Dynamic Observation of Localized Strain Pulsation Generated in the Plastic Deformation Process by Electronic Speckle Pattern Interferometry

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(Received April 3, 2000; accepted for publication November 1, 2000)

An electronic speckle pattern interferometry (ESPI) system, which makes it possible to observe dynamic phenomena, was applied to investigate the plastic deformation process in tensile experiments of aluminum alloy samples. The dynamic behavior of a strain-localized band which propagated through a specimen was thoroughly investigated. A pulsating fringe variation of the order of 1 Hz was discovered to be the fine structure of the propagating band. Fringe pulsation is caused by localized strain pulsation which suggests that the stress relaxation process propagates periodically with a time constant which governs the dissipative characteristics of a heterogeneous material.

KEYWORDS: dynamic ESPI, band propagation, plastic deformation waves, localized strain pulsation, physical mesomechanics

1. Introduction

Nondestructive testing (NDT) and inspection of structural materials are becoming increasingly important to assure the safety in the present industrial society. Conventional NDT methods have been developed mainly to detect and measure visible defects such as microcracks. However, crack generation usually occurs in the latter half of material life. It is important to investigate the material degradation processes that occurs before crack generation.

Conventional descriptions of plastic deformation and fracture are based on two approaches: (1) continuum mechanics and (2) dislocation theory. Over more than one decade, Panin et al. developed a new theory of physical mesomechanics. In their theory, plastic deformation is interpreted as a stress relaxation process associated with energy dissipation of deformational structural elements in a heterogeneous medium. They derived fundamental wave equations governing plastic deformation based on the gauge theory. There is a solution expected that plastic deformation propagates in a material as waves of self-consistent translation-rotation motion.

To reveal wave phenomena of deformation, spatiotemporal observation of a deforming object must be conducted. Motivated by the theory of physical mesomechanics, we began to try experiments on speckle interferometry or electronic speckle pattern interferometry (ESPI). In a series of tensile experiments of aluminum alloys and iron-based alloys, characteristic bandlike patterns which swept over the specimen were observed in a plastic deformation state in situ or in real time.

In this paper, the dynamic structures of the bandlike patterns observed in tensile experiments of aluminum alloy specimens are thoroughly investigated by ESPI. We discovered the interesting phenomenon of fringe pulsation accompanied by band propagation.

2. Experimental Procedure of Dynamic ESPI

Figure 1 shows the experimental setup and data acquisition flow of dynamic ESPI. A tensile specimen is illuminated symmetrically by two collimated laser beams in the xz-plane. Interference speckle patterns formed by the superposition of scattered light of two illuminating beams were taken using a charge-coupled device (CCD) camera. If the object is deformed by \( u \) along the incident plane, the optical path of each speckle between two frames is changed by

\[
\Delta = 2u \sin \alpha,
\]

where \( \alpha \) is the incident angle of the illuminating beams to the surface normal of the specimen. If \( \Delta = n\lambda (n = 0, 1, 2, \ldots) \), the correlation between two speckle patterns becomes maximum, where \( \lambda \) is the wavelength of the light. If two frames of speckle patterns in a deformation process of the specimen are subtracted, correlated areas become dark and decorrelated areas become bright. Correlation fringes of the contour of in-plane deformation can be obtained. Fringe sensitivity or the amount of deformation per unit fringe spacing is given by \( \lambda/2 \sin \theta \). In the experiment, the second-harmonic generation

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3. Experimental Results

3.1 Stress curve

Specimens of dumbbell shaped plates of polycrystalline aluminum alloy A2017 shown in Fig. 2 were prepared. They were annealed in air of 450 ± 5°C for 1 h and cooled spontaneously in furnace to the room temperature. Grain size was estimated to be 40 ± 5 µm by microscopic observation of the etched surface. The specimen was stretched on a tensile machine at a constant tensile speed, typically 3.9 ± 0.1 mm/s, in such a manner that the lower hole of the specimen caught on a cylindrical rod which was fixed at a cramp grip and the upper hole caught on a cylinder which was fixed on a moving crosshead.

Figure 3 shows a stress curve in which the stress increases linearly in the elastic deformation state which is followed by the plastic deformation state after yielding with fine zigzag variation. The observed zigzag variation, or serration, is known to be associated with strain aging called the Portevin-LeChatelier effect.8) After the maximum peak of the stress at about 5000 s, the specimen exhibited local necking and finally fractured.

3.2 Observation of band propagation on the specimen

As mentioned above, using the coarse sampling system, the entire process of deformation from the beginning to the end of a tensile test was observed in the form of animated images of fringe patterns. Original speckle patterns were taken by 40 frames/min and correlation fringes were obtained by subtraction between two frames separated by an interval of 5 frames or 7.5 s. The net movement of the upper cross-head within the interval corresponds to 30 ± 0.3 mm. In the elastic deformation state, spatially uniform fringes appeared, though fringe spacing and orientation were not regular, because fringes were affected not only by the deformation of the specimen but also by the slight tilt of the specimen introduced by unexpected frictional force around the holes catching on the cylindrical rods.

