

SHEAR BANDS AND DYNAMIC FRACTURE

G. Sundararajan

Defence Metallurgical Research Laboratory, Hyderabad-500258, India

ABSTRACT

The conventional treatment of the shear strain localization problem assumes deformation under adiabatic conditions and further disregards completely the kinetic and structural factors like strain rate, thermal diffusivity and the nature of strain inhomogeneities. In this paper, the adiabaticity assumption has been relaxed and in addition, the effect of structural and kinetic factors on shear band initiation has been specifically considered. It is shown that both the kinetic and structural factors play a prominent role in determining the probability of shear band formation.

KEYWORDS

Shear band; dynamic fracture; adiabatic deformation; strain localization; high strain rate.

INTRODUCTION

It is well known that the temperature rise accompanying plastic deformation under conditions of restricted heat transfer can cause the strain to localize within a band and thus induce premature fracture or failure of the component (Wingrove, 1973; Samuels and Lamborn, 1978; Rogers, 1979). The 'shear plugging' mode of failure experienced by high strength alloy targets when impacted by a hard projectile is a classic example of such a phenomena. The shatter of projectiles caused by crack propagation along the concentrated shear bands is yet another example of the same phenomena.

The various events that occur in series to cause shear band induced dynamic fracture of the type described above can be listed as follows:

- (1) Initiation of the shear band. This usually occurs at a critical strain or equivalently at a critical depth of penetration.
- (2) Propagation of the shear band.
- (3) Void nucleation, growth and coalescence within the band resulting in a material separation across the band.

Of these three events, it is important to determine the one which largely determines the probability of fracture. This can be most conveniently done in terms of energy absorption accompanying each event since an effective armour or projectile is the one which absorbs the maximum energy prior to fracture.

As noted earlier, shear band initiation requires a critical strain to be exceeded in the material. Prior to the attainment of this strain, the deformation of the material occurs in a homogeneous fashion and over a large volume. Hence, the energy absorbed, defined as the product of the flow stress of the target, its mean strain and volume undergoing deformation, is quite high. But once the shear band is nucleated, all further deformation is concentrated mainly within these bands, whose volume can be even three orders of magnitude smaller than the original volume undergoing homogeneous deformation. In addition, the temperature rise within the band can be quite significant resulting in a reduction of the shear flow stresses of the band material inspite of extensive straining experienced by it. As a result, the energy consumed in propagating the band should be considerably smaller than that required for shear band initiation. Finally, since the shear band material experiences very high strains (Samuels and Lamborn, 1978), void nucleation, growth and coalescence will occur quite easily and with negligible energy expenditure. Thus, in terms of energy absorption, shear band initiation is the critical event and the only effective way to postpone dynamic fracture is to maximize the critical strain for shear band initiation.

In the present paper, the parameters affecting the shear band initiation will be considered in detail. In particular, it will be shown that when the assumption of adiabatic deformation is relaxed, kinetic and structural factors like strain rate of deformation, thermal diffusivity and the nature of inhomogenities acting as strain concentrators also become important in determining the probability of shear band initiation.

SHEAR BAND INITIATION

Initiation and the subsequent sustenance of a shear band requires a number of criteria to be satisfied. First, the deformation should become unstable so that the localization of strain within a narrow shear band is energetically favourable. This is in fact a 'thermodynamic' criterion and can be suitably expressed in terms of a critical strain for localization (E_c) as will be shown below. The

second requirement is that the material should contain pre-existing strain inhomogenities like inclusions, second phase particles and cracks. Without these structural defects or inhomogenities, no shear bands will form even above the critical strain for localization; only a general softening of the material close to the projectile-target interface will occur. Thus, the 'structural' factors are quite important. Finally, if the shear band width is such that a significant fraction of the heat generated within the band is lost to the surroundings, the critical condition for shear band initiation will also depend on kinetic factors like strain rate of deformation and thermal diffusivity. So, a complete treatment of the shear band initiation problem requires the consideration of thermodynamic, structural and kinetic factors.

