Numerical and Experimental Investigation of Adiabatic Shear Bands in Metals under Low-Velocity Impact Conditions

E. Irick, C. Heinol, T. Clayton, J. Hashemi, J.F. Cardenas-Garcia, and R. Sadhneni

Adiabatic shear bands are localized regions of intense plastic deformation that form when materials are subjected to high-strain-rate loading and are generally considered to be precursors to fracture. The objectives of this paper were to study adiabatic shear bands generated in commercially pure titanium and pearlitic AISI 4140 steel utilizing a controlled-penetration impact setup and to model the dynamic shear-band formation process using a Lagrangian finite-element code. Results showed that utilization of the controlled-penetration impact experimental apparatus significantly lowered the required impact velocity for formation of adiabatic shear bands in the materials tested. The length and location of the formed shear bands were controllable and extremely sensitive to the prescribed depth of penetration, allowing for the generation of crack-free shear bands. Microhardness testing of the band material revealed it to be considerably harder than the surrounding material, which possibly indicates rapid quenching of the heated band material. The finite-element simulation results showed that it is possible to realistically model adiabatic shear banding for a range of different materials.

Keywords
adiabatic shear bands, simulation, steel, structure, titanium

1. Introduction

MECHANICAL LOADING of materials at low strain rates allows the heat generated by plastic strain to dissipate in almost isothermal conditions. Thus, materials proceed to strain harden, and the flow stress is found to increase monotonically with strain until failure. At high strain rates, however, the heat generated by plastic strain has no time to flow to neighboring regions, and the deformation process is closer to adiabatic. This localized heat generation and temperature increase result in a thermal softening effect in the affected region. Therefore, at high strain rates, the material undergoes not only strain-hardening effects but also thermal-softening effects. Consequently, if the thermal-softening rate overcomes the strain-hardening rate, the flow stress decreases with strain, resulting in a convex stress-strain curve with a maximum flow stress separating the hardening and softening regimes.

For example, in the practical case of a workpiece undergoing dynamic loading, a small region in the workpiece may be subjected to a strain-softening regime while the majority of the workpiece material, in the surrounding region, is still in the strain-hardening regime. Further dynamic loading of the workpiece will cause this small strain-softened region to deform more than the surrounding harder material, resulting in additional heat generation and temperature rise, thus making this region even more susceptible to further localized deformation. This localized strain condition usually manifests itself in the form of shear-band formation, with measured widths of anywhere from 5 to 100 μm and strains of 5 to 100 (Ref 1, 2). The corresponding strain rate in the formed shear band is estimated to be between 10^4 and 10^6/s, and the temperature rise in the shear band is estimated to be several hundred degrees Celsius (Ref 3). Two types of shear bands may be observed: deformed bands and transformed bands. Deformed bands show no microstructural differences between the material within and outside the band. Transformed bands do show microstructural differences, which are associated with a phase change of the material within the band.

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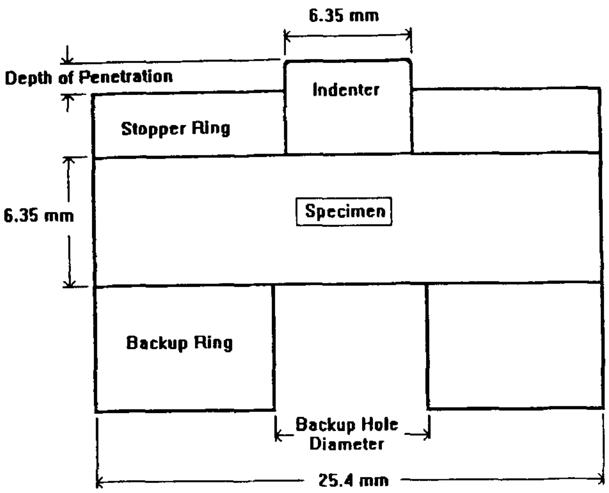
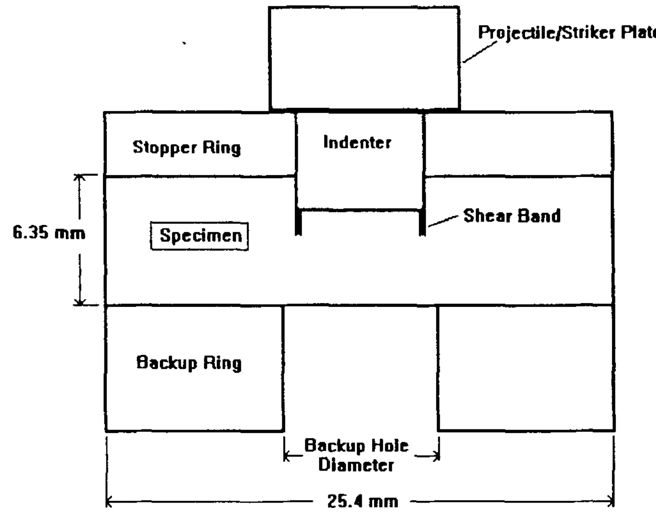
Adiabatic shear-band formation has been studied extensively in recent years (Ref 4-6). It plays an important role in many diverse areas, such as ballistic impact, explosive fragmentation, high-speed forming and shaping, machining, and impact initiation of explosives. Although shear banding has been primarily studied experimentally, the development of analytical theory and, more recently, numerical simulation approaches has benefited its study. The main methods used to generate shear bands experimentally include: explosively loaded cylinders (Ref 7), high-speed machining tests (Ref 8), dynamic torsion tests (Ref 9, 10), and dynamic impact tests (Ref 11). The study of shear bands with these sophisticated experimental techniques is difficult at best, due to problems related to controlling shear-banding location and length. Furthermore, all the test techniques mentioned here require the imparting of extremely large forces on the workpiece.

