Dynamic Shear Stress of Tough-Pitch Copper at High Strain and High Strain-Rate

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Dynamic shear tests for the tough-pitch copper at high strain and high strain rate was performed. The Split Hopkinson Pressure Bar (SHPB) compression test system was modified to yield a shear deformation in the specimen. Hat-shaped specimens for the tough-pitch copper were adopted to generate high strain of $\gamma=3\sim4$ and high strain-rate of $\dot{\gamma}=10^4$/s. The dynamic analysis by ABAQUS 5.5/EXPLICIT code verified that shear zone can be localized in hat-shaped specimens. A proper impact velocity and the axial length of the shear localization region were determined through the elastic wave analysis. The displacement in a hat-shaped specimen is limited by a spacer ring which was installed between the specimen and the incident bar. The shear bands were obtained by measuring the direction of shear deformation and the width of deformed grain in the shear zone. The decrease of specimen length has been measured on the optical displacement transducer. Dynamic shear stress-strain relations in the tough-pitch copper were obtained at two strain-rates.

Key Words : SHPB, Shear, High Strain, High Strain-Rate

Nomenclature

d_e : Outer diameter of the specimen
d_i : Inner diameter of the specimen
E : Young's modulus of the elastic bar
h : Axial height of the shear zone in specimen
V : Velocity of the striker
v : Velocity of the incident bar
W : Width of the shear zone
α : Deflection angle in the shear zone
τ_s : Average shear stress in the specimen
ε_I : Incident pulse wave in the incident bar
ε_R : Reflected pulse wave in the incident bar
ε_T : Transmitted pulse wave in the transmit bar
γ : Shear strain in the specimen
δ : Controlled displacement of the specimen
$\dot{\gamma}$: Average shear strain rate in the specimen

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1. Introduction

Some of metal materials in the structure and the mechanical part experience dynamic or impact loading. Researches for materials under impact loading have been widely studied for many years in interesting fields of engineering. It is essential to acquire material properties at high strain-rate in order to design and analyze the deformation behavior of any structure and mechanical part under dynamic load at high velocity impact.

Although most of the researches for materials in high strain-rate have been focused on material behaviors at low strain ($\varepsilon<0.5$), metals used in various engineering fields such as metal forming, high-speed machining, high-velocity impact, penetration mechanics, and shaped charge have high strain ($\varepsilon>1$) at high strain-rate. The understanding of mechanical behaviors of materials at high strain and high strain-rate is very important. The Split Hopkinson Pressure Bar (SHPB) introduced by Kolsky in 1940 has been used to determine dynamic stress-strain relations in materials. SHPB has been applied to tension (Yang and Min, 2000), torsion and shear test as well as compression test (Seo and Min, 1998), and for each case a number of experimental fixtures have been developed. The torsion test system is capable of measuring the shear stress-strain relations. But, in this paper the Hopkinson compression system has been modified in order to measure the shear behavior of metal. Specimens used in the shear test were designed by Meyer and Manwaring (1986). Meyers et al. (1995) have performed the shear test for titanium with hat-shaped specimens and Andrade et al. (1994) have done for copper. Copper has been used in the research for material behaviors at high strain and high strain-rate because of its extensive ductility.

In this paper, SHPB test system was designed and developed for the shear test with hat-shaped specimen. The shear width was determined by measuring the deformed grain in the shear zone and the displacement by instrumenting an optical displacement transducer. The effects of the axial length of shear localization region in specimens were analyzed and dynamic shear stress-strain relations in tough-pitch copper were estimated at high strain and high strain-rate.

2. Experimental Techniques

2.1 Theory

The schematic of SHPB shear test system and X-t diagram of characteristic line in elastic wave propagation are shown in Fig. 1. This experimental system is consists of the specimen, the spacer ring, the striker bar, and incident and transmit bars. As the striker bar at velocity V impacts the incident bar of the cross section A, an elastic wave which is two times of the length of the striker bar, is generated and propagated through the incident bar.

