

ON THE THERMO-VISCO-PLASTIC INSTABILITY FOR MATERIAL FAILURE UNDER IMPACT

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This study aims to investigate the strain hardening, strain-rate hardening and thermal softening components contributing in the increase of stress in metallic materials submitted to impact, for different regimes corresponding to specific types of instability and material failure. Hopkinson bar compression tests conducted at a very high loading rate, corresponding to the impact level, illustrate some typical adiabatic shear banding processes in steels and titanium, which are shown to be associated with phase structure transformation under shock. Details are given for Ti where the local temperature reached is higher than the critical temperature under pressure for phase transition. A numerical method based on the assumption of a linear relationship between stress and temperature is also proposed as a critical criterion for material failure for use in the empirical Johnson-Cook model for dynamic stress calculations.

INTRODUCTION

The constitutive law for a material submitted to loading at high strain-rates, i.e., the increase of the dynamic stress  $\sigma$ , is dependent on strain  $\epsilon$ , strain-rate  $\dot{\epsilon}$  and (internal) temperature  $T$ . The corresponding criterion for dynamic material failure can be expressed following the Culver's model (1) as a thermo-visco-plastic instability by the balance between the strain hardening  $\partial\sigma / \partial\epsilon (>0)$ , the strain-rate hardening  $\partial\sigma / \partial\dot{\epsilon} (>0)$  and the thermal softening  $\partial\sigma / \partial T (<0)$ :

$$\frac{d\sigma}{d\epsilon} = \frac{\partial\sigma}{\partial\epsilon} + \frac{\partial\sigma}{\partial\dot{\epsilon}} \cdot \frac{d\dot{\epsilon}}{d\epsilon} + \frac{\partial\sigma}{\partial T} \cdot \frac{dT}{d\epsilon} = 0 \dots\dots\dots(1)$$

The effect of these three components in the increase of stress will be dependent on the strain-rate level, but corresponding to different aspects of the material behaviour will produce different types of instability and material failure.

The split Hopkinson pressure bar (SHPB) is well known e.g. from Follansbee (2) in the field of measurement of material properties at very high strain-rates of about  $10^2$  up to  $10^4 \text{ s}^{-1}$ , in particular for compression testing, where the cylindrical

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material specimen will be impacted dynamically between the two free-flying measurement bars. By using Hopkinson bar compression tests with some chosen specimen materials, it is then possible to illustrate some important parameters influencing this thermo-visco-plastic instability under impact and their corresponding material failure modes.

THERMO-VISCO-PLASTIC INSTABILITY LEVELS

Dynamic Plastic Instability at Low Impact Level. At low strain-rates or fracture toughness rates up to about  $10^2 \text{ s}^{-1}$  and  $10^6 \text{ MPa.m}^{1/2}.\text{s}^{-1}$ , respectively, conventional plastic deformation still finds enough time to occur in the impacted material and any adiabatic temperature rise would be dissipated. Dynamic fracture however, already at this regime, is different from quasi-static crack propagation, taking place far away from the impacted surface and following the ductile void coalescence process proposed by Shockey *et al.* (3, 4). The strain-hardening term in Eq. 1 increases strongly with the material deformation capability in delaying the moment of material instability, following the well-known constitutive law:

$$\Delta\sigma_{\epsilon} = k. \epsilon^n \dots\dots\dots(2)$$

where n is the strain-hardening exponent and k is a material constant.

Thermo-Plastic Instability at High Impact Level. Above an upper strain-rate (impact) level or fracture toughness rate of about  $10^3 \text{ s}^{-1}$  and  $10^7 \text{ MPa.m}^{1/2}.\text{s}^{-1}$ , respectively, the strain-hardening term can be neglected in comparison with the two other ones in Eq. 1. Reduced as a balance only between two terms, material instability thus occurs more easily and is therefore very sensitive to thermal softening, which can be expressed by an exponential function of the temperature:

$$\Delta\sigma_T = -f(\epsilon). T^m \dots\dots\dots(3)$$

where m is a material constant and f(ε) a certain function of strain. As shown schematically in Figure 1, this thermally activated stress component causes material instability when it exceeds the other strain-rate hardening component from Eq. 1. Otherwise, it will be delimited by a maximum temperature, which depends on the strain-rate, beyond which the mechanical process becomes athermal. In most cases however, instability can still be avoided because stress at this high impact level increases also quite rapidly with strain-rate, following an other type of constitutive law as the one proposed by Alder and Phillips (5):