There are several variations in the implementation of dynamic impact tests. Zener and Hollomon (Ref 12), who were among the first to study shear bands, used a dropped weight on a punch experimental setup to produce shear bands. Stock and Wingrove (Ref 11) employed a basic dynamic punching apparatus to study the energy required for shearing of steel rods. Wingrove (Ref 13) later used a "stepped" projectile to investigate shear banding. Recent techniques have been developed to study the formation of adiabatic shear bands to achieve a more controlled testing environment. One such approach uses a hat-shaped specimen load in a split Hopkinson bar (Ref 14), which



(a)



(b)

Fig. 1 Controlled-penetration impact apparatus. (a) Before impact. (b) After impact

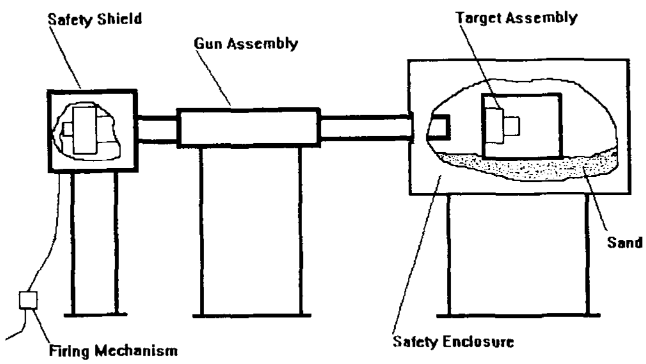


Fig. 2 Powder gun setup

allowed the investigators to arrest the deformation process and permitted the development of shear bands under controlled stress conditions. A disadvantage of using this technique is the required use of a split Hopkinson bar, a specialty instrument. In addition, precision machining of the test specimen needs to be performed prior to testing. The simplest approach to the creation of controlled shear bands was that proposed by Chou et al. (Ref 15), which achieved controlled-penetration impact using a simple drop-weight apparatus to test various types of steel specimens. The most salient characteristic of this experimental approach is its ability to achieve shear-band formation in the materials tested at low impact velocities.

In this paper, the apparatus developed by Chou et al. (Ref 15) is utilized to study adiabatic shear bands generated in commercially pure titanium and pearlitic AISI 4140 steel (Ref 21). It is shown that by using this apparatus, well-defined shear bands with no accompanying cracks can be formed by controlling the loading conditions and depth of penetration. This is especially important when studying titanium, because formation of shear bands and crack generation are believed to be inseparable in this material. In addition, a Lagrangian finite-element code is utilized to model the dynamic shear-band formation process.

2. Experimental Setup

A schematic diagram, with dimensions, of the cross-sectional view of the controlled-penetration impact apparatus proposed by Chou et al. (Ref 15) and used in this investigation is shown in Fig. 1. Included in this experimental setup are a projectile, an indenter, a stopper, and a backup ring. The projectile may be launched toward the indenter in a drop-weight configuration for low-velocity impact (less than 10 m/s) or from a powder gun for higher-velocity impact (greater than 10 m/s). The projectile then drives the indenter into the target specimen. A stopper ring is positioned around the penetrator to stop the projectile as it comes in contact with the stopper ring (the momentum of the projectile is dispersed onto a larger contact area when it comes in contact with the stopper ring). The depth of penetration is controlled by the difference in height of the penetrator and the stopper. As a result, the projectile does not contact the target, and the depth of penetration is fully controlled. A backup ring is situated below the target to stop the axial flow of the target material everywhere except directly under the indenter region. This allows forced flow of metal into the backup hole region, making shear banding more probable at lower velocities. A backup hole diameter of 6.4 mm was used in this research. Different stopper thicknesses were used with a constant indenter height of 1.778 mm, resulting in various depths of penetration.

2.1 *Target Material*

AISI 4140 steel in its pearlitic condition and commercially pure titanium were used as target materials. Test specimens for both materials were machined to a diameter of 25.4 mm and a height of 6.4 mm. The steel target specimens were machined and then austenitized at 810 °C for 1 h, after which they were allowed to air cool back to room temperature. Titanium was used as is, except for machining it into shape. The pearlitic steel specimens exhibited a microhardness of 28 HRC, while the titanium target specimens exhibited a microhardness of 99 HRB.