Thermodynamic Criterion

In this section we derive a simple expression for the critical strain (E_c) corresponding to the onset of unstable deformation. Since this aspect has been dealt with repeatedly in the literature (Argon, 1973; Culver, 1973; Bai, 1981; Dodd and Atkins, 1983), it will be considered only briefly here. Any material, once

it reaches the 'ideally plastic state' will experience deformation instability (Chakrabarti and Spretnak, 1975). If we assume a constant strain rate (E°), ideal plastic state is obtained just when the flow stress decrement due to thermal softening just balances the flow stress increment due to strain hardening. This condition can be expressed mathematically as,

$$S = 0 = (\Delta S/\Delta E)_{E,T} \cdot \Delta E + (\Delta S/\Delta T)_{E,E} \cdot \Delta T \quad (1)$$

In equation 1, S is the shear flow stress, E is the shear strain and T is the temperature. The first term in eqn.1 represents the flow stress increment due to strain hardening and the second term the flow stress decrement due to thermal softening. If we now assume a constitutive relation of the form, $S = S_0$

$(1-CT)E^n$ (S_0 = strength coefficient, n = strain hardening exponent and C = a material constant determining the temperature dependence of the flow stress) and deformation under adiabatic conditions, i.e., $T = S \cdot dE/D_t \cdot C_p$ (D_t = target density and C_p = target specific heat), we obtain from eqn.1 the critical strain for the onset of deformation instability under adiabatic conditions (E_{cad}) as,

$$E_{cad} = (n \cdot D_t \cdot C_p / S_0 \cdot C)^{1/n+1} \quad (2)$$

The value of C in eqn.2 depends on the nature of the operating deformation mechanism. In the strain rate regimes where shear plugging of the target and projectile shatter occurs ($10^4 - 10^5/s$), neither diffusional nor the thermally activated mechanisms will contribute significantly to the overall flow stress (Klahn, Mukherjee and Dorn, 1970). Thus, the flow stress will be mainly determined by the athermal barriers to dislocation motion. Hence, C in eqn.2 should be equated to the temperature coefficient of the shear modulus.

Table 1 gives the values of the various material parameters involved in eqn.2 for typical metals and alloys. The last column in the same table gives the values of E_{cad} for all these materials calculated using eqn.2. At one extreme pure metals like copper, aluminium and iron exhibit very high values of E_{cad} and hence are very resistant to deformation instability. At the other extreme, materials like Al 7075-T6 and Ti-6Al-4V exhibit very low instability strains.

Since adiabatic deformation was assumed while deriving eqn.2, kinetic factors like strain rate of deformation and thermal diffusivity (D) of the target material have no role to play in determining the susceptibility of materials to shear band formation.

Kinetic Factors

In this section we will first estimate the minimum width (L_{ad}) the shear band should have if the deformation within it is to occur under adiabatic conditions. Assume that the deformation is adiabatic if less than 10 percent of the heat generated is lost to the surroundings. Then, based on the 'heat band' solution (Carslaw and Jaeger, 1959), one finds that the thermal number (N) should be greater than 50 for adiabatic conditions to be valid, i.e.,

$$N = L_{ad}^2 / Dt = L_{ad}^2 \cdot E^\circ / DE_{cad} \geq 50 \quad (3)$$

where, t is the impact duration and equals E_{cad}/E° . Hence we obtain,

$$L_{ad} = (50 \cdot D \cdot E_{cad}/E^{\circ})^{1/2}$$

(4)

TABLE 1 The Values of E_{cad} for Typical Metals and Alloys

Material	S_0 (MPa)	n	$D \times 10^5$ m^2/s	C_p J/Kg K	D_t Kg/m ³	$C \times 10^4$ K ⁻¹	E_{cad}
Copper	296	0.38	11.40	385	8900	3.97	5.7
Aluminium	103	0.32	3.60	963	2710	5.40	7.8
Iron	289	0.21	1.50	513	7860	3.30	6.1
Titanium	510	0.17	0.70	540	4540	6.20	1.3
Brass	515	0.49	8.60	370	8600	3.97	3.9
Al 6065-T4	238	0.08	6.10	960	2710	5.40	1.5
Al 7075-T6	485	0.02	4.50	960	2800	5.40	0.2
C Steel (0.6)	902	0.10	1.00	513	7860	3.30	1.3
Ti-6Al-4V	673	0.08	0.35	540	4460	6.20	0.5

Data collected from handbooks, text books.