$$\Delta\sigma_{\epsilon'} = A. \ln \epsilon' \dots\dots\dots(4)$$

where A is a material constant. The adiabatic temperature rise in the material can therefore be high, as shown e.g. by Chokshi and Meyers (6), and furthermore, because of the short duration of the event, is concentrated within narrow bands at locations of maximum shear stress. Material failure can thus happen following the so-called adiabatic shear banding mode as explained e.g. by Dornmeval (7). Because of the temperature rise, the material within the shear band can possibly melt or more usually, as suggested by Meyers (8), its microstructure will be dynamically recrystallized into very fine grains. Moreover, a further critical temperature can eventually be reached locally, corresponding to a phase transformation in the material structure within the band. This temperature for pressure induced phase transition, from which some examples are given by Duvall and Graham (9), is even lower than for the normal equilibrium conditions. Because of the difference in the

volume contraction under shock between the two phases before and after transition, a discontinuity results which causes an additional instability in the material of the shear band. This critical temperature, which is lowered down by rise in strain-rate, and also the temperature for melting are shown in Figure 1.

Visco-Plastic Instability at Very High Impact Level. In the so-called hydrodynamics range corresponding to upper strain or fracture toughness rates above about  $10^5 \text{ s}^{-1}$  and  $10^9 \text{ MPa}\cdot\text{m}^{1/2}\cdot\text{s}^{-1}$ , respectively, there is a damping of the dislocation motion and most of the deformation can only be done in a geometrical manner, i.e., by viscous drag as explained e.g. in reference (8). The stress increase is particularly high, following a further constitutive law where the stress increases almost proportionally to strain-rate as in the model proposed by Walters (10):

$$\Delta\sigma_{\epsilon'} = \mu \cdot \epsilon' \dots\dots\dots(5)$$

where  $\mu$  represents the dynamic viscosity coefficient of the material (which decreases when strain-rate increases). As indicated in Figure 1, this viscous drag is known to be invariant with the increase in temperature and material instability can (theoretically) only be caused by a strong fluctuation of viscosity.

EXPERIMENTATION AND METALLURGICAL INVESTIGATIONS

Split Hopkinson pressure bar experiments. Hopkinson bar compression tests were conducted using the apparatus at EMPA (11), with impact and measurement bars of 10 mm diameter and with cylindrical specimens of 4 mm thickness and 6 mm diameter. For the test specimens, metallic materials having the possibility for structure phase transformation by elevating (adiabatically) the temperature were chosen: a pure titanium (ASTM Grade 2) susceptible to hcp->bcc phase transition, a maraging steel (X 2 NiCoMoTi 18 12 4) and a nitrogen steel (X 5 CrMnN 18 18) with  $\alpha'$ -martensite phase structure susceptible to be changed to  $\gamma$ -austenite phase. Strain-rate values from  $10^3$  up to  $10^4 \text{ s}^{-1}$  were measured.

Local adiabatic temperature rise. With the common assumption that about 90% of the impact energy has been converted into heat, the adiabatic temperature rise in the impacted specimen can be estimated from the measured stress-strain curve:

$$\Delta T_{(^\circ\text{K})} = (0,9 / (\rho \cdot C_p)) \cdot \int \sigma \cdot d\epsilon \dots\dots\dots(6)$$

where  $\rho$  and  $C_p$  are the material density and specific heat capacity, respectively. Then the temperature reached locally in the shear band should be higher and can be found by applying the thermal trapping model proposed by Grady and Asay (12):

$$T_l (^\circ\text{K}) = T_g (^\circ\text{K}) \cdot e^{(\gamma \cdot \epsilon)} \dots\dots\dots(7)$$

where  $T_g$  is the global temperature in the impacted specimen calculated from Eq. 6,  $\gamma$  and  $\epsilon$  are the Grüneisen ratio ( $\gamma=(1/\rho) \cdot (\partial p/\partial E)_p$ ,  $p$  pressure,  $E$  internal energy) and the strain from the specimen material at the shocked state, respectively. This local temperature in adiabatic shear band can thus reach very high values. On the other side, the critical temperature for phase transition in the material is lowered down by pressure and can then be reached locally in the adiabatic shear band. Calculations applying Eq. 6 and 7 were made for titanium as specimen material used ( $\rho=4,53 \cdot 10^3 \text{ kg/m}^3$ ,  $C_p=6,1 \cdot 10^2 \text{ J/kg}\cdot^\circ\text{K}$  and  $\gamma=1,09$ ), by taking the measured stress-strain curve on top of Figure 2. The values found were  $104 \text{ }^\circ\text{K}$  for the global adiabatic temperature rise and  $713 \text{ }^\circ\text{K}$  for the local temperature reached in the

adiabatic shear band. This local temperature is thus much higher than the value of 370 °K reported as the critical temperature for phase transition under shock for titanium by McQueen *et al.*(13).