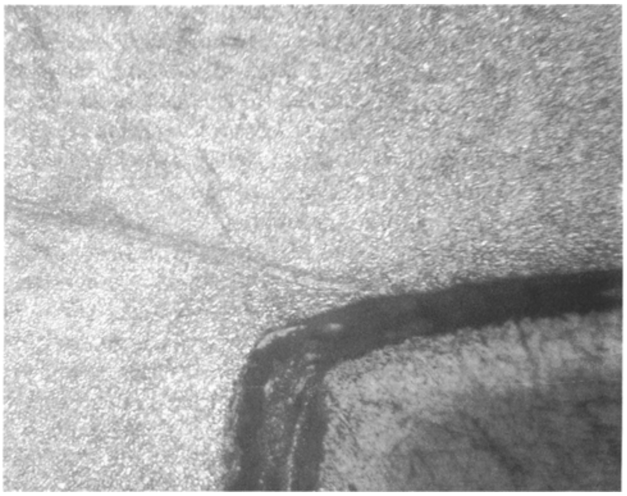


Fig. 3 AISI 4140 (pearlitic structure), transformed band. 200×

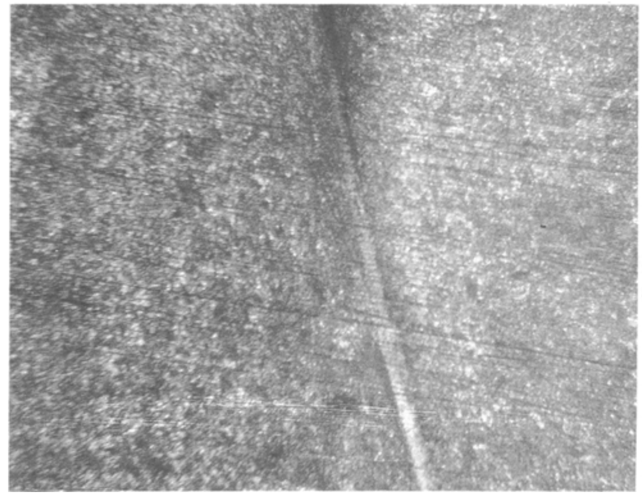


Fig. 4 AISI 4140 (pearlitic structure), transformed band. 200×

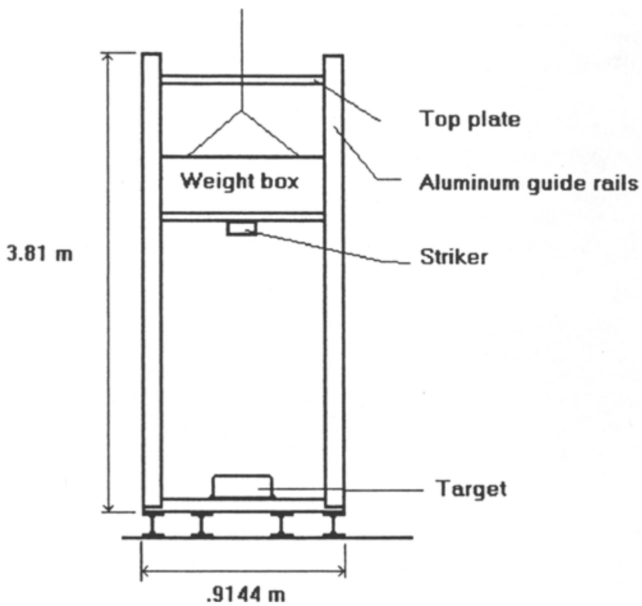


Fig. 5 Schematic of the drop-weight apparatus

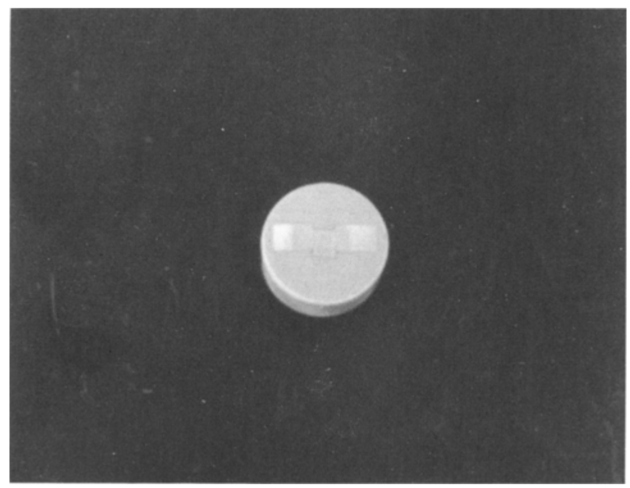


Fig. 6 Sectioned, polished, and etched specimen showing plugging

2.2 *AISI 4140 Steel Test Results*

The first series of tests was performed on AISI 4140 steel. The initial test was performed with a prescribed depth of penetration of 0.75 mm, a backup hole diameter of 6.4 mm, and a powder-gun driven projectile speed of 95 m/s. The gun/target assembly is schematically presented in Fig. 2, which shows components of the controlled-penetration apparatus positioned in the target fixture. After testing, all target specimens were sectioned, mounted, polished, and etched (2% nital solution). This first test failed to achieve the desired result of shear-band formation without fracture. The results, presented in the micrograph in Fig. 3, show a deformed and transformed shear band accompanied by fracture. The transformed band, etched white due to the application of the nital etchant, represents a phase change of the material within the band (ferrite is transformed to face-centered cubic austenite, which, due to fast quenching by surrounding material, forms martensite). This phase change is a direct result of the rise in temperature within the band due to plastic strain deformation.

