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The relationship between micro-structural evolution and deformation mechanisms for nanocrystalline Ni under high strain rate

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ABSTRACT

To inspect deformation mechanisms of nanocrystalline materials under high strain rate, bulk NC Ni samples are prepared by plasma evaporation combined with hot pressure sintering, and dynamic impact mechanical properties of the samples are tested under different high strain rates on Split Hopkinson Pressure Bar (SHPB). After impact testing, the micro-structural parameters of the samples, such as grain size and micro-strain, are investigated by X-ray diffraction (XRD). The mean strain rate sensitivity of the samples under high strain rate is calculated according to the impact mechanical properties. In addition, the microscopic grain morphologies after the impact testing are investigated through transmission electron microscope (TEM). The results show that grain sizes of the impacted samples decrease compared with those of sintered samples, while the micro-strain of the grains increases. Meanwhile, the grains of the impacted bulk sample are elongated, and impact stress–strain responses of the bulk samples are rate-dependent. The mean strain rate sensitivity of the bulk samples is far bigger than that of NC metals under quasi-static strain rate. Finally, the special deformation mechanisms of the bulk NC sample under impact loading are described based on the experimental results.

1. Introduction

Nanocrystalline (NC) materials have attracted much attention currently due to their unusual mechanical properties, such as ultra-high yield strength, enhanced superplastic formability and superior wear resistance [1]. The special mechanical behaviors indicate that NC materials possess different fundamental physical deformation mechanisms compared with their conventional coarse-grained counterparts. To inspect the deformation mechanisms of NC materials, many experiments [2–5] and theoretical predictions [6–9] have been carried out under quasi-static state. Schwaiger et al. [2] investigated the rate-independent plastic flow under quasi-static for the fully dense NC Ni sample. Cheng et al. [3] reported an improved combination of tensile strength and ductility of NC Cu and observed the nearly perfectly plastic behavior for NC Cu under quasi-static strain rate. Jia et al. [4] observed that the deformation of the NC Fe is progressed by the shear band nucleation and propagation under the quasi-static compressive load. Zhu et al. [5] considered that the early failure of NC Ni can be attributed to the non-homogennous deformation in form of shear band under quasi-static tensile load. For the theoretical modeling of NC materials under quasi-static loading, Kim et al. [6] proposed a phase mixture model to describe the deformation behavior of NC materials based on dislocation density evolution. Fu et al. [7] built a phenomenological constitutive equation predicting the effect of grain size on the yield stress of NC metals. Yang and Wang [8] proposed a micromechanics theory for the creep deformation of NC materials by extracting the deformation response from a model of a 9-grain cluster. Zhu et al. [9] constructed a multi-scale modeling predicting shear localization under quasi-static strain rate in NC Ni, and predicted the shear banding behavior of the NC Ni sample by using the modeling.

However, the deformation mechanism of NC materials under high strain rate ($\geq 10\ s^{-1}$) has not been well-understood so far. Even for the same material, the deformation mechanism will also vary with increasing strain rate. Yoo et al. [10] studied the effect of grain size on dynamic compression properties of NC tantalum consolidated by plasma pressure compaction, but the discussion on the deformation mechanism for their tests were not presented. Jia et al. [4] systematically investigated the mechanical behaviors of consolidated iron with average grain sizes from tens of nanometers to tens of microns under uniaxial compression over a wide range of strain rates. They indicated that the deformation of NC iron may become non-uniform in the plastic deformation under high strain rate. However, the differences in deformation

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mechanism were not given between the low strain rate and high strain rate loading. Zhu et al. [11] built a constitutive modeling to predict the deformation mechanism of NC Ni prepared by high energy ball milling under high strain rate. However, the evolution of micro-structure during the impact process has not been discussed further.

Recently, some new methods investigating the evolution of microstructure during plastic deformation [12–14] have been developed to study the deformation mechanism of NC materials. Although stress modes and impurity elements may affect the microstructure evolution of NC materials, most of them found that the stability of microstructure associates with grain boundaries, and high grain boundary energy in NC materials may be a driving force of microstructure evolution of NC materials. The similar results [15–17] have been obtained in molecular dynamic simulation.

In this paper, bulk NC Ni samples are prepared by plasma evaporation method combined with hot pressure sintering first. Then dynamic impact tests for the samples are carried out under different high strain rates on SHPB, and impact mechanical properties including strength and strain rate sensitivity of the bulk samples are studied. During the impact plastic flow, the evolution of microstructure for the bulk samples is analyzed in details. Finally, the underlying deformation mechanisms under impact loading are discussed based on the experimental results.

