Numerical Analysis of Adiabatic Shear Band in an Early Stage of Its Propagation

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Abstract

An adiabatic shear and produced by simple shearing in a rectangular body with a notch is analyzed numerically by the finite element method, using a stress-strain curve for the adiabatic condition, which shows an instability region due to the strain softening. Formation and propagation of the shear band are investigated for different geometrical conditions and compared with the plastic deformation of a material which has no instability region. When the plastic strain near the notch tip reaches the instability strain, the shear band starts to propagate faster than the expansion of plastic deformation area in the stable hardening material and the velocity of the shear band increases acceleratedly. A width of the shear band is estimated to be about 7 μm.

Introduction

An adiabatic shear band is a strain localization phenomenon that occurs when the rate of softening due to temperature increase is greater than the rate of work hardening due to plastic deformation. Destabilizing effect of the thermal softening in nearly adiabatic deformation was first recognized by Zener, et al.[1]. Nucleation of the shear band was correlated with the shear strain at which a slope of an adiabatic stress-strain curve is zero by Recht[2] and developed by other researchers [3,4,5]. An elementary linear perturbation analysis for the nucleation of the shear band was presented by Clifton, et al.[6] and applied by other researchers[7,8,9]. Formation of the shear band was analyzed numerically by Olson, et al.[10] using the HEMP code and by Lindholm, et al.[11] using the EPIC-2 code. The adiabatic shear band is produced not only in a dynamic deformation by high velocity impact but also in a quasi-static deformation by machining[12].

This paper deals with the formation of the shear band induced by the high speed impact. A stress-strain curve for the adiabatic condition is used to simplify governing equations for the shear band propagation. Assuming that the adiabatic stress-strain curve is expressed by a monotonic curve, and that it has a transition point where the stable strain hardening changes to the strain softening, the adiabatic shear band produced by

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simple shearing in a rectangular body with a notch is analyzed numerically by using the finite element method for an elasto-plastic material. Formation and propagation of the adiabatic shear band in an early stage of its propagation are investigated for different geometical conditions and compared with the expansion of plastic deformation produced in the same geometry of a material which shows a parabolic work hardening and no instability region due to the absence of strain softening.

Adiabatic shear band

It has been reported that the adiabatic shear bands are observed under loading conditions corresponding to simple tension, pure shear, and combined compression and shear, that cracks and voids are often found along the shear band, and that the shear band frequently precedes fragmentation and fracture[12]. The shear bands produced in a target of Ti-6%Al-4%V and in a projectile of steel (1.2%C, 0.2%Mn) are shown in Fig. 1, obtained by one of the authors and Grebe [13]. Fig. 1(a) shows that the adiabatic shear band propagated along the slip-line [14] which inclines at 45 degrees to an axis of principal stress and the shear band is so narrow as 1-8 μm wide. Fig. 1(b) shows that the width of shear bands is rather large like 1-100 μm. Heat generated by the large plastic deformation makes the material so softened that the material shows a mechanical behavior of instability when the thermal softening overcomes the strain hardening and the strain-rate hardening.

The propagation of shear band is supposed to start from the tip of a microcrack or groove near an impact surface and to be accelerated by the shear stress. It is very difficult to obtain a solution which satisfies the mechanical equations and boundary conditions perfectly. Because, the shear band takes place as a transient phenomenon and the mechanics for this problem includes the increase of the flow stress of the material at high

Fig. 1. (a) Adiabatic shear band in the target of Ti-6%Al-4%V, and (b) extensive shear band in the projectile of steel.

strain-rate, heat generation due to the plastic deformation, its thermal conductivity, and inertia term not only in the shear band but also in the whole area induced by the high velocity impact. The authors investigate the propagation of the shear band produced by simple shearing in the rectangular body with the notch and one in the early stage of its propagation to neglect the inertia term in the shear band. Owing to the propagation and reflection of the shear stress wave induced by the high velocity impact, deformation of the rectangular body is considered to approach asymptotically to a deformation in quasi-static equilibrium produced by simple shearing. Then, the authors use the experimental stress-strain curve for the adiabatic condition instead of considering the inertia term necessary for the propagation of the shear stress wave, which means that the increase of flow stress at high strain-rate is considered, that the thermal energy converted from the plastic work is stored in every element of the body, and that the thermal conductivity is not considered.