Another test was performed with a prescribed depth of penetration of 0.49 mm and a projectile velocity of 100 m/s. The depth of penetration was reduced to attempt to form a partial shear band with no fracture lines. This test was successful in producing a transformed band of approximately 2.18 mm length and an average width of 40 μm without fractures along the shear band. The micrograph of this test result is shown in Fig. 4.

It is notable that, in both cases, shear bands were generated at projectile impact velocities significantly lower than the velocities normally associated with shear-band generation in steel (anywhere from 700 to 1500 m/s using typical projectile impact experimental setups). In addition, the microhardness within the band was found to have increased to 66 HRC, indicating formation of martensite.

2.3 *Titanium Test Results*

The titanium targets were tested using a drop-weight apparatus because of their significantly softer composition as compared to steel. A schematic of the experimental setup is shown in Fig. 5. The first three tests were performed at a prescribed penetration depth of 3.12 mm, with a backup hole diameter of 6.4 mm for all tests. The mass of the striking weight was 22.5 kg. The drop height varied from 1.82 m (for an impact velocity of 5.97 m/s) in test 1 to 1.52 m (for an impact velocity of 5.45 m/s) in test 2 and 1.21 m (for an impact velocity of 4.85 m/s) in test 3. After each test, the specimens were sectioned, mounted, polished, and etched (ammonium hydroxide). In all cases plugging was observed; a typical result is shown in Fig. 6.

Careful examination of the prepared test 1 and test 2 samples revealed regions of intense deformation followed by fracture (Fig. 7 and 8). Figure 7 shows an area close to the plugging region where signs of intense strain leading to crack formation are discernible. Another region of the same specimen (Fig. 8) shows a white shear band that exhibits no distinguishable microstructure, which hints at formation of a transformed shear band in titanium. It appears that the simultaneous existence of shear bands and cracks is common in titanium under the experimental conditions employed for these two tests.

The experimental conditions used for the third test were successful in generating a shear band without the disadvantage of a crack. A clearly formed shear band is shown in Fig. 9. A higher-magnification micrograph of this same region is presented in Fig. 10, which shows the intense shearing action in the shear band with greater clarity. It is clear that the material in the band is heavily distorted, and no granular microstructure is discernible within the band. These results serve to illustrate the versatility of the experimental setup used, so as to control shear-band formation with or without cracking.

Additional tests were performed to explore less severe shear banding by dropping a weight from a height of 1.21 m, with a

