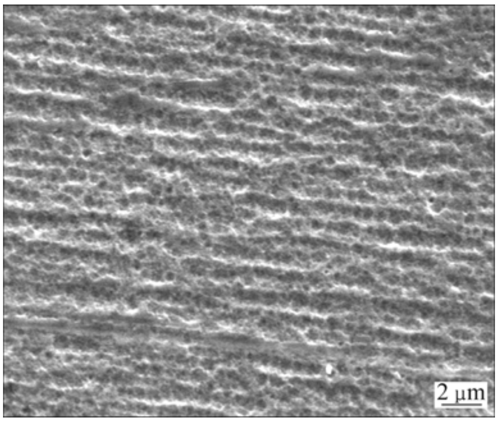

Fig.3 Second electron image of specimen A showing colony structures in electroformed nickel liner of shaped charge

Fig.4 shows the TEM bright-field image and the electron diffraction pattern of specimen A. It is clear that grains have a nano-sized scale and the grains have an average size of 30 nm. It can be considered that the additive saccharin results in a transition to the colony morphology with a nano-sized grain. Similar microstructure was also recognized by EL-SHERIK and ERB[13]. As a result, the use of additive results in the inhibition of large grains growth and formation of colony microstructure.

Fig.5 shows the pole figure obtained from specimen A. It can be seen that specimen A has a mixture of ⟨100⟩ and ⟨111⟩ textures. It has been reported that an increase in the saccharin concentration in the bath leads to a progressive change in the preferred orientation from a strong ⟨100⟩ fibre texture to a ⟨111⟩−⟨100⟩ double fibre texture[13]. The present result is in agreement with the observations reported by NAKAMURA et al[12] on the preferred orientation of D.C.-plated nickel from the Watts bath containing saccharin. In previous studies[14]. Specimen A was analyzed using XRD. Saccharin in the bath resulted in expansion of diffraction peaks due to the minimized grain size. It is confirmed that the grain size of specimen A is 29 nm, as determined from the full-width at half-maximum of (111) reflection by the Scherrer equation. This calculation value from X-ray diffraction pattern is very close to that observed by TEM as shown in Fig.4.

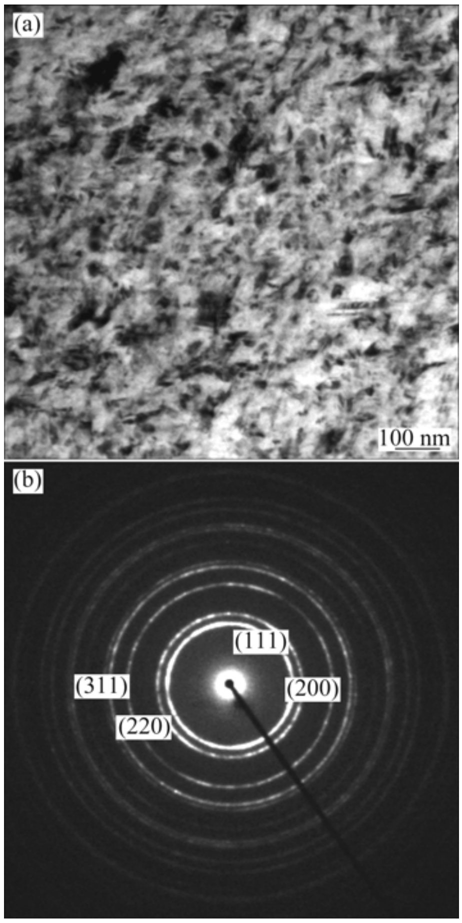

Fig.4 TEM bright field image (a) and electron diffraction pattern (b) of specimen A showing nano-sized grains in electroformed nickel liner of shaped charge