The adiabatic stress-strain curve is expressed by using the effective stress $\overline{\sigma}$ and the effective plastic strain $\overline{\varepsilon}_p$ as [10],

$$\overline{\sigma}=\overline{\sigma}_0(1+\alpha'\overline{\varepsilon}_p)\exp(-\beta'\overline{\varepsilon}_p). \quad (1)$$

Material constants at high shear strain-rate of $\dot{\gamma}=10^2$/s for high-strength steel (HY-TUF) are $\overline{\sigma}_0$ =1588.3 MPa, α'=13.6, and β'=7.24. Maximum stress $\overline{\sigma}_{max}$ of the curve at the transition point is 1868.9 MPa where $\overline{\varepsilon}_{pi}$=0.0646. Material constants for the elastic deformation are E=2.067x10^5 MPa for Young's modulus and ν =0.28 for Poisson's ratio. This kind of material has already been used to examine the formation of shear band by Olson, et al.[10]. The adiabatic stress-strain curve of Eq. (1) is shown in Fig. 2 by a solid curve In order

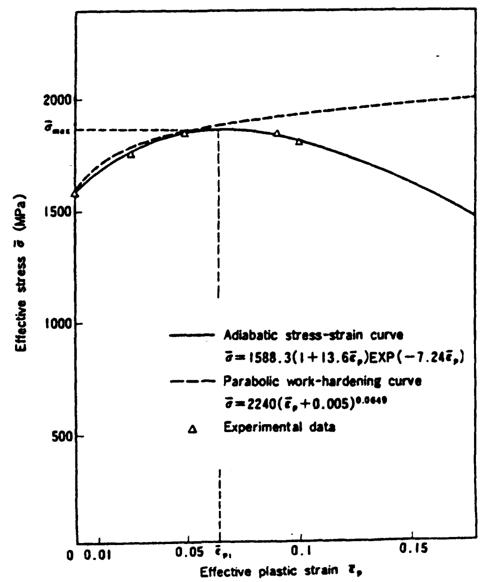

Fig. 2. Stress-strain curves used in FEM code and experimental data from a literature [10].

to compare the propagation of the shear band with expansion of the plastic deformation area produced in the material which has no instability region, the parabolic work-hardening curve shown by a broken curve in Fig. 2 is used. The curve is expressed by

$$\bar{\sigma}=2240(\bar{\varepsilon}_p+0.005)^{0.0649}. \quad (2)$$

Numerical Analysis

The finite element method for elasto-plastic material[15] modified from Swedlow's code[16] is used for analysis. The mechanical behavior of the material obeys the von Mises flow criterion and the incremental theory of Prandtl-Reuss. Deformation of the rectangular body is treated as a problem of plane strain and tangential displacements are given along clamping points to produce shear deformation. The displacement function of triangular elements is expressed by a linear polynomial. The Gauss elimination method is used.

A mesh division used for analysis by the finite element method is shown in Fig. 3, where the specimen is a rectangle of 400 μm in width and 500 μm in length having a notch of 60 μm in depth and 20 μm in width with a semicircular end of 10 μm in radius. A boundary BAB′ corresponds to a groove and a boundary CC′ to a free surface near an impacted area. The tangential displacement is given along the boundary CD of the clamping points in x-direction to produce simple shear deformation due to the high velocity impact and the boundary C′D′ in opposite and their boundaries in y-direction are fixed. A boundary line DED′ keeps linear during the displacement of the line in x-direction as shown in Fig. 3(b), and no point on the line moves in y-direction.

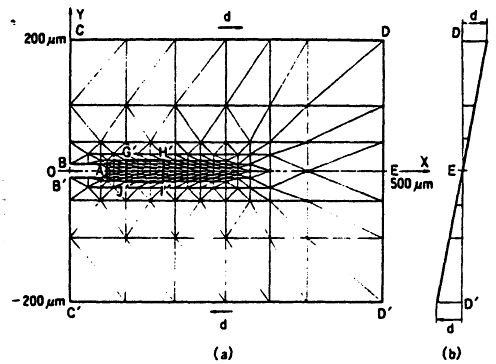

Fig. 3. (a) Mesh division used for simple shear deformation, and (b) boundary displacement imposed along boundary DED′.