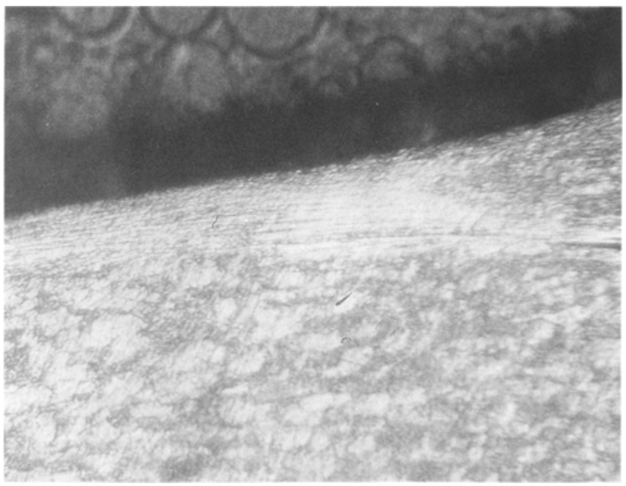


Fig. 7 Intense deformation band in titanium. 200×

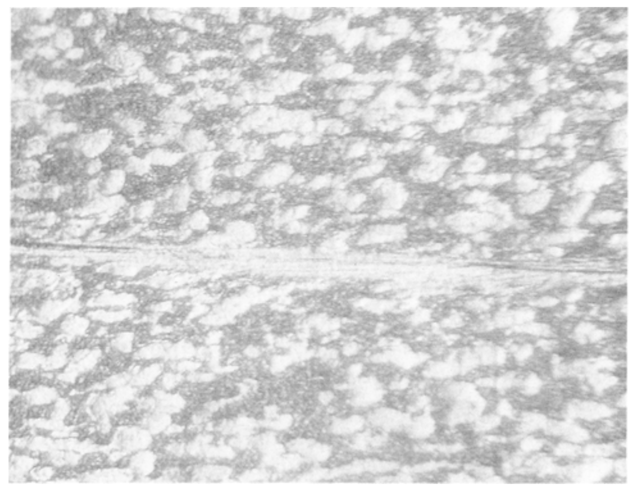


Fig. 8 Transformed band in titanium accompanied by fracture. 200×

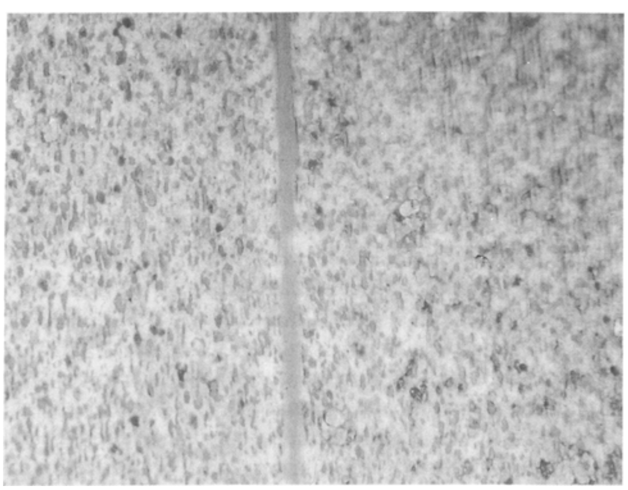


Fig. 9 Transformed band formed in titanium without fracture. 200×

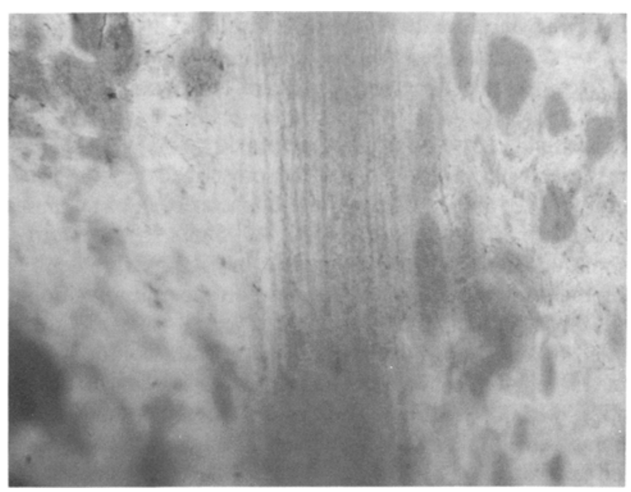


Fig. 10 Higher-magnification view of transformed band shown in Fig. 9. 2000×

prescribed depth of penetration of 1.52 mm. These tests resulted in minor bulging in the tested specimen without any plugging. Microstructural examination of the target material revealed less discernible shear-band formation (Fig. 11). Other tests were also performed in which the target material temperature was raised to 800 °C prior to impact. Microstructural examination of the tested specimens revealed a much wider shear band.

3. Numerical Experiments

Numerous attempts have been made to model adiabatic shear bands in metals. Most modeling has been done under conditions of plane-strain compression or tension, with varying specimen geometries: incorporating a central hole, without a central hole, or with artificial disturbances introduced at their centers (Ref 16-18). More recent work by Chou et al. (Ref 15) deals with the problem of shear banding due to the axisymmetric penetration of a cylindrical specimen by a projectile/indenter and is pertinent to the experimental work presented in this paper. The modeling work done by Chou et al. is performed using a hydrocode, DEFEL, incorporating the Johnson-Cook constitutive equation.

DEFEL computer code is a two-dimensional Lagrangian hydrocode designed for analysis of impact problems. The theoretical formulation of this compute code, its capabilities, and its effectiveness in dealing with strain-localization problems have been extensively demonstrated (Ref 15, 19). One feature of this computer code is that it uses constant-strain, triangular-mesh elements to model the shear-banding process, a feature that is extensively accepted for modeling localized flow problems. The inherent rigidity of these elements makes them suitable for large deformation analysis of impact problems and precludes the introduction of artificial defects or disturbances in the mesh to initiate the localization process.

A finite-element mesh of the previously described experimental setup was generated and is presented in Fig. 12. Several computer simulations were then implemented using the DEFEL computer code to model the formation of adiabatic shear bands in copper, steel, and tungsten under identical impact conditions. Titanium was not used in these simulations due to the unavailability of the Johnson-Cook equation constants. In all cases the backup hole diameter was set at 11 mm, the depth of penetration at 0.8 mm, and the impact speed at 50 m/s.

Figure 13(a) shows the true stress/true strain curves as depicted by Johnson and Cook (Ref 20) for the three materials. Figure 13(b) shows the corresponding simulation results of modeling shear banding in these three materials. It is evident from Fig. 13(b) that the simulation for steel shows localized deformation in a band. This localization is found to be primarily due to the strain-hardening rate being overcome by the high thermal-softening rate in steel. In order to attempt a demonstration of the qualitative validity of the simulation model in steel,

