

STRAIN / STRAIN-RATE CONTROLLED AND GEOMETRY / MICROSTRUCTURE
DEPENDENT DYNAMIC MATERIAL FAILURE

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At upper strain-rates dynamic failure occurs when the strain / strain-rate controlled adiabatic temperature rise reaches locally a critical temperature for pressure induced phase transition, or even melting, thus depending on the impacted material's microstructure. Material instability results within shear bands giving rise to inside cracks. Complete fracture depends furthermore on the geometry and the capability for plastic deformation of the specimen. These influences are experimentally investigated in the particular case of pure titanium from dynamic mechanical tests using the Split Hopkinson Pressure Bar. On the basis of a local numerical thermal trapping model and also an analytical method using the mathematical code Maple, constitutive equations related to dynamic fracture for the same case of pure titanium have been formulated and solved.

INTRODUCTION

The increase of stress in the constitutive equation of a material submitted to high strain-rates depends on strain, strain-rate and (internal) temperature. Dynamic failure can be expressed following the Culver's model (1) as a thermo-visco-plastic instability, i.e., as the balance of the strain hardening $\partial\sigma/\partial\varepsilon$ (>0), the strain-rate hardening $\partial\sigma/\partial\dot{\varepsilon}$ (>0) and the thermal softening $\partial\sigma/\partial T$ (<0). In a previous work (2), the author has investigated these strain hardening, strain-rate hardening and thermal softening components, intervening in the increase of stress in metallic materials submitted to impact, for different regimes corresponding to specific types of instability and material failure. At upper strain-rates above about 10^3 s^{-1} , dynamic fracture occurs mainly by adiabatic shear banding, which is induced by local thermal instability due to a pressure induced phase transition of the material microstructure, as it has been otherwise previously studied by the author (3). Even in a specimen impacted in compression (e.g. from a test with the Split Hopkinson Pressure Bar as presented by Follansbee (4)) and due to multiple reflection of the shock waves at face and radial specimen boundaries (depending thus on the specimen geometry), some material regions are put in a shear state, where adiabatic shear banding may occur. The present work aims to extend the analytical study of these dynamic fracture processes in focusing particularly on the influence of strain / strain-rate and geometry / microstructure.

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THERMAL INSTABILITY CRITERIA FOR ADIABATIC SHEAR BANDING

In the case where a first instability caused by thermal softening doesn't happen, the temperature can rise adiabatically further, as it is shown in Ref. (2). Using the common assumption that about 90% of the impact energy has been converted into heat, this adiabatic temperature rise globally in the impacted specimen increases proportionally to the area under the dynamic stress-strain curve (σ - ϵ):

$$\Delta T_{(°K)} = (0.9 / (\rho \cdot C_p)) \cdot \int \sigma \cdot d\epsilon \dots\dots\dots (1)$$

where ρ and C_p are the material density and specific heat capacity, respectively. As it is known (e.g. by the Hopkinson-bar test method) that the stress and also the strain reach much greater values at high strain-rates than in quasi-static loading, this adiabatic temperature rise can be very high, especially for materials with small values for ρ and C_p .

Furthermore, this temperature rise will only be concentrated inside of narrow material bands of maximum shear stress. The temperature then locally reached inside these adiabatic shear bands should even be much higher and can be found e.g. by applying the thermal trapping model proposed by Grady and Asay (5):

$$T_l (°K) = T_g (°K) \cdot \exp(\gamma \cdot \epsilon) \dots\dots\dots (2)$$

where T_g is the global temperature in the impacted specimen calculated from Eq. 1, γ and ϵ 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. Because of this further and exponential function of the dynamic strain, which is itself proportional to strain-rate, very high local temperatures can be reached, especially for materials with a great value for γ .