Detection of the phase transition under impact. This pressure induced phase transition, changing deeply the material structure, is known to happen within a very short time. The registered high frequency signals from Hopkinson bar tests were able to detect this change for both Ti and high-strength steel specimens. An example is shown in Figure 2 by comparison of the stress-strain curves obtained with Ti specimens beneath and beyond a critical value for the impact velocity, respectively. This instability in stress and strain levels can be explained by the differences in mechanical properties between the hardened structure phase before the phase transition and the one formed thereafter with combined shock release.

Observations of adiabatic shear bands. This phase transition under shock coincided with the same impact test level corresponding to the critical impact velocity, and also with the formation of adiabatic shear bands in the Ti and steel Hopkinson compression specimens. This provoked sudden fracture in the maraging steel specimens tested, which did not deform itself obviously when being impacted below the critical level, but broke up when being impacted only lightly above it, as reported in a previous work (11). Fracture should result from a crack development within an extremely narrow band, where one face slides on the other one under an impact induced shear stress state and where the material is locally and very quickly heated adiabatically. Figure 3 shows an adiabatic shear band in Ti test specimens, with a length of about 0.8 mm following a quite perfect shear angle, with a thickness reducing from about 15 to 5 μm and ending at a crack. Figure 4 shows some displacements of structure grain boundaries in maraging steel test specimens, as an evidence of the sliding mode from both sides of shear bands. These bands observed in steels were also much finer (but more numerous) than in titanium.

#### NUMERICAL FORMULATION FOR DYNAMIC MATERIAL INSTABILITY

A critical criterion for material failure, in calculations of the instantaneous stress, strain and temperature states, is obtained by derivation of the stress from Eq. 1, which is possible with a constitutive law displaying linearity between stress and temperature as in Wang's model (14). Otherwise, a numerical method consists to use empirical constitute relations, such as e.g. the Johnson-Cook-model (15) which is commonly integrated as a data base in many dynamic FE/FD-sofwares:

$$\sigma = (\sigma_0 + k \cdot \epsilon^n) \cdot (1 + A \cdot \ln \epsilon'^*) \cdot (1 - T^{*m}) \dots\dots\dots(8)$$

where  $\epsilon'^* = \dot{\epsilon}' / \epsilon_0'$  is the dimensionless strain-rate for  $\epsilon_0' = 1,0 \text{ s}^{-1}$ ,  $T^*$  is the homologous temperature and  $\sigma_0$ ,  $k$ ,  $n$ ,  $A$  and  $m$  are five material constants (similar to those in Eq. 2-4). In order to take into account in this model the analytical criterion for material failure, the material data bases would have to be (slightly) modified, with the temperature term's exponent  $m$  now put equal to 1.

#### CONCLUSIONS

A theoretical analysis of the thermo-visco-plastic instability for material failure under impact was proposed. This instability remains dominated by plasticity at low

strain-rates and is visco-plastic at very high strain-rates. It has its greatest importance at strain-rates ranging from  $10^3$  to  $10^5$  s<sup>-1</sup>, where it is essentially thermo-plastic, i.e., with strong effects inside the material due to thermal softening and also pressure induced phase transition because of the very high local adiabatic temperature rise. From split Hopkinson pressure bar experiments with Ti and steels, these critical effects were visible on the measured stress-strain curves. They coincided with formation of adiabatic shear bands in the test specimens, where observations revealed inside cracks and grain boundary displacements. A linearity between stress and temperature was proposed for the criterion of material failure, to be introduced into the data bases from the Johnson-Cook model.