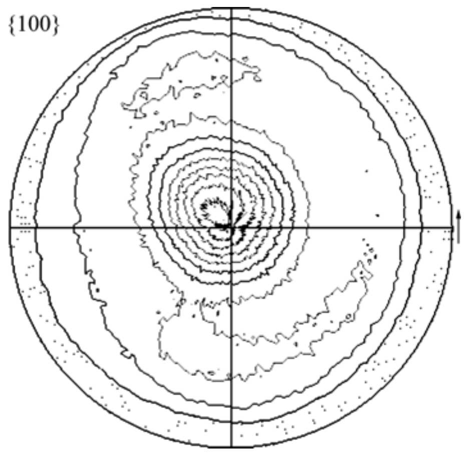

Fig.5 {100} pole figure of specimen A

3.2 Microstructure in recovered nickel slug

Fig.6 shows the cross sectional view of the microstructure in the recovered nickel slug of specimen B. It can be seen that there is a clear borderline in outer zone of cross sectional view of specimen B. The grain size inside the slug is not uniform due to the different plastic strains for different positions of the slug. Plastic deformation degree of the slug is very different for different parts of the slug across the section of the slug, and the temperature of the slug raises because the plastic deformation is an adiabatic process. There exists a temperature distribution across the section of the slug due to the different plastic strains for different parts of the slug. In fact, the microstructure of the cross section at view of recovered slug is different from that observed in previous studies of copper liner[5, 7−8]. It is very interesting that there are two completely different microstructures in recovered nickel slug, which are separated by a clear borderline.

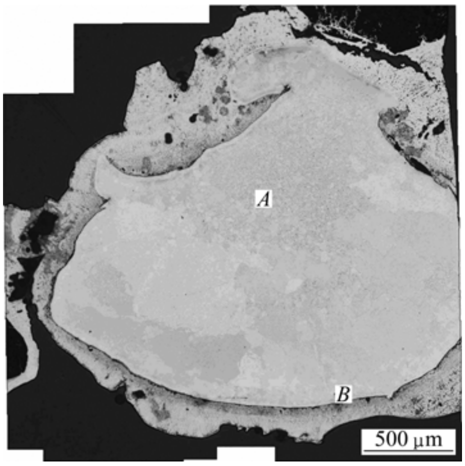

Fig.6 Cross sectional view of recovered nickel slug in specimen B

Fig.7(a) shows the magnified image of region *A* marked in Fig.6. Grain size in region *A* is about 25 μm. Fig.7(b) shows the magnified image of region *B* marked in Fig.6. It is clear that the grains near the inter part show a columnar shape which is formed during solidification, similar to the case of solidification in a cast mould. Furthermore, the energy dispersive X-ray spectrometer (EDS) was employed to analyze the component of samples. The EDS results outside borderline show that the mass fractions of Ni and Fe are 55.96% and 44.04% in this area, which are very close to those of permalloy in composition. However, the EDS result of area inside borderline indicates that only nickel element exists. EDS analysis results indicate that the area near the outer surface of the slug contains iron element and forms an binary Fe-Ni alloy. It should be mentioned that this part of slug near the surface of the steel target is formed during the early pass of jet fragments. A melting phenomenon between the jet fragment and steel target occurred during explosive detonation due to an adiabatic process. It can be considered that the initial nano-grained