Both shear plugging failure and projectile shatter occur at nominal strain rates in the range 10^4 to $10^5/s$. Due to the presence of strain inhomogeneities, the actual strain rate at the shear band nucleation site will be much higher—may be by a factor of 10 at the most. So, in table 2, the values of L_{ad} calculated according to eqn.4 are given for the strain rate values 10^5 and $10^6/s$. The table shows that in the case of pure metals like copper and aluminium, the minimum shear band width required for adiabatic condition to be met is very high (200 to 500 microns). On the other hand, in the case of materials like Ti-6Al-4V, Titanium, 0.6 carbon steel and Al 7075-T6, a shear band width of 10 to 20 microns is sufficient to achieve adiabatic conditions. It is also obvious from Table 2, that kinetic factors like D and E° now play a significant role in determining the magnitude of L_{ad} .

TABLE 2 The Values of L_{ad} and L for Typical Materials

Material	L_{ad} (microns)		L (microns) for $R=2$	
	$E^{\circ} = 10^5/s$	$10^6/s$	$10^5/s$	$10^6/s$
Copper	570	180	171	54
Aluminium	578	183	173	55
Iron	214	68	64	20
Titanium	66	21	20	6
Brass	272	86	82	26
Al 6065-T4	212	67	64	20
Al 7075-T6	69	22	21	7
C Steel	81	26	24	8
Ti-6Al-4V	30	9	9	3

It is not necessary that shear bands should have a minimum width equalling L_{ad} when they nucleate. Their width (L) can be less than L_{ad} . In that event, the deformation will be no longer adiabatic and the temperature rise within the band will be lower than that in the adiabatic case. As a result, the critical strain for the onset of deformation instability (E_c) will be higher than the

corresponding value under adiabatic conditions (E_{cad}) as shown below.

The temperature rise, ΔT , under non-adiabatic conditions is given by an equation of the form,

$$\Delta T = \Delta T_{ad} \cdot f(N) \quad (5)$$

where, ΔT_{ad} is the temperature rise under adiabatic conditions, N is the thermal number ($=L^2 E^{\circ}/D E_c$) and $f(N)$ is a function of N and always less than or equal to one. The variation of $f(N)$ with N can be accurately determined using the heat band solution (Carslaw and Jaeger, 1959). But in that case $f(N)$ cannot be expressed as a simple analytical function. So, a less accurate but a simpler analytical function was obtained by trial and error as,

$$f(N) = 1/(1 + (2/N))^{N^{0.177}} \quad \text{for } N > 0.02 \quad (6)$$

Equation (6), a purely empirical expression, satisfies the boundary conditions namely that $f(N) = 0.9$ when $N = 50$ and $f(N) = 0.1$ when $N = 1/50$. Substituting eqn.6 in eqn.5 and using this expression for ΔT in eqn.1, one obtains the following expression for the critical strain (E_c) for deformation instability under non-adiabatic conditions.

$$R = E_c/E_{cad} = (1 + R/25 P^2)^q \quad (7)$$

where, $q = (1/n+1) (50 P^2/R)^{0.177}$, $P = L/L_{ad}$. Figure 1 shows the variation of R with the parameter P , as predicted by eqn.7, for a wide range of metals and alloys. The figure shows that R (and hence E_c) increases with decreasing P , slowly at first and then more rapidly. It is also obvious that as long as P is greater than about 0.3, the value of R (for a given P) is quite insensitive to material properties. But, for $P < 0.3$, the actual R value depends significantly on the material properties especially n . The figure also indicates that the physically possible lower bound value for P is about 0.3 since for $P < 0.3$, R increases dramatically with decreasing P and it is unlikely that such high strains ($E_c = R \cdot E_{cad}$) can be generated during the impact process. Table 2 indicates this lower bound value for L ($=0.3 L_{ad}$) at two strain rates. In the case of pure metals like copper

and aluminium, even the lower bound value for the shear band width is quite high.