Some of the fringe pattern variations in the plastic deformation state, indicated by an arrow, after yielding of the specimen in Fig. 3 are shown in Fig. 4. The viewing area is 30 mm × 70 mm which includes the straight part of the specimen. Order numbers to obtain fringe patterns are indicated under the pictures. Fringes vary in a complicated manner but there are stable bandlike patterns which make an angle of about 45° to the tensile axis. The band patterns have no internal fringe structure. In Fig. 4, a fringe anomaly appears...
in the lower part of the 1231st pattern and it becomes a band pattern which runs over the specimen upward to the 1321st pattern. The next band appears again and runs from 1421st to the 1501st pattern. If we could see these phenomena in animated images, some interesting features of moving bands could be observed. The band would abruptly appear somewhere on the specimen and sweep over the specimen up and down at almost constant speed, and the inclination direction of the band would sometimes invert abruptly. Such complicated band movement occurred repeatedly until the specimen fractured.

Yoshida et al. were the first to observe the band phenomena. They named the band pattern the “white band”. The white band was interpreted to be generated by speckle decorrelation caused by highly localized deformation. In Fig. 4, however, the band area is indicated by a gray area rather than a white area. As will be shown in the next experiment using the fine sampling system, the band area consists of dense fringes which exceed the spatial resolution of the system and appear gray.

The average positions of moving bands were measured and plotted in Fig. 5. The trace of the band positions versus time can be approximated by a straight line. The propagation speed of the band was estimated from the gradient of the fitted line to be 0.87 mm/s.

3.3 Observation of fringe pulsation

The fine sampling system was used to observe the short-term variation of the band movement precisely in the plastic deformation state of the specimen. A sampling rate of 30 frames/s was used to acquire original speckle patterns, and correlation fringes were obtained by subtracting two frames separated by an interval of 5 frames or 1/6 s. The net movement of the upper cross-head in the interval was 0.65 μm. Some fringe patterns, in which a small area of 20 mm × 17 mm on the specimen including the band is selected, are shown in Fig. 6. The numbers given under the pictures indicate the order number to obtain correlation fringe patterns. Fringe structures can be clearly seen within the band area. The fringes vary in a complicated manner in spite of the constant loading speed. In pattern No. 2, there is no fringe except the coarse intensity variation near the bottom-right corner of the pattern. In the next pattern, No. 32 which was taken one second after pattern No. 2, fine fringes appear. In the next pattern, No. 44, fringe density becomes low again. In the next pattern, No. 68, fringe density becomes dense again. Fringes become sparse in pattern No. 87. This kind of density variation is repeated. If we observe animated images, we would see a very interesting feature of fringe pulsation as a periodic pattern of fringe density alteration. As the band front moves forward, the fringe density would alternately increase and decrease. The spatial variation of fringe density of the pattern in Fig. 6 corresponds to the gradient of local deformation in a constant time interval or localized strain velocity, which is proportional to \( \partial / \partial t (\partial u / \partial x) \). Measured results are plotted in Fig. 7 which shows that localized strain velocity varies periodically by a frequency of the order of 1 Hz. The fringe pulsation suggests that strain propagates accompanied by stable pulsating variation; we named this phenomenon “localized strain pulsation (LSP)” which will be discussed in the next section.

By comparing the fringe patterns in Figs. 4 and 6, we can understand why the band area in Fig. 4 has no fringe structure. For example, there were 31 subtracted fringe patterns for one second between fringe patterns No. 2 and No. 32 in Fig. 6. On the other hand, in Fig. 4, there is only one subtracted fringe pattern in the same interval. Therefore, there were too many fringes in the band area to be resolved using the coarse sampling system.

4. Discussions and Conclusions

In this study, we investigated the temporal dependence of the behavior of band propagation. As shown in Fig. 5, the propagation speed of the band is almost constant during one term of band propagation. The same measurement was done for four observation points as plastic deformation progressed.
The band propagation speed gradually decreased as is shown in Fig. 8. Finally, the location of the band became stationary and the specimen fractured. We observed the same phenomenon in our previous experiments.\(^7,9,10\) In the present experiment, more precise variations of the moving band were observed using the fine sampling system. Measurement of fringe pulsation was also done for four observation points. Each pulsation frequency is plotted in Fig. 8. The frequency variation also monotonously decreases.

To our knowledge, no phenomenon such as LSP in a tensile experiment under constant loading speed had been observed. The behavior we observed in this study is strongly related to the serrated variation of a stress curve. Dynamic behavior of serrated variation has been investigated for a long time, mainly from a microscopic viewpoint.\(^11\) In this study we fabricated a new tool with which to investigate spatiotemporal behavior of this phenomena. Qualitatively, the LSP seems to suggest that the stress relaxation process propagates periodically with a time constant which governs the dissipative characteristics of a heterogeneous material. Based on the physical mesomechanics presented by Panin et al., plastic deformation is interpreted as a continuous process of stress relaxation. From this point of view, plastic deformation can be interpreted as a self-organized wave due to the synergetic interaction between translational and rotational modes of displacement through which the material releases energy.\(^1,2,10\) Because of the spatial nonuniformity of the dynamics, this wave characteristic has a vortical nature. As plastic deformation progresses, the enhancement of spatial nonuniformity causes the increase in the scale level of the deformation structural element. The frequency of the LSP may depend on an eigenstate of the dynamic system of the material which is related to the scale levels of the deformation structural element. In the process, the defect density increases and the material becomes more dissipative. It is accompanied by the increase of the scale levels of the associated plastic deformation wave. This may cause the decrease in the frequency of the LSP. The moving localized band, which was observed using the coarse sampling system can be interpreted to be a result of averaging the LSP over a longer period.

**Acknowledgement**

This research was supported by a Grant-in-Aid (90019753) for Science Research of the Ministry of Education, Science, Sports and Culture, Japan. We greatly thank Dr. Sanichiro Yoshida for helpful discussions especially for his interpretation of the propagating localized band based on the physical mesomechanics.