Formation of Shear Band

Simple shear deformation of the rectangular body and contour lines of isostress (effective stress $\bar{\sigma}$) and of isostrain (effective plastic strain $\bar{\varepsilon}_p$) are shown in Fig. 4, when the tangential displacement d is 6.87 μm. The plastic deformation produced by the simple shearing is confined to a small area around the notch tip but takes place deep along the notch direction in the specimen.

A solid curve in Fig. 4 shows a contour line of $\bar{\varepsilon}_p=0.0646$, which value corresponds to the instability strain $\bar{\varepsilon}_{pi}$. The stress outside the contour line increases with the increasing plastic strain owing to strain hardening, but the stress inside the contour line decreases due to strain softening. This behavior is seen in more detail in Fig. 5, which shows the distributions of stress and plastic strain in the vicinity of the notch tip. A strip-zone surrounded by the solid curve in Figs. 4 and 5 is considered to correspond to the shear band. A tip of the contour line

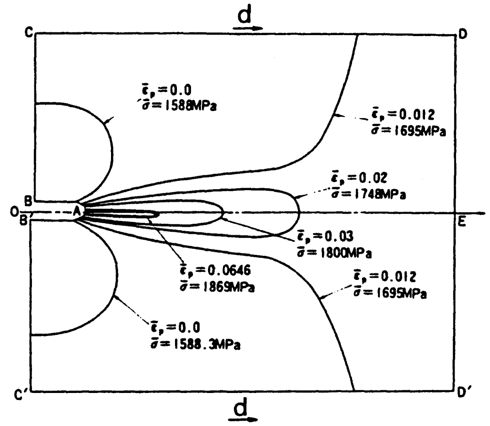

Fig. 4. Deformation of the notched body produced by tangential displacement of d=6.87 μm, and isostress ($\bar{\sigma}$) and isostrain ($\bar{\varepsilon}_p$) contour lines in material with adiabatic curve.

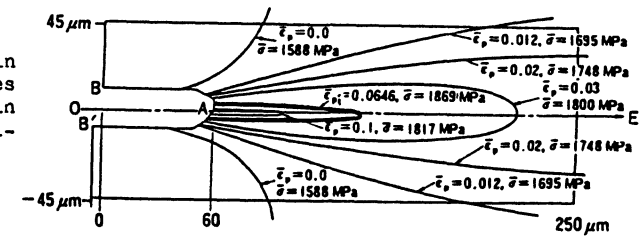

Fig. 5. Isostress ($\bar{\sigma}$) and isostrain ($\bar{\varepsilon}_p$) contour lines near the notch in material with adiabatic curve.

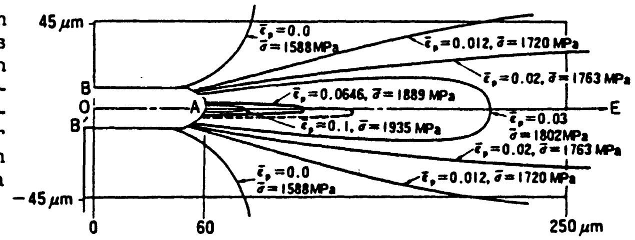

Fig. 6. Isostress ($\bar{\sigma}$) and isostrain ($\bar{\varepsilon}_p$) contour lines near the notch in material of parabolic curve. Propagation of the shear band of $\bar{\varepsilon}_{pi}$ in Fig. 5 is shown by a broken curve.

of the shear band reaches a distance of 80 μm from the notch tip.

Figure 6 shows the distributions of stress and plastic strain at d=6.87 μm in the vicinity of the notch tip in the material which shows no instability region of Eq. (2). The deformation of the body and the distributions of stress and strain are almost the same with those in the material of the adiabatic curve except in the vicinity of the notch tip. A contour line of isostrain $\overline{\varepsilon}_p$ =0.0646 is shown by a solid curve in Fig. 6. The stress inside the contour line increases with the increasing plastic strain. This behavior is opposite to the result obtained in the adiabatic curve.

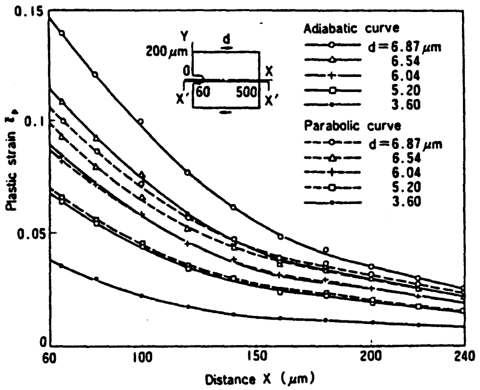

Fig. 7. Comparison of plastic strain distributions along X′X′ between material with adiabatic curve and material with parabolic curve.