This strain/strain-rate controlled local adiabatic temperature rise can then eventually reach a critical temperature corresponding to a phase transition (or even melting) of the material microstructure within the shear band, as it is described in Ref. (2). Moreover, the temperature for pressure induced phase transition is even reduced by a rise in pressure and can be much lower than for the normal equilibrium conditions. This microstructure dependent critical temperature is thus itself also controlled by the imposed strain-rate. One obtains, in combining Eq. 1 and 2, the relationship for dynamic material instability between the temperature for pressure induced phase transition T_c and the critical strain ϵ_c :

$$T_{c(\epsilon')} - (0.9 / (\rho \cdot C_p)) \cdot \int \sigma \cdot d\epsilon \cdot \exp(\gamma \cdot \epsilon_c) = 0 \dots\dots\dots (3)$$

Because of the volume change under shock at the transition between the two phases, followed by the hysteresis between compression and shock release, a discontinuity results, which causes an instability locally in the material of the shear band. As the shear band's sides are already under a maximum shear stress state, this instability helps to the formation of a shear crack, which is normally observed in inside of the shear bands. It could be at the origin of dynamic complete fracture when this crack is (geographically) enough extended to reach the boundaries of the specimen. Dynamic material failure is therefore geometry dependent, not only in the build up of the critical shear stress state by the reflection of stress waves on the specimen boundaries, but also because of the possibility of extension of this stress state up to the specimen boundaries.

EXPERIMENTATION USING THE SPLIT HOPKINSON PRESSURE BAR

Different series of Hopkinson-bar compression tests with a wide range of specimen materials have already been conducted using the apparatus at EMPA. As it is reported in

Ref. (3), dynamic brittle-like fracture by adiabatic shearing effectively occurred, however, among all the materials tested, only for those having the possibility of a structure phase transition, i.e., pure titanium, with a *hcp* phase structure susceptible to twinning and also to phase transformation to a *bcc* structure, and high-strength steels, with a α' martensite phase structure susceptible to be changed to γ austenite phase. This fracture was complete and instantaneous for all steels specimens and was not preceded by any observable specimen deformation. For titanium specimens, material fracture was uncompleted because it was preceded by non negligible specimen deformation. It can be explained by the thermal material instability formulated above, where the critical temperature for phase transition has been reached locally within the formed shear bands. Very fine (but numerous) adiabatic shear bands were found in the steels specimens, when those for titanium were wider.

As a support to the present study of the influence of strain/strain-rate and also of the specimen geometry, further dynamic mechanical tests using the Split Hopkinson Pressure Bar at EMPA were done for the particular case of titanium by varying some of the test conditions. For the values of stress, strain and strain-rate, respectively, which are calculated from signal measurements using strain-gages, the basic expressions given in Ref. (4) can be combined together to give the following expressions for the strain-rate ϵ' , which is imposed to the Hopkinson compression specimen, in function of the velocity v_0 of the impact on the input bar (and also of the strength σ_{max} of the specimen material):

$$\epsilon' = c_b/l_0 \cdot (v_0/c_b - 2\sigma_{max}/E_b \cdot D_0^2/D_b) \dots\dots\dots (4)$$

and for the maximum strain ϵ_{max} in the Hopkinson compression specimen, at this strain-rate ϵ' , in function of the length L_b chosen for the impact bar in the apparatus:

$$\epsilon_{max} = \epsilon' \cdot 2L_b/c_b \dots\dots\dots (5)$$

with impact and measurement bars of 10 mm diameter D_b , made in maraging steel of 5100 m/s longitudinal sound velocity c_b and of 210 GPa Young's modulus E_b , and with cylindrical specimens of 4 mm thickness l_0 and 6 mm diameter D_0 .

Figure 1 shows the photograph of (about half of) one Hopkinson compression specimen in titanium after a test done above the critical impact velocity, with the evidence of an adiabatic shear band fracturing the specimen (the impact direction is pointed out by an arrow). This impact velocity can be related through Eq. 4 to a critical strain-rate, itself corresponding to a critical strain, as indicated in Eq. 5, with the length of 400 mm chosen in this test for the impact bar. Test measurements gave the corresponding values of about 5000 s^{-1} for strain-rate, about 85 % for strain and about 2000 MPa for strength. As described in the preceding chapter, this over-critical strain value of about 85 % can also be related through Eq. 3 to a local adiabatic temperature rise calculated to be 713 °K, which has thus happened within the shear band before fracturing the specimen and which should be higher than the pressure induced phase transition temperature for titanium. The temperature of 370 °K reported in Ref. (3) for phase transition under shock for titanium is effectively lower than this calculated over-critical local adiabatic temperature rise.