#### REFERENCES

- (1) Culver, R.S., "Thermal Instability Strain in Dynamic Plastic Deformation", in "Metallurgical Effects at High Strain Rates". Edited by R.W. Rhode *et al.*, Plenum Press, N.Y., 1973.
- (2) Follansbee, P.S., ASM Metals Handbook, Vol. 8, 1985, pp. 198-203.
- (3) Shockey, D.A., Seaman, L. and Curran, D.R., "Application of Microstatistical Fracture Mechanics to Dynamic Fracture Problems", Proc. of the Sagamore Army Mat. Res. Conf. 29. Edited by J. Mescall and V. Weiss, Plenum Press, N.Y., 1983.
- (4) Curran, D.R., Seaman, L. and Shockey, D.A., Phys. Rep., Vol. 147, Nos.5 & 6, 1987, pp. 253-388.
- (5) Alder, J.F. and Phillips, V.A., J. Inst. Met., Vol. 83, 1954-55, pp. 80-86.
- (6) Chokshi, A. and Meyers, M., Scr. Met. et Mat., Vol. 24, 1990, pp. 605-610.
- (7) Dormeval, R., "Adiabatic Shear Phenomena", Proc. of the Int. Conf. on Impact Loading and Dynamic Behaviour of Materials IMPACT'87. Edited by C.Y. Chiem *et al.*, DGM Inf.Ges., Oberursel, Germany, 1987.
- (8) Meyers, M.A., "Dynamic Behavior of Materials", J. Wiley & Sons, 1994.
- (9) Duvall, G.E. and Graham, R.A., Rev. of Modern Phys., Vol. 49, No. 3, 1977, pp. 523-579.
- (10) Walters, W.P., "Influence of Material Viscosity on the Theory of Shaped-Charge Jet Formation", BRL, Aberdeen, U.S.A., Mem. Rep. ARBRL-MR-02941, 1979.
- (11) Nguyen, C.H., "Evaluation of the elastic response to impact for high-strength steels", Proc. of the Int. Conf. on Met. and Mat. Appl. of Shock-Wave and High-Strain-Rate Phen. EXPLOMET'95. Edited by L.E. Murr *et al.*, Elsevier, 1995.
- (12) Grady, D.E. and Asay, J.R., J. Appl. Phys., Vol. 53, No. 11, 1982, pp. 7350-7354.
- (13) McQueen, R.G., Marsh, S.P., Taylor, J.W., Fritz, J.N. and Carter, W.J., "The Equation of State of Solids from Shock Wave Studies" in "High-Velocity Impact Phenomena". Edited by R. Kinslow, Academic Press, 1970.
- (14) Wang, L.L., Bao, H.S. and Lu, W.X., "The Dependence of Adiabatic Shear Banding in Strain-Rate, Strain and Temperature", Proc. of the Int. Conf. on Mech. and Phys. Behav. of Mat. under Dynamic Loading DYMAT 88. Edited by Les Ed. de Phys., Les Ulis, France, 1988.
- (15) Johnson, G.R. and Cook, W.H., "A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures", Proc. of the 7th Int. Symp. on Ballistics BALLISTICS'83. Edited by TNO, The Hague, 1983.

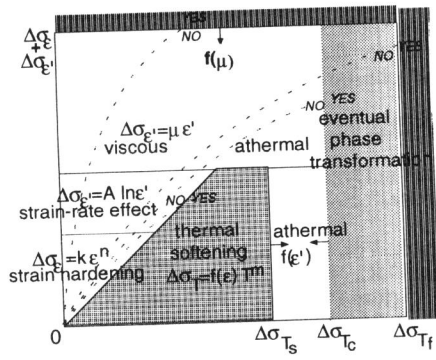


Figure 1. Thermo-visco-plastic instability at different strain-rates and temperatures

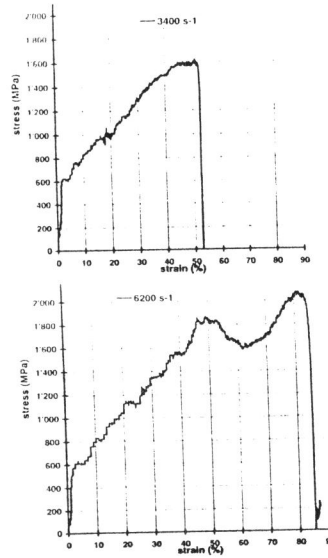


Figure 2. Stress-strain curves for Ti beneath and beyond the critical level

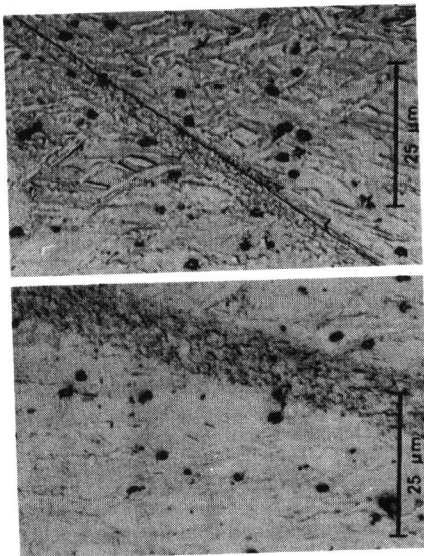


Figure 3. Adiabatic shear band in titanium (about 10 μm thick and with inside crack)

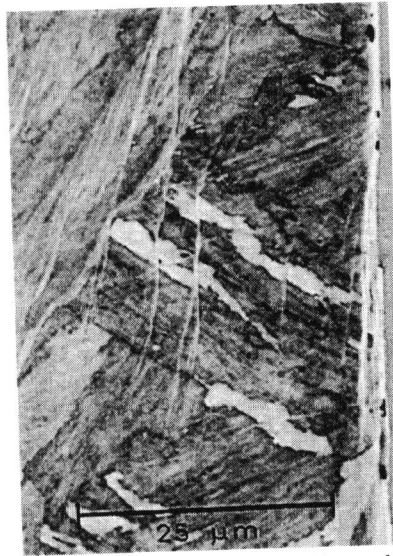


Figure 4. Adiabatic shear band in steel (with grain boundary displacements)