DYNAMIC COMPRESSION AND FRACTURE OF PLAIN CARBON STEEL

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In a dynamic compression test deformation is found to be non uniform due to friction. In cross sections the test specimens form a shear deformation zone. The width of this zone varies with both materials under test and the test conditions. The zone widths are found to decrease with both decreasing test temperature and increasing strain rate. The effects of friction can be removed by the application of the Cook and Larke method if the material microstructures are consistent. Tests results from a series of plain-carbon steel test specimens are presented in the form of load-time data, micro-structural examinations of the sectioned specimens, micro-hardness measurements taken across the deformation zones and Cook and Larke analysis.

INTRODUCTION

Deformation in a tensile test is normally considered to be uniform up to the point of general instability or necking when the strain become non-uniform. The compression test may be used in cases where true stress data is required at large strain values in the assumption that instability is suppressed and the strains stay uniform (1). The conditions experienced during a dynamic compression test do not stay constant, but will vary continuously throughout the duration of the test. When using a drop tower the nominal strain rate will reduce during deformation. Heating of the test specimen will occur and this will be concentrated within shear bands undergoing the most deformation.

End face friction will cause the test specimen behaviour to be dominated by the local behaviour within the deformation zones. The local strains within the zones will be higher than the net strain and similarly the strain rates encountered will also be higher. As the temperature within the deformation zone increases the local yield stress will decrease and the thermal conductivity also decreases with increasing temperature. If work hardening dominates, the shear bands will broaden, but if

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thermal softening dominates, the bands will become narrower and unstable leading to fracture. If the deformation zones become more concentrated, instability can occur causing a sudden drop in the load measured. The effects of heating and cooling can be so dramatic within the deformation zone to cause microstructural transformations. These effects can also be accompanied by fracture which produces a characteristic fracture surface.

End face friction can be eliminated by the use of lubricant, hollow or dished cylinders or by use of the Cook and Larke (2) method, where cylinders of different diameter to length ratio (D/L) are tested with no lubrication . Then iso-strain lines can be extrapolated graphically back to zero D/L to give friction free values as used by Singh (3) and Belk (4).

EXPERIMENTAL METHOD

A series of compression cylinders were machined from plain carbon steels of 0.2, 0.4 and 0.8% C and were tested dynamically at two D/L ratios of 0.64 and 0.8. The cylinders were all of the same length of 10mm to give the same initial strain rate of 4 x 10^2/sec, with an energy input of approximately 100J The specimens were prepared with the same end face surface finish to provide matching end face friction effects. The compression tests was conducted at 20°C using an instrumented drop tower with hardened and polished compression platens. The proof loads were extracted from the recorded data and used in a Cook and Larke analysis. In this work the graphical construction method was limited to single iso-strain values for each condition of the steel at the compressive 0.2% proof stress (approximately the compressive yield stress) and at only two D/L geometries of 0.8 and 0.64. The tested specimens were sectioned axially and mounted prior to polishing and etching to reveal the microstructures. Micro hardness measurements were taken at various points on the cross sections using a Vickers diamond pyramid indentor.

Additional dynamic tests were carried out at slightly higher strain rates of 6 x 10^2/sec and lower temperature (-100°C) on 0.8% carbon steel, with an energy input of about 600J. Some reference tests were additionally conducted pseudo-statically (10^{-3}/sec) both with and without lubricant on 0.2% carbon steel.

RESULTS AND DISCUSSION

Cross sections taken through the specimens revealed three regions separated by shear zones and the degree and mode of deformation differs in each case. The cylinders become barrelled with two conical regions at the top and bottom of the cylinder and a "doughnut" shaped region surrounding the cones. A shear band separates the cones from the surrounding ring the width varied with both material and test condition (figs 1&2). The shear bands were found to become narrower with increased strain rate, material hardness and reduced test temperature, eventually resulting in a transformed band as shown in figure 2.

Micro-hardness measurements taken across the shear zones indicate the width of the zones and the degree of work hardening which occurred in the bands and adjoining regions. A typical hardness traverse across a shear zone for 0.8% carbon steel in the quenched and tempered condition is shown in figure 3 where the high hardness in the shear zone separates the top (impacted) cone to the left and the "doughnut" region to the right, the width of this shear zone being approximately 0.25mm. Comparisons of the top and bottom conical regions show a consistently higher hardness in the top cone than that found in the bottom cone. The hardness in the doughnut region varied with carbon content and was lower than that in the top cone at low % Carbon but higher for higher % Carbon. These results in figures 5&6 to indicate that the degree of deformation in each region which causes work hardening will vary with material condition and is not consistent.