Propagation of Shear Band in Its Early Stage

Variations of the plastic-strain distribution with the tangential displacement d are shown in Figs. 7 and 8. The stress concentration around the notch produces a large plastic strain in a large extent far from the notch tip in Fig. 7, while the large plastic strain is restricted in a very narrow zone whose width is close to the notch width in Fig. 8. As the tangential displacement becomes more than 6.04 μm, a difference in plastic strain between the adiabatic curve and the parabolic curve increases rapidly.

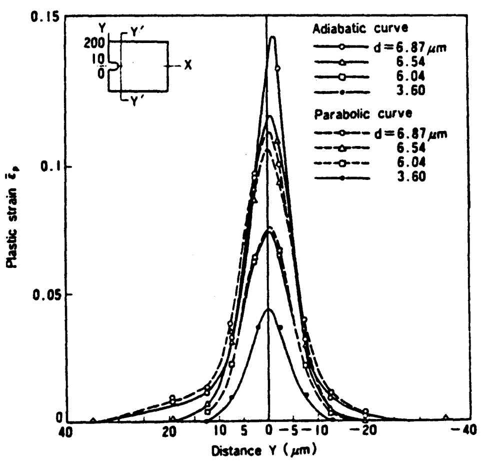

Fig. 8. Comparison of plastic strain distributions along Y′Y′ between material with adiabatic curve and material with parabolic curve

The increase of plastic strain near the notch tip is shown in Fig. 9. The travelling distance s of the plastic deformation area, defined as a distance from the tip of the contour line of $\overline{\varepsilon}_p$ =0.0646 to the notch tip, is shown in Fig. 10. When the displacement d is more than 6.0 μm, the plastic strain and the travelling distance in a case of the adiabatic curve increase rapidly, as compared with those in case of the parabolic curve.

To examine a propagating tip of the shear band precisely, deformation of a part surrounded by G′H′I′J′ in the rectangular body in Fig. 3(a) is re-analyzed, by using a finer mesh than that in Fig. 3(a) and giving the same displacement along the contour of the finer meshed area as the displacement obtained along the boundary G′H′I′J′. Numerical results of Fig. 11 show that the width of shear band shown by a solid curve is close to 7 μm in a case where the notch width is 20 μm.

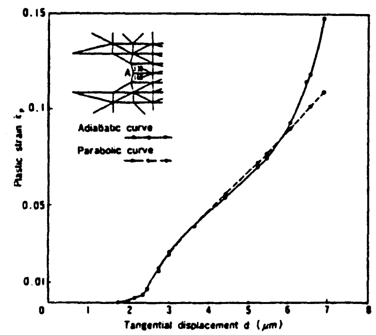

Fig. 9. Plastic strain $\overline{\varepsilon}_p$ in an element 160 as a function of tangential displacement d for both adiabatic and parabolic curves.

Geometrical Effect on Initiation of Shear Band

The numerical results in the previous sections show that the shear band is generated at a tip of the notch and propagated into a material in a deep notch. Therefore, the shear band in a

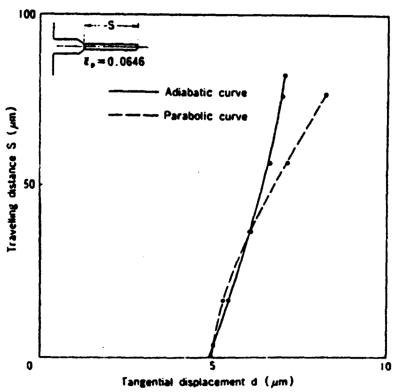

Fig. 10. length of shear band for adiabatic curve compared with corresponding distance s for parabolic curve

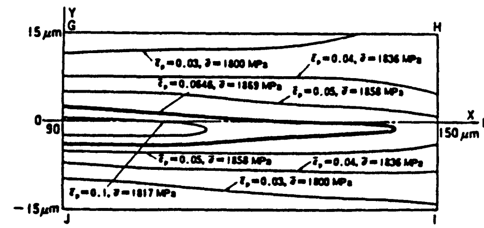

Fig. 11. Isostress ($\overline{\sigma}$) and isostrain ($\overline{\varepsilon}_p$) contour lines near a tip of the shear band in material with adiabatic curve.

shallow notch is investigated. The shallow notch is assumed to be a semicircle of 10 μm in depth, and distance L from the notch to the clamping points along which the tangential displacement is given is varied. Three of their numerical results are shown in Figs. 12 and 13.