2. Experimental procedure

The bulk NC Ni samples are prepared by plasma evaporation method combined with hot pressure sintering. First, NC powders are prepared by plasma evaporation system. As shown in Fig. 1, the plasma evaporation system contains work chamber and collected chamber. After the work chamber is cleaned and vacuum-pumped substantially, it is filled with Ar and H_2 with a volume ratio of 7–3. Then the plasma arc is triggered and the work current keeps as 600 A. Under the action of the plasma arc, raw material (coarse-grained Ni) is evaporated rapidly. Simultaneously, the metal steam is forced into a water-cooled cylinder that acts as a powder collected chamber by a blower and rapidly condensed into powders with nanometer gain size on filtration fabric or walls of the water-cooled cylinder.

Subsequently, the nano-powders are consolidated in a die that is made of heat treat Vasco steel with a compaction pressure of 1950 MPa for 5 min at room temperature, then the raw samples were reloaded and sintered at 725 °C under the pressure of 35 MPa for 1 h. Another 1 h of sintering is performed at the same temperature without pressure but under the protection of inert gas. During the sintering process, the constant elevation rate of temperature is 10 °C/min. The resultant cylindrical samples are 8 mm in diameter and 4 mm in thickness. The microstructures of the sintered samples are investigated by XRD and TEM. The density of the bulk sample is measured by adopting the Archimedes method.

Finally, the dynamic impact tests are preformed on a SHPB under different impact velocities respectively (corresponding to the different strain rates). For comparison, the mechanical behaviors of the NC Ni samples under different quasi-static strain rates are also investigated. The impacted samples are also examined by XRD and TEM to observe the evolution of microstructure after impact.

3. Results and discussions

3.1. Microstructure of powders and sintered samples

Fig. 2 shows the TEM micrograph of NC Ni powders prepared by plasma evaporation method. It reveals that particles of the powder are spherical and regular due to uniform nucleation mechanism during the evaporation. Meanwhile, the particles have a narrow distribution and the sizes keep in nano-scale. However, a few larger particles can be observed, the larger particles mainly caused by two reasons: (a) growth of the particles remained in plasma due to higher temperature and lower cooling rate in the arc column zone; (b) agglomeration of smaller particles that yield hard larger particles due to the larger surface energy of nano-scaled particles. Fig. 3 shows a statistical histogram of size distribution of particles based on the TEM micrograph. Obviously, the maximum of the particle size is about 85 nm and the mean particle size is about 45 nm calculated by statistical analysis.

After compaction and sintering, the representative TEM bright field image together with the corresponding selected area diffraction (SAD) pattern of the grain morphology for sintered sample is shown in Fig. 4. It is clear that the particle size distribution broadens compared with the initial powders due to the non-uniformity of temperature distribution during the sintering process. Meanwhile, from the TEM morphology, the average grain size of the sintered sample is about 78 nm, which increases approximately by 2 times from the initial powder stage. However, the grain size of the sintered sample is still in the nano-scale. Moreover, the closest first and second rings of the SAD pattern in the inset of Fig. 3 for the sintered sample, correspond to the {1 1 1}

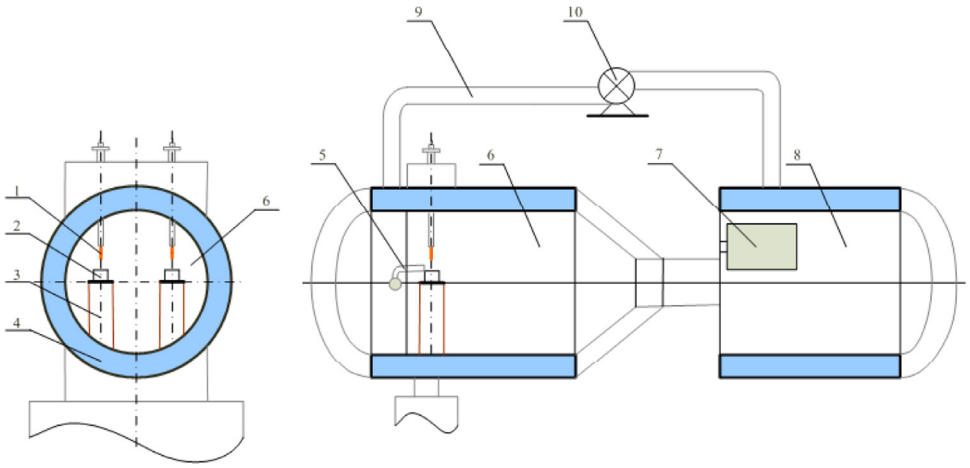

Fig. 1. Schematic drawing of device of continuous preparing nanometer-scale metallic powders (1 Tungsten electrode; 2 Crucible; 3 Water-cooled copper mold; 4 Water-cooled chamber; 5 Pressure gage; 6 Work chamber; 7 Filtration fabric; 8 Collected chamber; 9 Circulating gas path; 10 Circulating fan).