Furthermore, as the pressure induced structure phase transition is known to happen within a very short time, the registered high frequency signals from the tests with Hopkinson bar were able to detect this change. As shown in Figure 2, for the tests beyond the critical impact velocity, the measured stress-strain curves showed, above a critical strain value, a sudden fall & rise in the strain and stress values. This change in stress and strain levels would probably be related to the differences in mechanical properties between

the shock hardened structure phase before the phase transition and the one formed thereafter, with combined pressure hysteresis due to shock release.

By reducing, in the Hopkinson bar compression tests with titanium, the impact velocity down to a value corresponding to a measured strain-rate of about 4000 s⁻¹ and by using further on the same impact bar of 400 mm length, the fall & rise in the strain and stress values were no longer detected (Figure 2). No specimen fracturing was also observed after the test. This means that test conditions with the strain-rate of about 4000 s⁻¹, corresponding also to a reduced strain of about 50 %, were under-critical. In this case, the local adiabatic temperature rise in the titanium specimen should not have reached the phase transition temperature of about 370 °K, i.e., was not enough high for inducing adiabatic shear banding, before being dissipated after the test.

A third case consisted in Hopkinson bar compression tests with titanium at the (same as in the first case) critical strain-rate of about 5000 s⁻¹ but with the use of a shorter impact bar of 300 mm length, where only the beginning of the fall & rise in the strain and stress values have been detected (Figure 2). It seems here that the adiabatic shear banding process has been interrupted before its end, i.e., the local temperature for pressure induced phase transition has probably been reached but has not been followed by a complete material instability through crack formation. This case should therefore give the measured critical strain of about 70 % as the exact value corresponding to the phase transition temperature of about 370 °K in such Hopkinson compression specimens in titanium.

ANALYTICAL STUDY OF THE THERMO-VISCO-PLASTIC INSTABILITY

The analytical expression of the thermo-visco-plastic instability according to Ref. (1) can be used to write a criterion for dynamic material failure as the following:

$$\frac{d\sigma}{d\varepsilon} = \frac{\partial\sigma}{\partial\varepsilon} + \frac{\partial\sigma}{\partial\varepsilon'} \cdot \frac{d\varepsilon'}{d\varepsilon} + \frac{\partial\sigma}{\partial T} \cdot \frac{dT}{d\varepsilon} = 0 \dots\dots\dots (6)$$

If the constitutive equation of the material is explicit enough, i.e. with separated terms for the stress in function of the three variables strain, strain-rate and temperature, respectively, it would be able to solve this criterion in Eq. 6. One can thus first derive the stress upon all the three variables combined together, then put this derivation as equal to 0 giving an equation containing only the derivation terms between the three variables, finally integrate upwards in order to find one (unknown) variable in function of the two other ones.

As an example for this analytical study, one uses the Mathematical Software MAPLE-Version V4 (6) (denoting differently in the code κ as the strain-rate), with a constitutive equation following the Johnson-Cook model (7):

$$\sigma = (A + B \varepsilon^n) (1 + C \ln(\kappa)) \left(1 - \frac{T - 300}{\theta - 300} \right) \dots\dots\dots (7)$$

where A, B, C, n and θ are material constants (which are experimentally determined; a further constant m, as the exponent of the temperature term in the model, has been here lightly changed and always put equal to 1 to have linearity making the derivation possible).