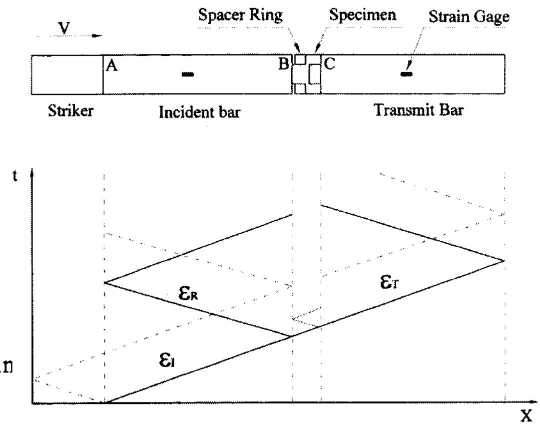

Fig. 1 The schematic of SHPB and characteristic diagram

Specimen is installed between the cross section B of the incident bar and the cross section C of the transmit bar. As an elastic wave propagating through the incident bar reaches B, the elastic wave is partly transmitted through the specimen and partly reflected to the incident bar. The elastic stress wave propagating into the specimen deforms the specimen. The shear stress τ_s in the specimen can be obtained by measuring the tran smitted wave $\varepsilon_T(t)$, using strain gage installed on the transmit bar, which is approximately equal to (Mayer, 1994 ; Davies and Hunters, 1963)

$$\tau_s = E\frac{A}{A_s}\varepsilon_T(t) \quad (1)$$

In which E and A are the Young's modulus and the cross-sectional area of elastic bar, respectively, and A_s is the circumferential area of the plastic deformation region in the specimen. The area of the plastic deformation is illustrated with the section view of the specimen in Fig. 2.

A shear experiment in SHPB is quite different from the compressive one because the shear strain cannot be obtained by picking up signals of the reflected wave. The shear strain in the hat-shaped

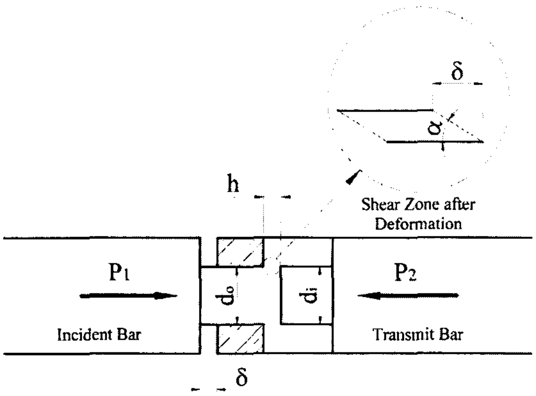

Fig. 2 Elastic bars and section view of the shear specimen

specimen can be calculated by measuring the direction of the grain deformation in the shear zone and the displacement of the hap-shaped specimen, which is limited by the thickness of a spacer ring. The shear strain γ is given by (Mayer et al., 1995 ; Andrade et al., 1994)

$$\gamma=\frac{\delta}{W} \tag{2}$$

or

$$\gamma=\frac{1}{\tan\alpha} \tag{3}$$

On the other hand, the average strain-rate when the incident bar end impacts the specimen with velocity v is given by

$$\dot{\gamma}=\frac{v}{\delta\tan\alpha} \tag{4}$$

where δ is the controlled displacement by the spacer ring installed between the specimen and the incident bar, W the shear width, and α the deflection angle in shear zone. The direction of the grain deformation in shear zone can be estimated with optical micrograph (Nemat-Nasser et al., 1998). The specimen used in the optical micrograph can be obtained by cutting through the shear zone parallel to the compression direction.

2.2 SHPB experimental system

The SHPB experimental system consists of the two elastic bars, the alignment support, an acceleration tube, the velocity measurement sensor, and the instrument for velocity measurement of the specimen. The schematic of SHPB shear test system is shown in Fig. 3.