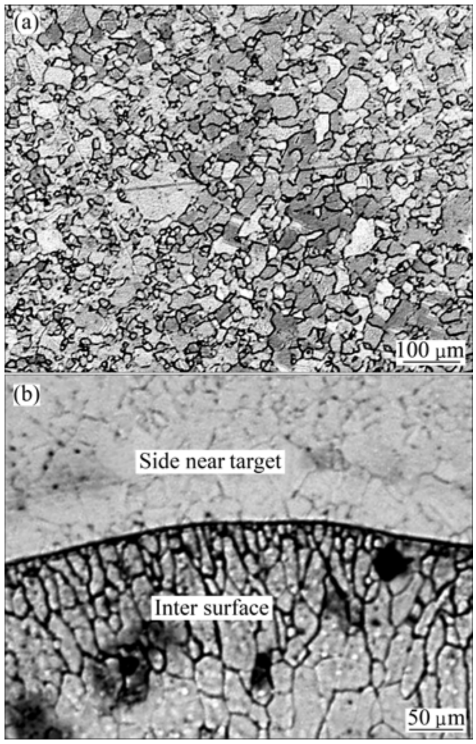

Fig.7 Magnified images of area *A* (a) and area *B* (b) marked in Fig.6

nickel liner has undergone melting phenomenon for jet fragments during penetration detonation. It can be also considered that nano-grained nickel liner stores high energy due to the small grain and much grain boundary. This leads to a remarkable raise of the temperature during explosive detonation. From these microstructure, one can see that the outside and inside of borderline come from different parts of metal liners. The jet, which is strained about 1 000% at strain rates over 10^6 s^{-1}, forms from roughly 1/5 of the inner cone wall. The remaining 4/5 of the liner mass flows plastically into an accelerating slug, which is lagging behind the tail of the jet at a slower velocity. Thus, it is not arbitrary to suppose that the outside of borderline belongs to the jet, and the inside of borderline belongs to the slug. The melt-metal in the outer side of the borderline shows a typical classical solidification. Inside of borderline toward the center of the slug is a typical microstructure of recrystallization. From the observed microstructure of outside of the borderline, we assume the jet is liquid flow, and the temperature of the jets exceeds T_m (melt point). However, the temperature of the slug is below T_m, and the slug remains solid state.

Fig.8 shows the optical microscope image of longitudinal section of slug. Crystal grains exhibit equiaxed shape and show an average grain size of about 25 μm. It was reported that the slug of electroformed copper liner of shaped charge has a grain size of 30−100 μm which is larger than that in the liner of shaped charge before deformation in the previous study[2]. It is of particular interest that the grain size in recovered slug transferred from the nano-sized liner of shaped charge increases by a level of 10^3 orders. This is a typical recrystallization structure and indicates that the original nano-grained nickel liner has undergone a dynamic recovery and recrystallization for the slug during penetration detonation. Deformation at extremely high strains and/or strain rates, which approaches a strain rate of 10^7 s^{-1}, can be considered as an adiabatic process essentially. After plastic deformation, the associated process temperatures are considered to be larger than $0.6T_m$. ZERNOW and LOWRY[15] estimated that temperatures in copper jets exceeded about 0.7 times of melting temperature, but in the case of tantalum shaped charges, the jet temperature would exceed 2 000 °C which was 0.7 times of melting temperature. Finite element simulation of shaped charge[16] shows in particular that there exists a temperature variation across the width of jet. It is demonstrated that the variation is the result of shearing deformation across the jet. The temperature increases regularly with the formation of the jet. The heat is mostly generated by plastic work. The plastic deformation degree and thus the temperature are the highest in the center of the jet. After nano-grained electroformed nickel liner of shaped charge undergoes a plastic deformation by explosive detonation, the temperature of slug is lower than that of jet. In the present study, the jet is in a melting state, whereas the slug is still in a solid state. Fig.9 shows the TEM bright field image of specimen B. Moving dislocations exist in the slug, but dislocation cell wall in slug changed from the electroformed copper liner could not observed.

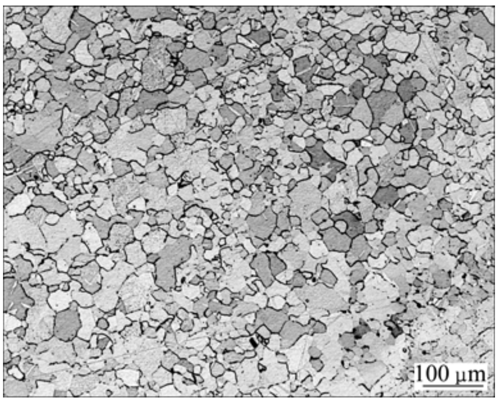

Fig.8 Optical microscope image of longitudinal section of slug

3.3 Microtexture in recovered nickel slug

In order to understand the change in microtexture after explosive detonation, EBSP technique was employed to investigate the microtexture of recovered slug. Figs.10 (a) and (b) show the pole figure and inverse

