Friction in Dynamic Compression Testing

by Stephen Walley (University of Cambridge, UK)

Contact: smw14@phy.cam.ac.uk

Although friction has been studied for many years and the mechanisms that give rise to it are quite well-understood (1-8) it is not possible to predict its magnitude for any given pair of materials under specified conditions (9), though there have been a few recent attempts at doing so (10-12). To put it another way, constitutive equations have not yet been developed which describe friction and this is a major hindrance to the numerical modelling of contact problems (13).
The main problems are that the surfaces of two materials in contact (i) have different mechanical properties to the bulk due to surface oxide layers, absorbed dirt or lubricants, (ii) are rough, and (iii) change with time during the deformation (14), even melting if the sliding speed is high enough (15, 16).

Most studies of friction have been concerned with sliding, but there is also a considerable literature on its effects in 'upset forging' e.g. (17-20) due to the importance of this technique in the forming of materials into desired shapes (21). Friction in this geometry has two major effects: (i) it generates a shear stress at the specimen/anvil interface and so changes the state of stress in the specimen from uniaxial to triaxial (22). This in turn causes the measured stress to be higher than the true yield stress of the material (23); (ii) the specimen does not preserve its original geometry but 'barrels' (22) If such a specimen is cross-sectioned after deformation, it often shows an 'X'-shaped pattern of intense shear due to frictional locking of the surface producing truncated cones of non-deforming material which slide over the unconstrained material at the sides (22). If the strain rates are high enough, substantial local temperature rises may occur in these shear zones, known as 'heat crosses' (24)or, more generally, 'adiabatic shear bands' (25). Friction can also lead to cracking of the specimen e.g. (26).

The standard test for measuring friction in the upset forging geometry is to deform an annulus of the test material (27). If the ratio of the inner to outer diameter remains constant then the lubrication conditions are perfect (zero friction). However, this has only been achieved for low strength materials such as polymers (28) and even then the lubrication is found to break down after a certain strain is exceeded (29). No combination of surface preparation and lubrication system has been found which reduces friction to zero for metals in this geometry (30), though it can be reduced to low values (3-4% of the shear yield strength at high rates of deformation (19)).

The standard ring test involves deforming the annulus to a certain strain, removing it from the apparatus and measuring the change in the radius of the hole and the change in thickness of the specimen. This measurement is then compared with a set of theoretical curves to read off a value for the friction e.g. (31, 32). There are several assumptions made in this procedure: (i) the specimen dimensions do not change between the time the deformation stopped and the measurement was made (this is probably reasonable for metals but certainly not for polymers (29)). (ii) The friction remains constant during the deformation (this is probably reasonable for small strains but not for large plastic deformation as 'foldover' occurs in which material from the sides ends up on the top surface (33). Also the lubricant can be squeezed out during the deformation). (iii) The theory is true. These assumptions can be and are being checked using high-speed photography (34)

1. F P Bowden & D Tabor, "The Friction and Lubrication of Solids. Part I", publ. Oxford University Press, Oxford, 1950.
2. F P Bowden & D Tabor, "The Friction and Lubrication of Solids. Part II", publ. Oxford University Press, Oxford, 1964.
3. I L Singer & H M Pollock, "Fundamentals of Friction: Macroscopic and Microscopic Processes" publ. Kluwer Academic, Dordrecht, The Netherlands, 1992.
4. J Krim, "Friction at the atomic scale" Scient. Amer. 275(4) (1996) 74-80.
5. J F Ganghoffer & J Schultz, "Interactions between adhesion and friction. 1: Theoretical aspects" J. Mech. Phys. Solids 45 (1997) 151-174.
6. K L Johnson, "Adhesion and friction between a smooth elastic asperity and a plane surface" Proc. R. Soc. Lond. A453 (1997) 163-179.
7. A A Batista & J M Carlson, "Bifurcations from steady sliding to stock slip in boundary lubrication" Phys. Rev. E 57 (1998) 4986-4996.
8. F-J Elmer, "Controlling friction" Phys. Rev. E 57 (1998) 4903-4906.
9. R P Feynman, R B Leighton & M Sands, "Friction" in "The Feynman Lectures on Physics. Vol. 1." Chapter 12, pp. 3-5, publ. Addison-Wesley, Reading, Massachusetts, 1963.