Fig. 11 Deformed band formed in titanium. 200×

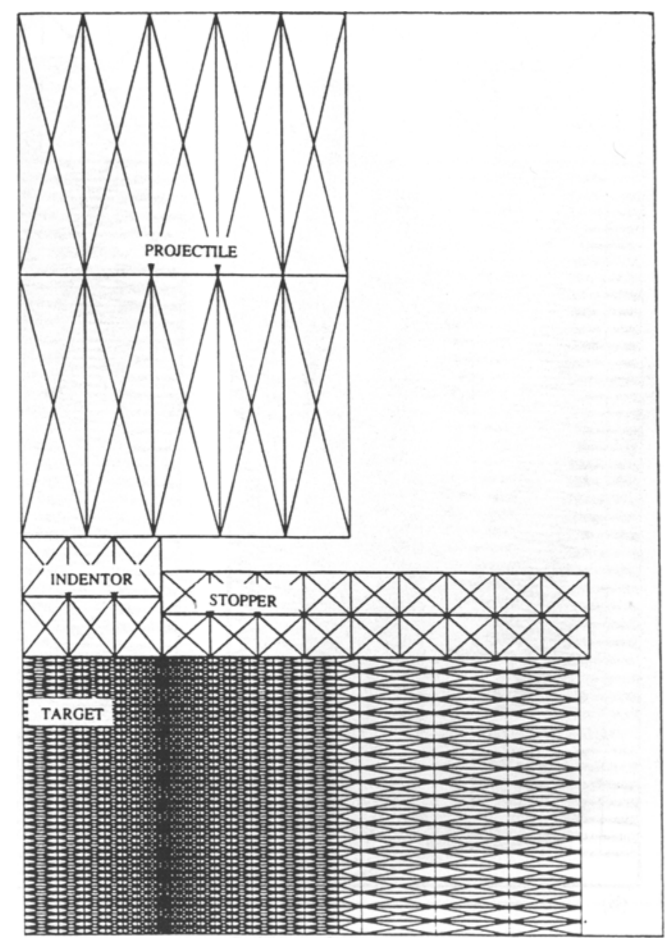


Fig. 12 Initial geometry of the finite-element model

a similar simulation was performed on copper, a material with little tendency toward localization of strain. All input parameters were the same except for those related to the material properties of copper, referred to above, in Fig. 13(a). Figure 13(b) shows the corresponding deformation field for copper, which does not show a high tendency toward localized deformation, pointing to the ability of the DEFEL code to discriminate between simulation materials. Another simulation was also per-

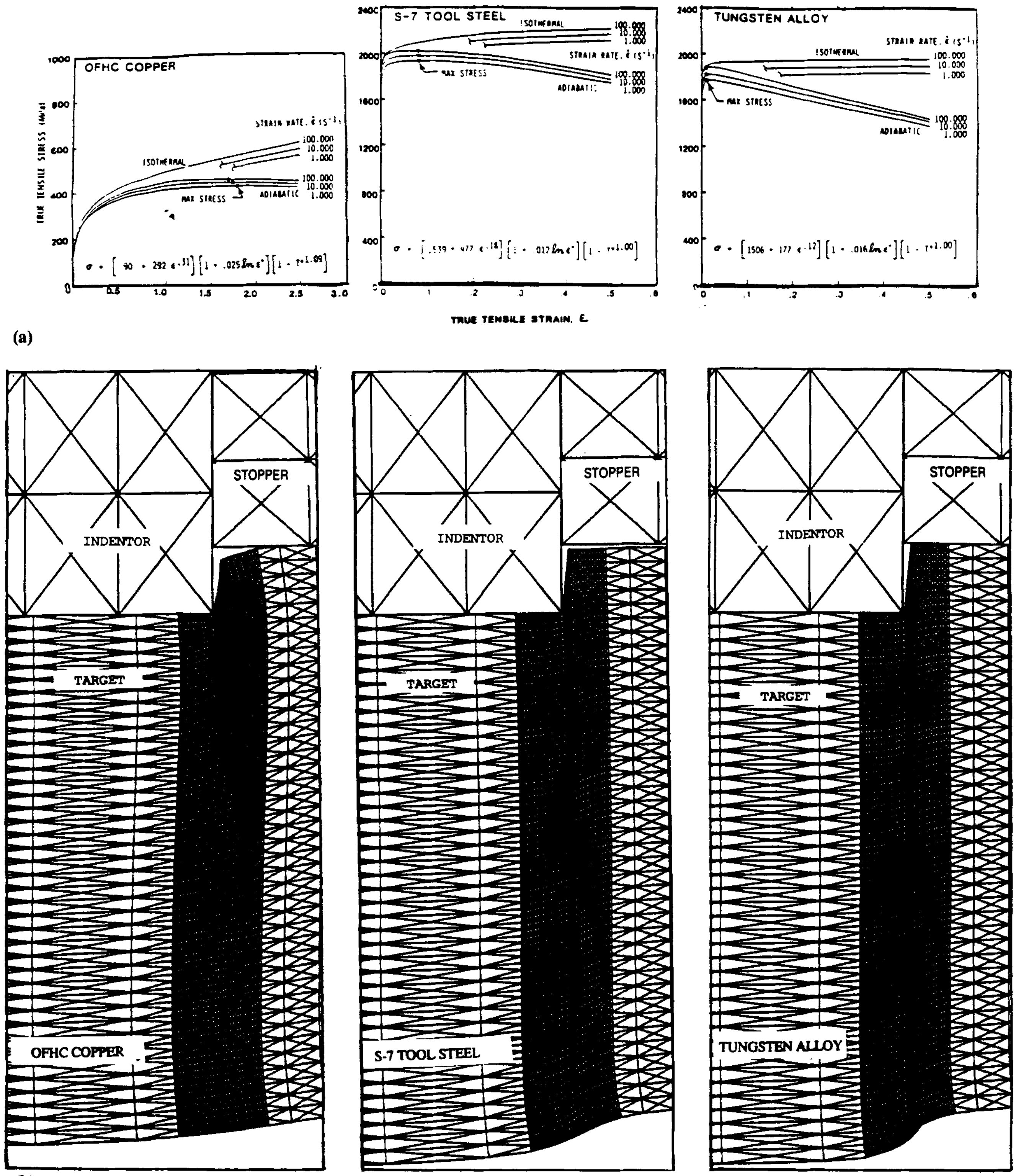


Fig. 13 (a) True stress/true strain curves for copper, steel, and tungsten (adopted from Ref 20). (b) Simulation of the deformation field in copper, steel, and tungsten targets after impact

formed with tungsten, a test material which Fig. 13(a) suggests is more susceptible to localized deformation than steel. The results in Fig. 13(b) clearly confirm this, once again showing the qualitative sensitivity of the DEFEL code simulation that distinguishes shear-band formation tendencies between materials.