Figure 7 shows the Cook and Larke extrapolations of dynamic compressive yield stress values (YS_{DC}) for each condition of steel, back to a friction free value of zero D/L. Four of the six lines extrapolate correctly, giving lower values of YS_{DC} as D/L is reduced, and their slopes increasing with strength order. Table 1 shows the friction correction factors obtained for the different steels and conditions.

Steel & Condition	**Ys_{DC} Measured at D/L = 0.8 (Mpa)**	**Ys_{DC} Friction Free at D/L = Zero (Mpa)**	**Component of Ys_{DC} Measured at D/L = 0.8 Due to Friction (%)**
0.2%C N	597	460	22.9
0.4%C N	776	535	31.1
0.8%C N	1174	690	41.2
0.8%C Q&T	1233	770	37.6

The friction correction factors ranged from around 20% at the 600 Mpa YS_{DC} level, to around 40% at the 1200 Mpa Ys_{DC} level, in keeping with other findings. The other two lines for 0.2%C Q&T and 0.4%C Q&T, appeared to extrapolate incorrectly, resulting in higher friction free values of yield stress. Subsequent checks on the microstructures showed the larger D/L cylinders to have 'slack quenched' in comparison to their smaller sister cylinders, thereby explaining the anomaly. These extrapolated values are typically greater than the compression tests performed pseudo-statically gave almost identical yield stress values of approximately 350 Mpa both with and without lubricant

The tests performed at low temperature and slightly higher strain rate on 0.8% carbon quenched and tempered steel resulted in the formation transformed bands on the top surface in contact with the compression platen and in the diagonal shear deformation zone. This was caused by the high degree of friction generating sufficient heat to cause austenitisation of the steel in a thin shear layer. When the compression forces dropped, the quenching effect of the platens caused a structural transformation to occur. A micro-hardness graph for this band is shown in figure 4.

with a maximum hardness of about 850 Hv and a width of approximately 0.002 mm. The hardness of the surrounding regions are similar to those found in the same type of specimens tested at 20°C, indicating that most of the additional energy (about 500 Joules more) was dissipated in the shear band. This type of behaviour is accompanied by a sudden reduction in force due to the instability caused and is commonly described as catastrophic shear. The force-time graph for a low temperature test is shown in figure 8, with a characteristic drop in force corresponding to a nominal strain of just over 0.6. Where the width of the band is very narrow and the structure undergoes a transformation, as in this case the bands are probably formed under adiabatic conditions and can be described as adiabatic shear bands. Because the structure transforms in these bands, further deformation may result in strains of sufficient magnitude to cause fracture within the band. This type of fracture was generated in the case of the low temperature tests and an example of the transformed band with a fracture in the centre is shown in figure 2. The fracture surfaces of these fractures have a characteristic described by Rogers (5) as 'knobbly'.

CONCLUSIONS

- Similar to a tensile test, large deformations in a dynamic compression test does not result in uniform strain.
- The degree of deformation and work hardening in a dynamic compression test varies with position, test material and conditions.
- The dynamic compressive yield stress can be determined from a Cook and Larke analysis of the results.
- When performing a Cook and Larke analysis, care must be taken to ensure the condition of the material microstructure is consistent.
- If a critical strain is exceeded in a dynamic compression test, instability may occur resulting in transformed bands.
- The formation of transformed bands may result in fracture formation within the bands.

REFERENCES

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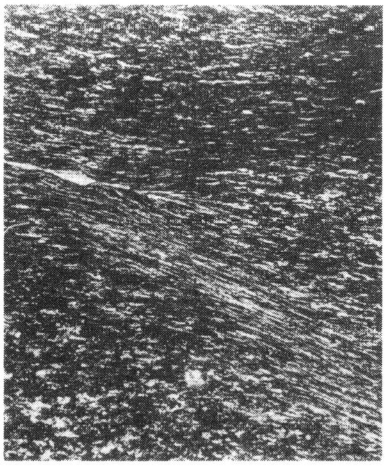

Fig. 1. Broad shear band in 0.8%C steel (norm.) test at 20°C --- .01mm.

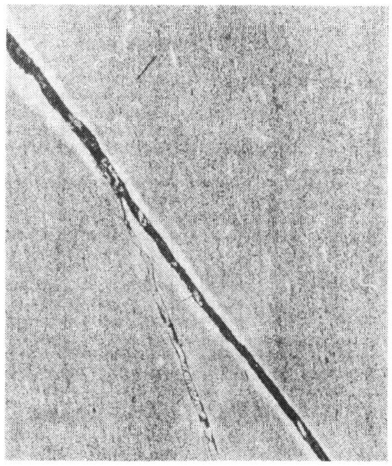

Fig. 2. Fractured transf. band in 0.8%C steel (Q&T) test at -100°C ------ .01mm.