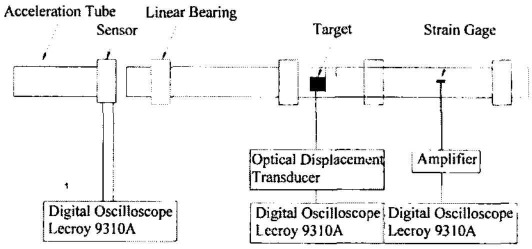

Fig. 3 Schematic of SHPB shear test system

Because the stress-strain relation in the specimen is obtained by the elastic wave analysis, the deformation of elastic bars, including the incident bar and the transmit bar, is restricted within elastic limits. The elastic bars have sufficiently enough yield strength such that the specimen experiences plastic deformation at high strain-rate. In this paper, the striker and the elastic bar of SM45C are used, which have 20 mm in diameter and 300 mm and 1300 mm in length, respectively. The modulus of elasticity and the yield stress of SM45C are 209 GPa and 490 MPa, respectively (Korea Standard Institution, 1996).

In order to collide heads-on, the faces of the striker, elastic bars, and the specimen are polished and aligned straightly. The striker bar carried on sabot of a polymer material (MC) is free to slide in the accelerating tube. The elastic bars are free to move along their axis. For measuring the elastic wave, while eliminating the effect of bending during impact, two strain gages (Model CEA-06-015UW-120, Micro Measurement) are mounted in the middle of the elastic bar (located at 650 mm from the impact face) in opposite position of circumference. A full bridge circuit with the strain gauges is used and the signals from the circuit are recorded on digital oscilloscope after amplifying with an amplifier (Measurement Group, 2210 system).

2.3 Optical dislacement transducer

In measuring high velocity motion of the specimen, an opto-electronical measuring device is adopted. This device converts the linear motion of a target into a voltage output proportional to the displacement. The target consists of a black and white surface with a high contrast ratio and a straight line made by its two colors, which is to be aligned in a right angle to the direction of movement. Size of the target with a black and white contrast is more than 15% for the measurement region. A halogen lamp of 6V-10W with an aspheric condensing lens illuminates the target. The light of illumination can be concentrated on target by controlling lens. Table 1 shows the specifications of this device. And, the schematic for measuring a displacement using optical displacement transducer is shown in Fig. 4.

In this paper, the target was made by adhering a white paper on it after painting a lacquer paint, and attached to the end of incident bar contacting with a specimen. Using this device, velocity of the specimen deformation v which is necessary to obtain $\dot{\gamma}$ in Eq. (4) can be measured by picking up the displacement of the end of incident bar in terms of time.

Table 1 Specifications of the optical displacement transducer system

Model	100D-5/zimmer OHG
Measurement Range (1)	5mm ($-5V \sim +5V$)
Working distance	213.5 mm
Resolution	0.008% of range (1)
Scanning width	7% of range (1)