One additional consideration relating to the performed numerical calculations is that the aspect ratio (the ratio of height to base of a triangular element) of the finite elements must be examined in order to evaluate its effect on the simulation. Thus, the simulation of shear banding in steel was performed using three different finite-element aspect ratios: 3 (Fig. 14a), 1 (Fig. 14b), and 1/3 (Fig. 14c). Because the width of the localized region is controlled by the size of the base of the triangle, aspect ratios of less than 1 predict unrealistic widths, underpredicting the length of the shear band. The results portrayed in Fig. 14 show that qualitatively best results for shear-band formation are produced when the aspect ratio is closer to 1.

4. Summary of Results and Conclusions

This paper has experimentally examined the formation of adiabatic shear bands in commercially pure titanium and pearlitic AISI 4140 steel utilizing a controlled-penetration impact experimental setup and has modeled the dynamic shear-band formation process using DEFEL, a Lagrangian finite-element code. The research results show that the utilization of the controlled-penetration impact experimental apparatus significantly lowered the required impact velocity for formation of adiabatic shear bands in the materials tested. The length and location of the formed shear bands were controllable and extremely sensitive to the prescribed depth of penetration, allowing for the generation of crack-free shear bands. Microhardness testing of the band material revealed it to be considerably harder than the surrounding material, which may indicate the existence of transformed shear bands due to the rapid quenching of the heated band material. The finite-element simulation results showed that it is possible to qualitatively and