10. K Miyoshi & D H Buckley, "Correlation of tensile and shear strengths of metals with their friction properties" ASLE Trans. 27 (1984) 15-23.
11. W T Carter Jr., "A model for friction in metal forming" Trans. ASME: J. Engng Mater. Technol. 116 (1994) 8-13.
12. T Baumberger, "Contact dynamics and friction at a solid-solid interface: Material versus statistical aspects" Solid State Commun. 102 (1997) 175-185.
13. J T Oden & J A C Martins, "Models and computational methods for dynamic friction phenomena" Comput. Meth. Appl. Mech. Engng 52 (1985) 527-634.
14. J F Archard, "The temperature of rubbing surfaces" Wear 2 (1958) 438-455.
15. F P Bowden & E H Freitag, "The friction of solids at very high speeds. I: Metal on metal. II: Metal on diamond" Proc. R. Soc. Lond. A248 (1958) 350-367.
16. R S Montgomery, "Evidence for the melt-lubrication of projectile bands" ASLE Trans. 28 (1985) 117-122.
17. J Klepaczko & Z Malinowski, "Dynamic frictional effects as measured from the split Hopkinson pressure bar" in "High Velocity Deformation of Solids", ed. K Kawata & J Shioiri, publ. Springer-Verlag, Berlin, 1978, pp. 403-416.
18. P Hartley, C E N Sturgess & G W Rowe, "Influence of friction on the prediction of forces, pressure distributions and properties in upset forging" Int. J. Mech. Sci. 22 (1980) 743-753.
19. D A Gorham, P H Pope & O Cox, "Sources of error in very high strain rate compression tests" Inst. Phys. Conf. Series 70 (1984) 151-158.
20. T-C Hsu & C-H Lee, "Refined friction modeling for simple upsetting" Trans. ASME: J. Manuf. Sci. Engng 119 (1997) 563-570.
21. G E Dieter, "Bulk workability testing" in "Metals Handbook, 9th Edition, Volume 8", publ. American Society of Metals, Metals Park, Ohio, 1985, pp. 571-597.
22. J Mescall, R Papirno & J McLaughlin, "Stress and deformation states associated with upset tests in metals" in "Compression Testing of Homogeneous Materials and Composites. ASTM STP 808", ed. R Chait & R Papirno, publ. American Society for Testing and Materials, Philadelphia, 1983, pp. 7-23.
23. J A Schey, T R Venner & S L Takomana, "The effect of friction on pressure in upsetting at low diameter-to-height ratios" J. Mech. Work. Technol. 6 (1982) 23-33.
24. W Johnson, G L Baraya & R A C Slater, "On heat lines or lines of thermal discontinuity" Int. J. Mech. Sci. 6 (1964) 409-414.
25. Y L Bai & B Dodd, "Adiabatic Shear Localization: Occurrence, Theories and Applications", publ. Pergamon, Oxford, 1992.
26. A Jenner, Y Bai & B Dodd, "A thermo-plastic shear instability criterion applied to surface cracking in upsetting and related processes" J. Strain Analysis 16 (1981) 159-164.
27. I A Martorell, "On the ring compression test" in "Compression Testing of Homogeneous Materials and Composites. ASTM STP 808", ed. R Chait & R Papirno, publ. American Society for Testing and Materials, Philadelphia, 1983, pp. 78-94.
28. B J Briscoe & R W Nosker, "The influence of interfacial friction on the deformation of HDPE in an SHPB" Wear 95 (1984) 241-262.
29. S M Walley, J E Field, P H Pope & N A Safford, "A study of the rapid deformation behaviour of a range of polymers" Phil. Trans. R. Soc. Lond. A328 (1989) 1-33.
30. M L Lovato & M G Stout, "Compression testing techniques to determine the stress/strain behavior of metals subject to finite deformation" Metall. Trans. A 23 (1992) 935-951.
31. B Avitzur, "Forging of hollow discs" Israel J. Technol. 2 (1964) 295-304.
32. V de Pierre & F Gurney, "A method for determining constant and varying friction factors during ring compression tests" Trans. ASME: J. Lub. Technol. 94 (1974) 482-488.
33. G W Pearsall & W A Backofen, "Frictional boundary conditions in plastic compression" Trans. ASME: J. Engng Indust. 85 (1963) 68-76.
34. S M Walley, P D Church, M Furth & J E Field, "A high-speed photographic study of the rapid deformation of metal annuli: A comparison of theory with experiment" J. Phys. IV France 7 Colloq. C3 (EURODYMAT 97) (1997) 317-322.