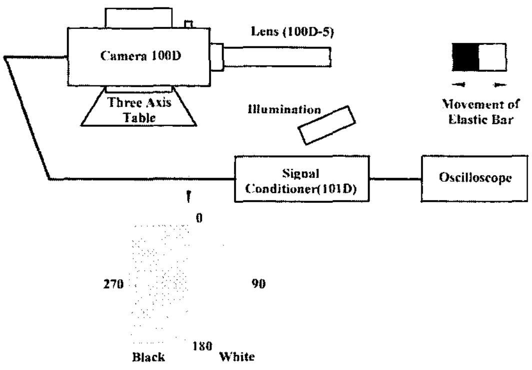

Fig. 4 Schematic of optical displacement transducer system

3. Simulation

FEM analysis preformed by ABAQUS 5.5/EXPLICIT verified that shear zone can be localized in hat-shaped specimen in the Hopkinson compression test apparatus. The shape and dimension of the numerical model were determined from the dimension of the experimental system as illustrated in Fig. 5. An axisymmetric model, as shown in Fig. 6, is discretized using CAX4R type element (4 node). Initial impact velocity of the striker is 7 m/s. The simulation has been carried out during 750 μs after impact. The elastic wave travels through the incident bar, specimen, and the transmit bar which becomes the length of 3015 mm at an estimated velocity of 5000 m/s. In this simulation, the elastic modulus E, the Poisson's ratio ν, and the density ρ are 209 GPa, 0.3, and 7850 kg/m^3, respectively. The contour of the shear stress in the central element of the specimen is shown in Fig. 7. This contour shows that shear stress concentrates on the neck of specimen and the considerable shear deformation appears in the deformed elements. From this simulation, we could know that shear localization region is formed enough in the shaped specimen in this condition.

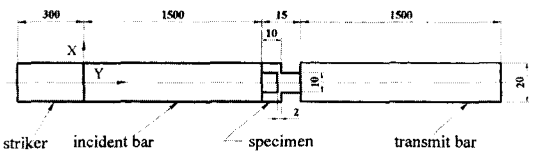

Fig. 5 Dimension for analytical model

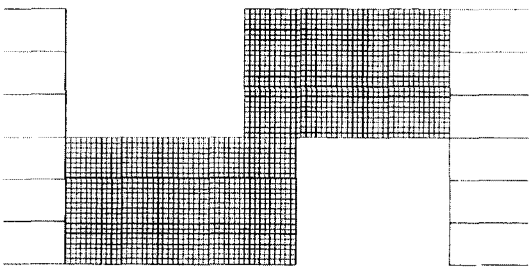

Fig. 6 Mesh of the specimen

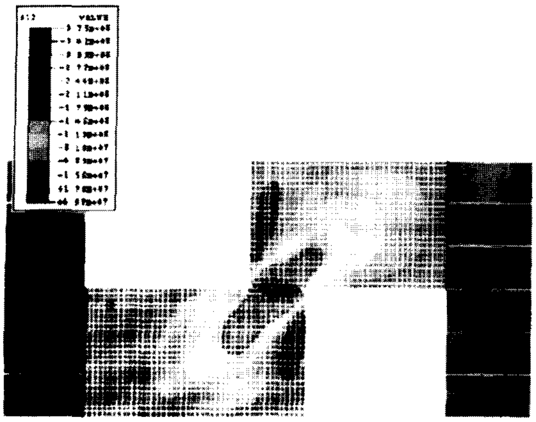

Fig. 7 The contour of shear stress s_{12} in hat-shaped specimen

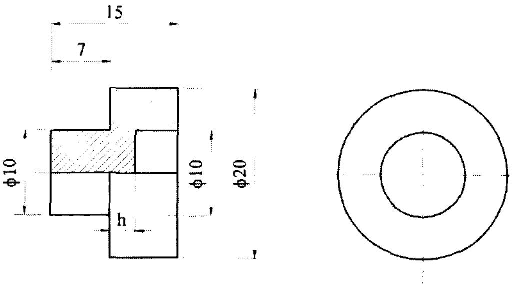

Fig. 8 Section view of hat-shaped specimen of SHPB shear test

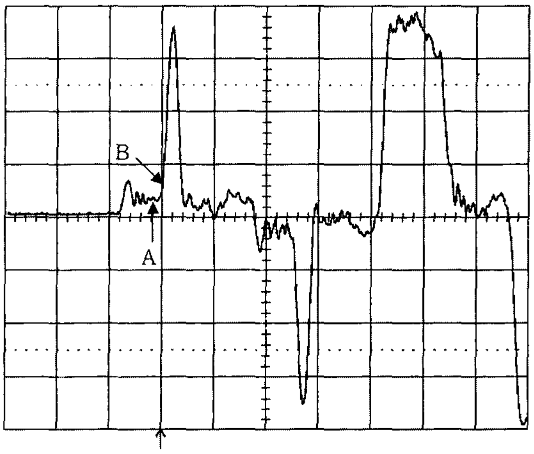

Fig. 9 A typical strain signal of transmit bar in shear test at impact velocity V=12.6 m/s (h=0.5, δ=1.0)