After assuming that the strain-rate remains constant during the dynamic process, it results from the final integration an expression of the temperature in function of the strain:

$$T(\epsilon) = \frac{\epsilon^n B \theta + \epsilon^n B \theta C \ln(\kappa) + 300 \frac{A(1+C \ln(\kappa)) \theta}{\theta - 300} - 90000 \frac{A(1+C \ln(\kappa))}{\theta - 300}}{A + A C \ln(\kappa) + \epsilon^n B + \epsilon^n B C \ln(\kappa)} \dots\dots (8)$$

which can be furthermore simplified to the following one, thus as a simple and direct correlation between strain and temperature independently of strain-rate:

$$T(\epsilon) = \frac{\epsilon^n B \theta + 300 A}{A + B \epsilon^n} \dots\dots\dots (9)$$

According to Eq. 9, the critical internal temperature in a material, at which dynamic failure occurs by adiabatic shear banding, can be determined from a measured value for critical strain, e.g. using Hopkinson bar compression tests as described above. Inversely, the critical strain, at which a material can be impacted before fracture, can be calculated from its pressure induced phase transition (or melting) temperature, which can be determined, e.g. from its equation of state.

To make an example, calculations were also made here for pure titanium. Entering in Eq. 9 the estimated material parameters (A = 850 MPa, B = 210 MPa, n = .10 and θ = 2260 °K) and the critical strain of 70 % determined in the preceding chapter by Hopkinson bar compression tests (Figure 2), one obtains an internal temperature of 677 °K in titanium. This value is effectively lower than the local temperature of 713 °K calculated above by an other method (from Eq. 3 using the proposed energy/thermal trapping model), which has already been shown to be over-critical for the impacted specimen, and also higher than the reported temperature for pressure induced phase transition in pure titanium.

CONCLUSIONS

By using an energy model together with a local thermal trapping in inside of shear bands, a direct correlation has been put between the adiabatic temperature rise and the strain/strain-rate within the impacted material. Dynamic material instability occurs when a material's microstructure dependent pressure induced phase transformation is reached, itself being lowered down with increased strain-rate. Complete fracture depends furthermore on the specimen's geometry. Compression tests with Hopkinson bar were able to detect this dynamic failure due to adiabatic shear banding and gave the critical values of 5000 s⁻¹ for strain-rate and 70 % for strain in the case of pure titanium. A further analytical study of the thermo-visco-plastic instability was completely done and gave the corresponding critical value of 677 °K for the adiabatic temperature rise, which is effectively higher than the pressure induced phase transition temperature of 370 °K in titanium.

MAIN SYMBOLS USED

- σ = instantaneous stress (MPa)
- ε = instantaneous strain (-)
- ε_c = critical strain obtained with the Split Hopkinson Pressure Bar (-)
- ε' = κ = instantaneous strain-rate (s⁻¹)
- ε'_c = critical strain-rate obtained with the Split Hopkinson Pressure Bar (s⁻¹)

- T = instantaneous internal temperature (°K)
 ΔT = adiabatic temperature rise (°K)
 T_c = temperature for pressure induced phase transition of the microstructure (°K)

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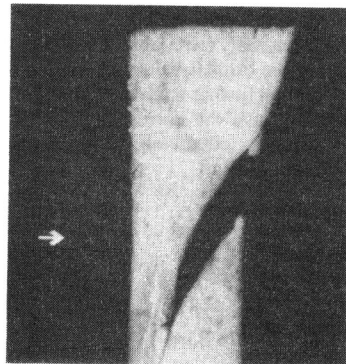


Figure 1. Shear banding in Hopkinson bar compression specimen in titanium

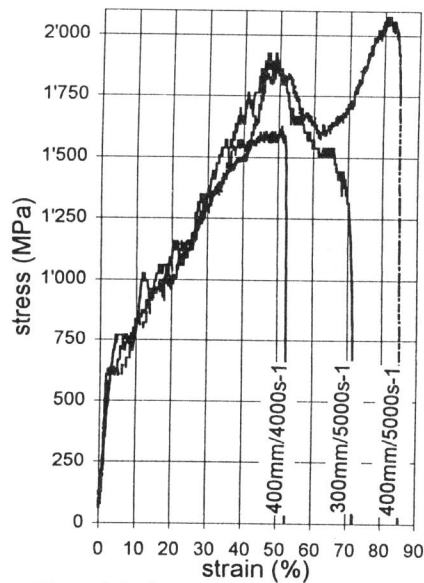


Figure 2. Influence of strain/strain-rate on stress vs. strain curve for titanium