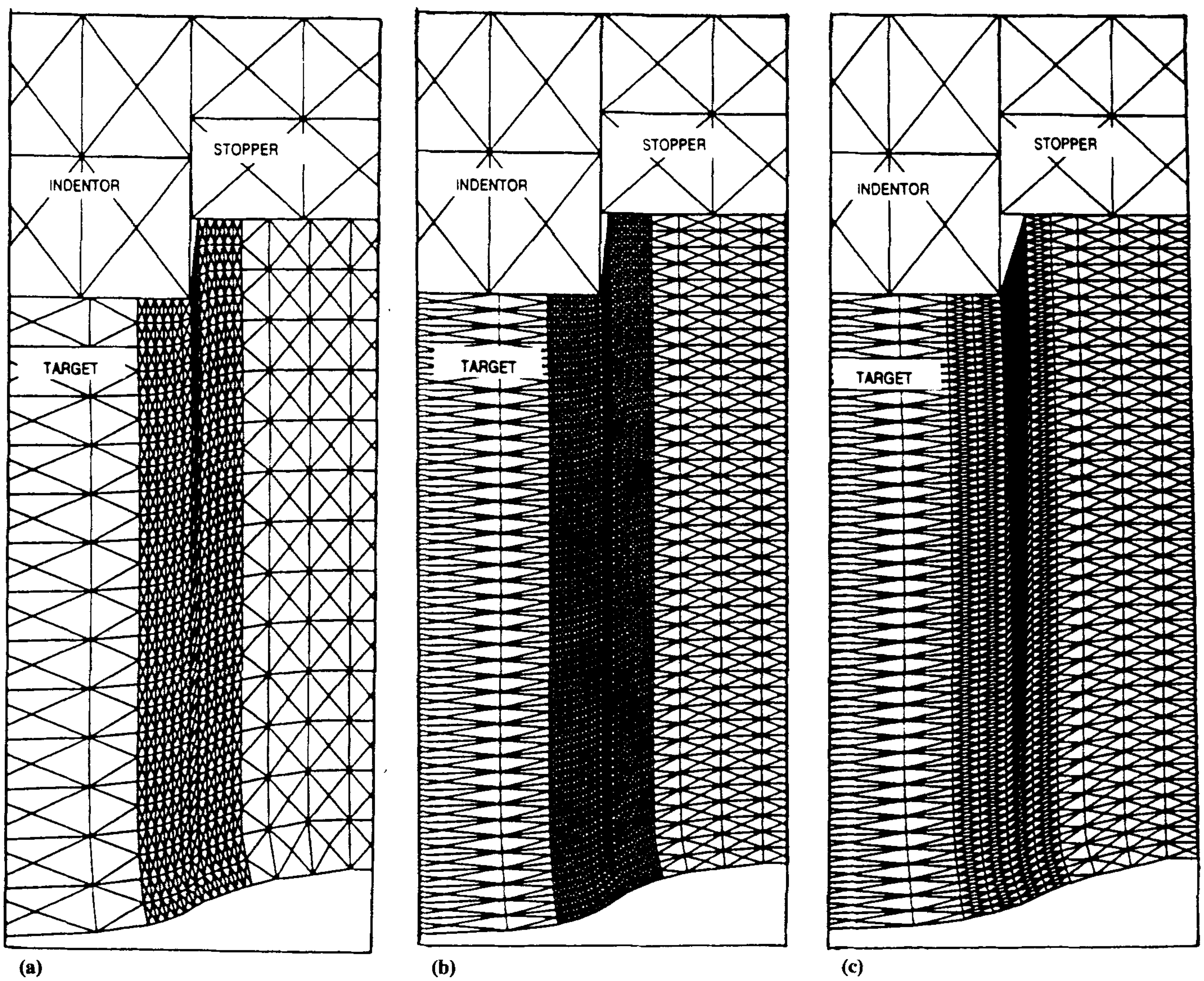


Fig. 14 Effect of aspect ratio (AR) on the deformation field. (a) AR = 3. (b) AR = 1. (c) AR = ⅓

realistically model adiabatic shear banding for a range of different materials.

Acknowledgments

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References

1. H.C. Rogers, Adiabatic Plastic Deformation, *Ann. Rev. Mater.*, Vol 9, 1979, p 283-311
2. H. Rogers and C. Shastry, *Shock Waves and High Strain Rate Phenomena in Metals: Concepts and Applications*, Plenum Press, 1981, p 285-298
3. L.S. Costin, E.E. Crisman, R.H. Hawley, and J. Duffy, *Mechanical Properties of Materials at High Rates of Strain*, J. Harding, Ed., 1979, p 90-100
4. R.J. Clifton, Plastic Waves: Theory and Experiment, *Mechanics Today*, Pergamon Press, Oxford, 1972, p 102
5. D.R. Curran, L. Seaman, and D.A. Shockey, Dynamic Failure in Solids, *Phys. Rep.*, Vol 147, 1987, p 253-388
6. R. Dormeval, The Adiabatic Shear Phenomenon, *Materials at High Strain Rate*, Elsevier Press, London, 1987, p 47-70
7. L. Seaman, D.R. Curran, and D.A. Shockey Scaling of Shear Band Fracture Processes, in *Materials under High Stress and Ultrahigh Loading Rates*, Plenum Press, 1983, p 295-307
8. R.F. Recht, Catastrophic Thermoplastic Shear, *J. Appl. Mech.*, Vol 18, 1964, p 189-193
9. J. Duffy, in *Mechanical Properties of Materials at High Rates of Strain*, J. Harding, Ed., Institute of Physics, London, 1979, p 1-15
10. A. Marchand and J. Duffy, An Experimental Study of the Formation Process of Adiabatic Shear Bands in a Structural Steel, *J. Mech. Phys. Solids*, Vol 36, 1988, p 261-283
11. T.A.C. Stock and A.L. Wingrove, *J. Mech. Eng. Sci.*, Vol 13, 1971, p 110-121
12. C. Zener and J.H. Hollomon, Effect of Strain Rate on Plastic Flow of Steel, *J. Appl Mech.*, Vol 15, 1944, p 22-32
13. A.L. Wingrove, The Influence of Projectile Geometry on Adiabatic Shear and Target Failure, *Metall. Trans. A*, Vol 4A, 1973, p 1829-1833
14. J.H. Beatty, L.W. Meyer, M.A. Meyers, and S. Nemat-Nasser, Formation of Adiabatic Shear Bands in AISI 4340 High Strength Steel, *Shock Waves and High Strain Rate Phenomenon*, Marcel Dekker, 1992, p 645-656
15. P.C. Chou, J. Hashemi, A. Chou, and H.C. Rogers, Experimentation and Finite Element Simulation of Adiabatic Shear Bands in Controlled Penetration Impact, *Int. J. Impact Eng.*, Vol 11 (No. 3), 1991, p 305-321
16. A. Needleman, Dynamic Shear Band Development in Plane Strain, *J. Appl. Mech.*, Vol 56, 1989, p 1-9
17. S. Nemat-Nasser, "Micromechanics of Failure at High Strain Rates: Theory, Experiment, and Computations," BRL Technical Report 178, Ballistic Research Laboratories, 1985
18. R.C. Batra and D. Liu, Adiabatic Shear Banding in Plane Strain Problems, *J. Appl. Mech.*, Vol 56, 1989, p 527-534
19. P.C. Chou and L. Wu, A Dynamic Relaxation Finite Element Method for Metal Forming Processes, *Int. J. Mech. Sci.*, Vol 28 (No. 4), 1986, p 231-250
20. G.R. Johnson and W.H. Cook, A Constitutive Model and Data for Metals Subjected to Large Strain Rates and High Temperatures, in *Proc. 7th Int. Symp. on Ballistics*, 1983, p 541-549
21. J. Hashemi, E. Irick, C. Heinol, and T. Clayton, Experimentation of Adiabatic Shear Bands in Titanium and Steel Under Low Velocity Impact Conditions, presented at the 1993 ASME/Winter Annual Meeting, Symposium of Recent Advances in Structural Mechanics, Chicago, IL, 1994, p 133-142