4. Experimental Results/Discussion

4.1 Experimental procedure

Experiments using the hat-shaped specimen for the tough-pitch copper have been performed. The thickness of a spacer ring was used to control the displacements of specimen. The hat-shaped specimen has the shear localization zone in a small axial length h, which is selected as 0.5-2 mm in order to intentionally concentrate plastic deformation. Since the most part of pressure transmits through the shear localization region, the specimen can be excessively deformed at high velocity and experienced a localized shear deformation. On the contrary, the shear band cannot be formed in a specimen at low velocity. Since the axial length of shear localization region is a principal parameter affecting the shear deformation, it must be properly determined by experiments. The dimension of the inner and outer diameters of the specimen are selected same as used in the simulation. Dimensions of specimen are shown in Fig. 8 where the axial length h and the difference in diameters are illustrated. The experiment is performed at the impact velocity of 10-20 m/s that does not generate plastic deformation in the elastic bar.

The formation of the shear band can be clearly distinguished in the strain signal of the transmitted wave (ε_T). For axial length h=0.5 and the impact velocity of 12.6 m/s, the transmitted strain signal is illustrated in Fig. 9. When the elastic wave propagates through the specimen into the transmit bar, the shape of the strain signal passing the deformed region has the form of the plateau as marked A in Fig. 9. When the incident bar contacts the spacer ring, which means that the deformation of the specimen stops, the shape of the strain signal shows a sharp increase as marked B in Fig. 9. This sharp increase of strain signal in the transmit bar indicates that the elastic wave begins to propagate through both the spacer ring and the shortened specimen.

For the axial length h=0.5 mm, δ=1.0 mm and an impact velocity of 18.3 m/s, the strain signal is illustrated in Fig. 10. It is clear that strain signal shows the excessive shear deformation. The strain signal shows the decrease of its strength as marked C in Fig. 10. This decrease in

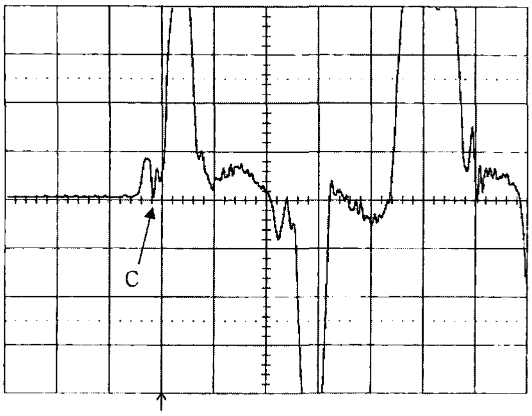

Fig. 10 Strain signal of transmit bar at impact velocity V=18.3 m/s (h=0.5, δ=1.0)

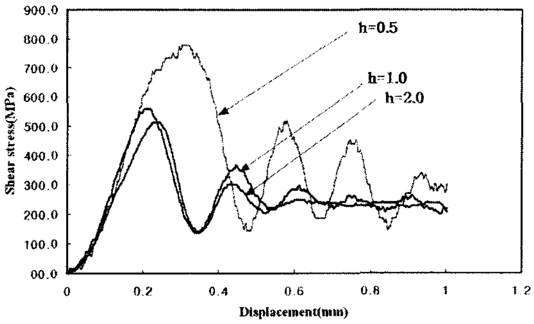

Fig. 11 Shear stress-displacement curve for three axial lengths (δ=1.0)

Fig. 12 Optical micrograph of tested hat-shaped specimen (h=2, δ=0.5, magnification : x50)

strain has been occurred when the wave is not properly propagated because of a partial fracture of the shear localization region.

The axial length of the shear localization region and the displacement controlled by a spacer ring are the principal variables which affect the determination of the shear stress-strain relation in a specimen. So, we should appropriately determine those variables.