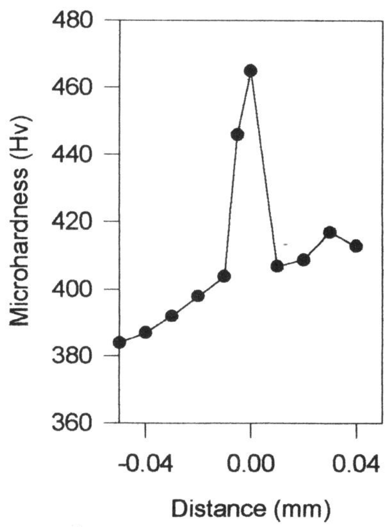

Fig. 3. Micro-hardness across shear band in fig. 1.

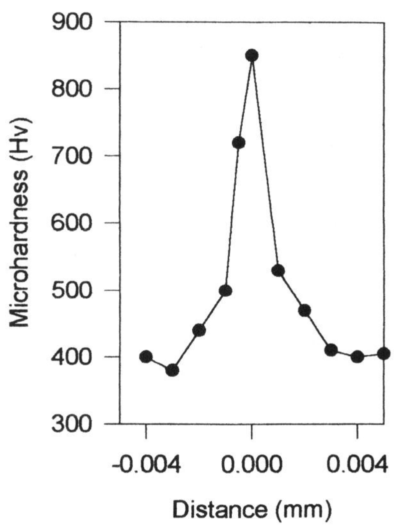

Fig. 4. Micro-hardness across transformed band in fig. 2.

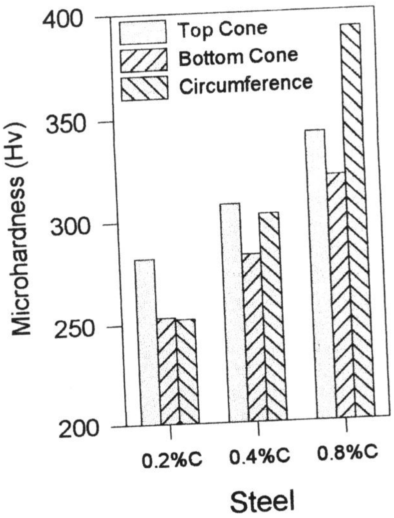

Fig. 5. Average hardness in the 3 regions of the Q&T steels.

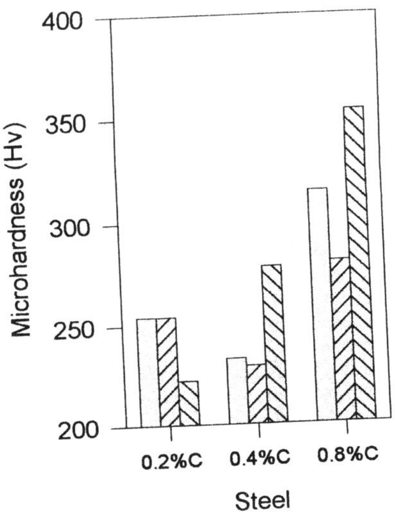

Fig. 6. Average hardness in the 3 regions of the normalised steels.

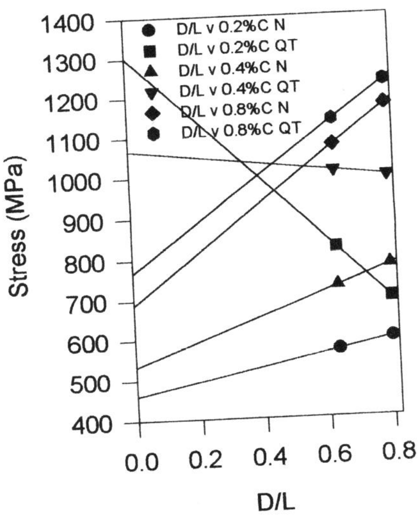

Fig. 7. Cook & Larke extrapolations for the samples tested at 20°C.

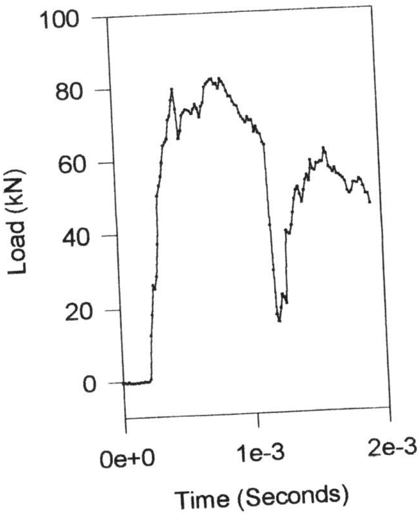

Fig. 8. Force time curve for test at -100°C showing instability.