Structural Factors

A necessary condition for the formation of shear bands is the presence of strain inhomogeneities, either pre-existing or formed during the impact process. The strain inhomogeneities can be characterized in terms of their strength (S_1) and size (S_2). The strength of an inhomogeneity (S_1) is defined as the ratio of the strain at the inhomogeneity (E_p) to the bulk strain (E_b). The size (S_2) of the inhomogeneity is the size of the region wherein the strain concentration exists. Under dynamic impact conditions, strain inhomogeneities can be induced in the material in a number of ways.

(1) Pre-existing inclusions and second phase particles can act as strain concentrators. In this case S_1 will lie in the range 1 to 3 and S_2 will roughly equal the inclusion or particle size.

- (2) Cracks or pits can also concentrate the strain. Such inhomogeneities are characterized by $S1 \approx 3$ and $S2 =$ plastic zone size ahead of the crack tip.
- (3) Surface instabilities resulting in the formation of strain inhomogeneities at the projectile-target interface can be triggered if the target surface is rough enough. In this case, above a critical strain, initial surface perturbations grow dramatically in size with a characteristic wavelength resulting in strain inhomogeneities with high $S1$ values (Hutchinson and Tvergaard, 1980).
- (4) In the specific case of dynamic impacts, even the projectiles can cause the deformation to be inhomogeneous. For example, flat ended projectiles cause the target material in contact with its leading edges to be severely strained resulting in strain inhomogeneities with extremely high $S1$ values.

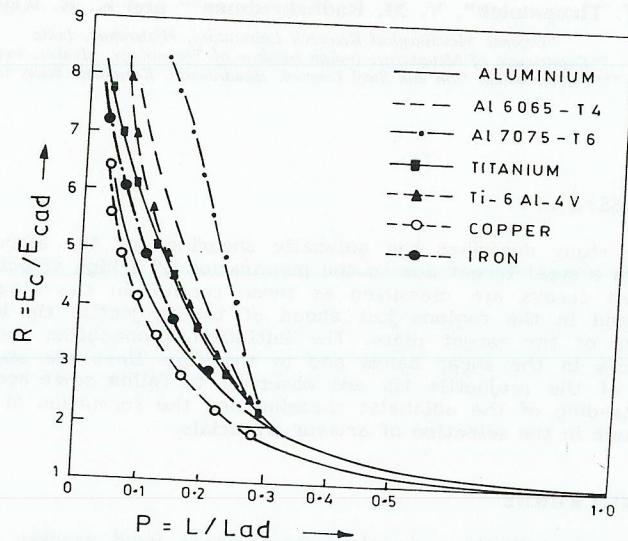


Fig. 1. The variation of R with P for typical materials.

Thus, any given target material will contain within it structural inhomogeneities which will cause strain inhomogeneities with varying strength and size to be formed. Now, let us consider the effect of the structural factors ($S1$ and $S2$) on the critical strain for shear band initiation. From the definition of $S1$, it follows that the critical bulk strain at which shear bands (E_{bc}) can be given as, $E_{bc} = E_c / S1 = E_{cad} \cdot R / S1$. Thus, the higher the strength of the inhomogeneity, the lower will be the bulk strain at which the critical strain for band initiation (E_c) is attained at the band initiation site. The effect of $S2$ on the critical strain is not so straight forward. The actual width of the band (L) should roughly equal the size ($S2$) of the strain inhomogeneity. So, if $S2$ is greater than or equal to L_{ad} (eqn.4), deformation within the band will occur under adiabatic conditions and hence $E_{bc} = E_{cad} / S1$. Under such conditions, shear band initiation

is not influenced by either the size of the inhomogeneity or the kinetic factors. On the other hand, if $S2$ is less than L_{ad} , deformation within the band will be no longer adiabatic and the critical bulk strain for shear band initiation (E_{bc}) will equal $E_{cad} \cdot R / S1$. In this case, R is dependent on P (see Fig.1) and P equals $S2 / L_{ad}$. Thus, E_{bc} will be influenced by the size of the inhomogeneity as well as the kinetic factors.

DISCUSSION

In this section we will consider the thermodynamic, kinetic and structural factors together and draw important conclusions regarding their relative importance. In particular, three different classes of materials will be defined and the relative importance of the various parameters in causing shear band nucleation will be considered for each class of material.