4.2 Discussion

The Compressive Hopkinson pressure bar test system was modified to carry out an experiment on a shear deformation. Hat-shaped specimen was used in order to localize shear deformation. The axial length and the width in which the shear deformation has to be concentrated are appropriately selected a priori by simulation and experimentation. Axial deformation in the specimen was controlled by the spacer ring between pressure bar and the specimen. Experiments for copper specimens were performed for a displacement δ=1.0 mm and the axial length of shear localization region h=0.5, 1.0, 2.0 mm. The velocities of the striker bar were at 12.6 m/s, 13 m/s, 13.5 m/s. The strain signals from the transmit bar have been converted to the dynamic shear stress-strain relation in tough-pitch copper, as shown in Fig. 11. Short axial length of the shear localization region in the hat-shaped specimen generally tends to increase the initial overstress and large stress oscillation after the shear band is formed.

Based on the above results, axial length of the shear localization region (h) was selected to be 2 mm. For an axial length h=2 mm and velocity of 10~15 m/s, the experiments have been performed by varying the magnitude of the displacement. In these cases, the displacement are δ=0.5 and 1.0 mm. For the h=2 mm, the optical micrographs of plastic-deformed shear localization regions in specimens are shown in Figs. 12 and 13. The measured data for these experiments are listed in Table 2.

Shear strain (Eqs. (2) and (3)) and strain-rate (Eq. (4)) were estimated by dividing the displacement and the velocity of the incident bar by the approximate width of shear zone W. However, the shear width was determined by measuring the direction of deformed grain in the shear zone (marked in Figs. 12 and 13) using equation of tan

Table 2 Test results of hat-shaped specimen

	Deflection angle (α)	With of shear zone (W)	Shear strain (γ)	Shear strain rate ($\dot{\gamma}$)
h=2.0 δ=0.5	20°	180 μm	2.8	1.22×10^4/s
h=2.0 δ=1.0	14°	250 μm	4	1.04×10^4/s

Fig. 13 Optical micrograph of tested hat-shaped specimen (h=2, δ=1.0, magnification : x50)

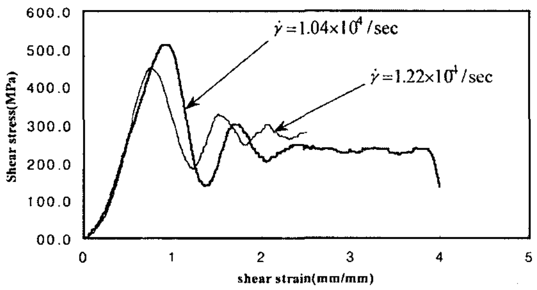

Fig. 14 The shear stress-strain curve of tough-pitch copper

α=W/δ because the thickness of the shear width is varying along the deformation direction.

Dynamic stress and strain data are plotted in Fig. 14. Where, an excessive oscillation is due to the inertia effect. The constant dynamic shear stress-strain relations in the tough-pitch copper at high strain-rates of $\dot{\gamma}=10^4$/s can be obtained when the undulation phenomena of dynamic shear stress has been replaced by an averaged one. Dynamic shear stress of tough-pitch copper has been estimated to be approximately 250 MPa.

5. Conclusions

The compressive split Hopkinson bar test was modified to perform a shear test using a hat-shaped specimen. Simulation of dynamic shear test was carried out in order to design the dimension and the shape of hat-shaped specimen. The deformation velocity was measured by picking up the displacement of the end of incident bar in terms of time using a non-contact opto-electrical equipment. And optical micrograph was used to measure the direction of shear deformation. Shear localization zone in hat-shaped specimen was determined by referring to the result of simulation and experiment. As the axial length of the shear localization region in hat-shaped specimen decreases, it generally tends to increase the initial overstress and stress oscillation after forming the shear band. With displacement of 1 mm and axial length of shear localization region of 1-2 mm, the shear zone was developed without fracture. Dynamic shear stress-strain relations in tough-pitch copper at strain-rate of $\dot{\gamma}=10^4$/s are obtained to be approximately 250 MPa.

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