When the distance L is 400 μm, the instability strain $\bar{\varepsilon}_{pi}$ occurs first on the element 83 far from the notch at 88th step. Thereafter, the element of instability spreads out along the boundaries D_1E and C_1D_1, but it does not reach the notch tip. When the distance L is 15 μm, the instability strain occurs first on the element 85 at 52nd step. Thereafter, the instability area propagates into the material from the notch tip.

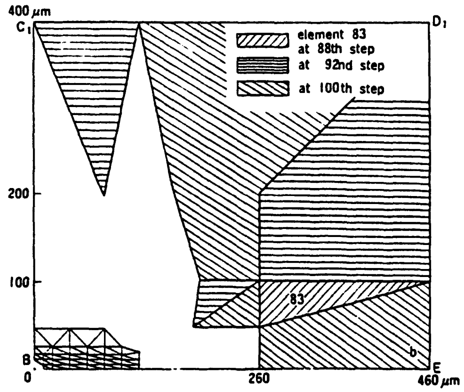

Fig. 12. Progression of the instability area $\bar{\varepsilon}_{pi}$ when L=400 μm.

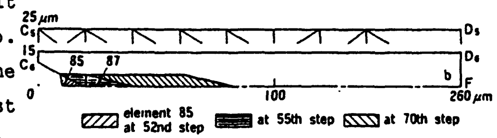

Fig. 13. Propagation of the instability area $\bar{\varepsilon}_{pi}$ when L=15 μm.

Conclusions

The adiabatic shear band produced by simple shearing in a rectangular body with a notch has been analyzed numerically by the finite element method, using the stress-strain curve for the adiabatic condition, which has the instability region due to strain softening. The following conclusions are obtained in comparison with the numerical results obtained in a material of parabolic work-hardening curve which shows no instability.

(1) Large plastic strain produced by simple shearing is limited in a small area around a tip of the notch and takes place deep along the notch direction. There is not a remarkable difference in the whole area except around the notch tip between both the materials of the adiabatic curve and the parabolic curve.

(2) However, large difference of the stress and strain distribution is seen near the notch. In a case of the adiabatic curve, the stress $\bar{\sigma}$ inside

the contour line of isostrain $\bar{\varepsilon}_{pi}$ (the instability plastic strain at the transition point) decreases due to strain softening with the increasing plastic strain. Though, in a case of the parabolic curve, the stress in the contour line increases due to work hardening. A narrow strip-zone surrounded by the contour line of isostrain $\bar{\varepsilon}_{pi}$ in the material of the adiabatic curve is considered to correspond to the adiabatic shear band.

(3) The shear band begins to propagate faster than the expansion of the plastic deformation area produced in the material of the parabolic curve and the velocity of the shear band increases acceleratedly, when the plastic strain on the several elements near the notch tip reaches the instability strain $\bar{\varepsilon}_{pi}$.

(4) The width of shear band is estimated to be about 7 μm in a case where the notch width is 20 μm.

(5) The shear band is generated at the notch tip and penetrates into the material in a case of the deep notch as mentioned above. However, in a case of the shallow notch, a small distance from the notch to the clamping points, along which the tangential displacement is given, is necessary to produce the shear band at the notch tip and propagate it into the material by means of only simple shearing. Because, the presence of a free surface near the notch relieves a stress concentration around the notch tip considerably.

From these conclusions, the authors consider that stresses transverse to the notch may have a strong influence on the initiation of shear band to make a large stress concentration even at common shallow grooves existing on the ordinary surface of the specimen. When the shear band propagates at a high speed, the flow stress of the material in the shear band is presumed to be decreased considerably because of thermal softening due to large plastic deformation in it. If the flow stress in the shear band is considered to be negligible, distributions of stress and strain around the tip of shear band may be inferred to be close to ones around the tip of deep notch described in this paper.

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