Class 1. Materials with high $S_0 / n \cdot D$ values like Ti-6Al-4V, quenched and tempered carbon steels, Al 7075-T6 and to some extent Titanium fall in this group. These materials exhibit low L_{ad} (table 2) and E_{cad} (table 1) values. Thus, inhomogeneities of low strength ($S1$) and size ($S2$) like those caused by inclusions and second phase particles can act as shear band nucleation sites. In a conventionally processed material, a large number of such nucleation sites will be present. Hence, shear band nucleation will be primarily controlled by thermodynamic factors and the postponing of shear band initiation and the attendant dynamic fracture will require either increasing n or decreasing S_0 . But if the material is specially processed (e.g., ESR process) to reduce the size of inclusion to below the L_{ad} value, shear band initiation and hence fracture will be postponed to higher strains. In fact, experiments with high strength armour steels have clearly shown that ESR steel is much more resistant to shear plugging type failure than the conventionally processed materials.

Class 2. Materials like aluminium and copper which exhibit very low $S_0 / n \cdot D$ values fall in this class. These materials exhibit very high values of L_{ad} and E_{cad} . As a result, strain inhomogeneities with very high $S1$ and $S2$ values are required for shear band initiation. It is impossible to form such severe inhomogeneities under normal conditions. Thus shear band formation is not favoured in these materials. This conclusion is in line with the experimental observations.

Class 3. Materials like Iron, Al 6065-T4 which exhibit intermediate $S_0 / n \cdot D$ values belong to this class. Within this class we have two possibilities.

- Low n and high S_0 and D . These materials exhibit low E_{cad} and intermediate L_{ad} values. So generation of inhomogeneities of sufficient size ($S2 \gtrsim L_{ad}$) will be the critical factor which will determine the probability of shear band formation.
- High n and low S_0 and D . These materials are characterized by high E_{cad} and intermediate L_{ad} values. Hence, the shear band formation will depend critically on the generation of strain inhomogeneities of sufficient strength.

CONCLUSIONS

The conventional treatment of the shear band formation assumes deformation under adiabatic conditions and further disregards completely the kinetic and structural factors. In this paper, the adiabaticity assumption has been relaxed

and in addition the effect of structural factors on the critical strain for shear band formation has been specifically considered. It is found that the kinetic factors are unimportant only in the case of materials with high $S_0/n.D$ values.

On the other hand, structural factors are found to play a prominent role in shear band formation, in the case of all materials.

ACKNOWLEDGEMENT

The author would like to express his gratitude to Dr. P. Rama Rao, Director, DMRL, for his constant encouragement and support.

REFERENCES

- Argon, A.S. (1973). In The Inhomogeneity of Plastic Deformation, ASM, Ohio. Chap.7.
- Bai, Y. (1981). In M.A.Meyers and L.E.Murr (Eds.), Shock Waves and High Strain Rate Phenomena in Metals, Plenum Press, NY.p.277.
- Carslaw, H.S., and J.C. Jaeger (1959). Conduction of Heat in Solids, Clarendon Press, Oxford.
- Chakrabarti, A.K., and J.W.Spretnak (1975). Metall.Trans., 6A, 733.
- Culver, R.S. (1973). In R.W.Rhode, B.M.Butcher, J.R.Holland and C.H.Karnes (Eds.), Metallurgical Effects at High Strain Rates, Plenum Press, NY.p.519.
- Dodd, B., and A.G.Atkins (1983). Acta Met., 31, 9.
- Hutchinson, J.W., and V.Tvergaard (1980). Int. J. Mech. Sci., 22, 339.
- Klahn, D., A.K.Mukherjee and J.E.Dorn (1970). In Proc. 2nd Int. Conf. on Strength of Metals and Alloys, ASM, Ohio. p.951.
- Rogers, H.C. (1979). Ann. Rev. Mater. Sci., 9, 283.
- Samuels, L.E., and I.R.Lamborn (1978). In J.L. McCall and P.M. French (Eds.), Metallography in Failure Analysis, Plenum Press, NY. p.167.
- Wingrove, A.L. (1973). Metall. Trans., 4, 1829.