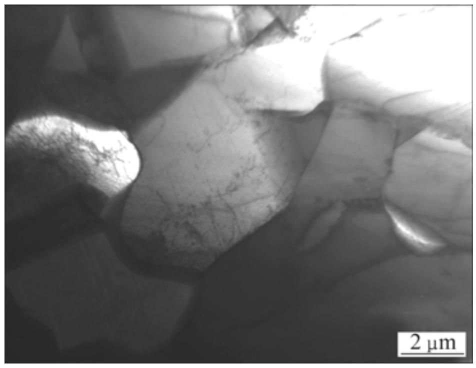

Fig.9 TEM bright field image of specimen B

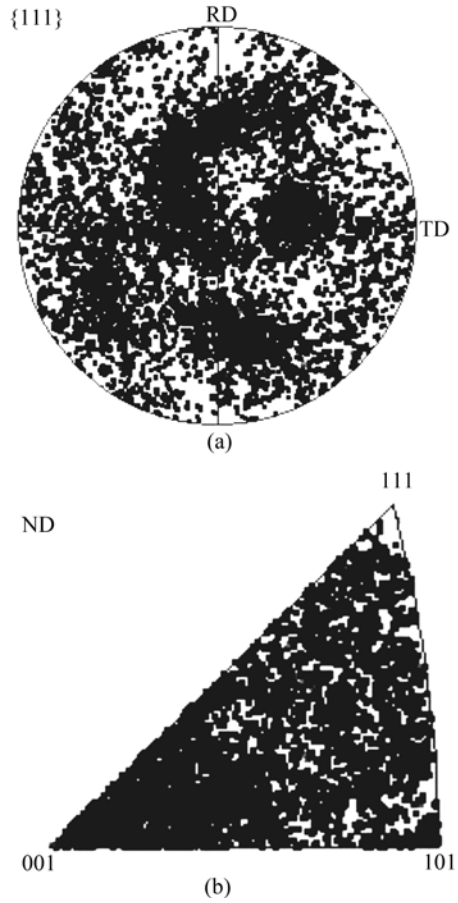

Fig.10 Pole (a) and inverse pole (b) figures of specimen B

pole figure of specimen B. It is clear that no texture exists in specimen B. It can be concluded that nano-grained nickel liner of shaped charge undergoes a dynamic recrystallization and recovery during explosive detonation. A mixture of ⟨100⟩ and ⟨111⟩ textures, which originally existed in the nickel liner of shaped charge, disappears by the deformation of explosive detonation. TIAN et al[17] compared the microstructures in electroformed copper liner of shaped charge before and after plastic deformation at different strain rates, and found that fibrous texture detected in as-electroformed copper liner disappeared after high-strain-rate plastic deformation. In the present study, it is also confirmed that dynamic recrystallization plays an important role in plastic deformation at ultra-high strain rate. Especially, melting phenomenon occurs in the jet fragment part.

Fig.11 shows the schematic illustration of the forming process of slug and jets. A shock wave created by TNT40 collapses the nickel liner, which forms a stretching jet and slug. The jets penetrate the target, with the jets keeping state of melting flow liquid. Some of jets remain on the cavity wall of the hole generated by the jets. After the slug penetrates into the target, it stays in the hole cavity and is surrounded by the jet remains. Slug remains in the target surrounded by the remained jet in cavity wall of the hole. Under this circumstance, remained jet in the hole wall will combine with the slug in the hole and form the microstructure observed in the present study.

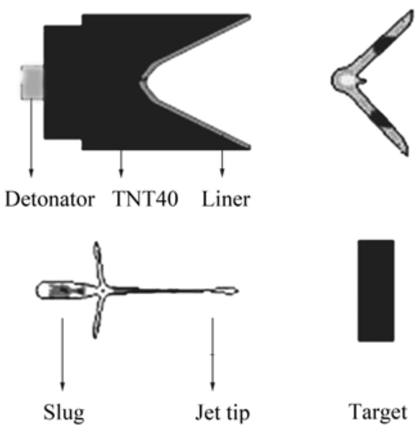

Fig.11 Schematic illustration of forming process of slug and jets

4 Conclusions

1) The nickel liner of shaped charge prepared by electroforming with additive saccharin is composed of a colony structure having a size of about 700 nm. Inside the colony area, many grains with a nanocrystalline structure with a grain size of about 30 nm can be observed. The use of saccharin makes the grains size decrease due to the acceleration of nucleation during electroformation.

2) After plastic deformation at ultra-high strain rate, the grain size in recovered slug transferred from the nano-sized liner of shaped charge increases by a level of 10^3 orders. Many moving dislocations exist in the slug. The mixture of ⟨100⟩ and ⟨111⟩ textures, existing in nickel liner of shaped charge disappears due to the explosive detonation.

3) Dynamic recovery and recrystallization play an important role in the deformed shaped charge, especially in the formed slug during explosive detonation. In addition, the temperature of the jet exceeds melting point due to an adiabatic deformation process. The following slug remains solid state even keeping a high temperature.

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