although the data are represented here as lying within ±5000 psi of a mean constant value of 96000 psi. A small increase in yield stress with pressure for tungsten is qualitatively in keeping with the decrease in screw dislocation mobility with pressure reported recently[17] for lithium fluoride and shown to be consistent with jog control of the mobility. While the mechanism(s) of yielding in tungsten are currently uncertain—in particular as to the cause of the strong dependence of the macroscopic yield stress for single crystals on their orientation and the sign of the applied

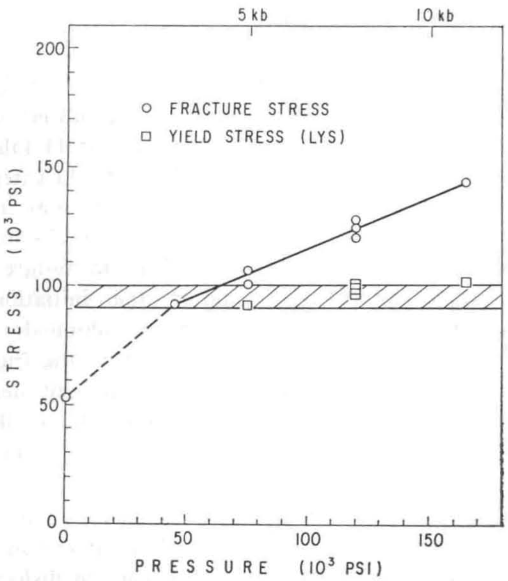

Fig. 6 Pressure dependence of yield and fracture stress in tension of recrystallised PM tungsten.

stress[18][19]—the jog-controlled mechanism proposed by Rose et al.[20] to account for the orientation dependence is also in accordance with the trend in yield stress with pressure observed here. Further clarification of this point is expected to result from the study currently in progress of the pressure dependence of the tensile behavior of higher purity, arc-melted tungsten in which the influence of the grain boundaries (as discussed later) should be less prominent.

Although Fig. 6 indicates that the fracture stress initially increases rapidly with pressure to 3 kilobars by an amount similar to the increase in applied hydrostatic stress, the fact that brittle fracture in tungsten at atmospheric pressure is well known to occur over a wide range of stress values suggests that this simple pressure dependence is only apparent. Beyond 3 kilobars, i.e., beyond the onset of plastic strain, the fracture stress increases linearly with pressure and at a rate much larger than for the accompanying change in yield stress. As the increase in fracture stress is less than the corresponding increase in hydrostatic stress, the concept of a constant net stress (the difference between applied unaxial tensile stress and the hydrostatic compressive stress) as a general criterion for fracture[7][11] does not hold for PM tungsten.

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(18) D. Hull, J. F. Byran and F. W. Noble : Can. J. Phys., **45** (1967), 1091.
(19) M. Garfinkle : Trans. AIME, **236** (1966), 1373.
(20) R. M. Rose, D. P. Ferriss and J. Wulff : Trans. AIME, **224** (1962), 981.

The temperature dependence of the yield stress in tension cannot be measured in recrystallized PM tungsten below some 150°C at atmospheric pressure due to the onset of brittle fracture, but measurements have been reported for the compression yield stress down to −196°C. The various yield stress values which have been published[14][21]~[26] are plotted in Fig. 7. The

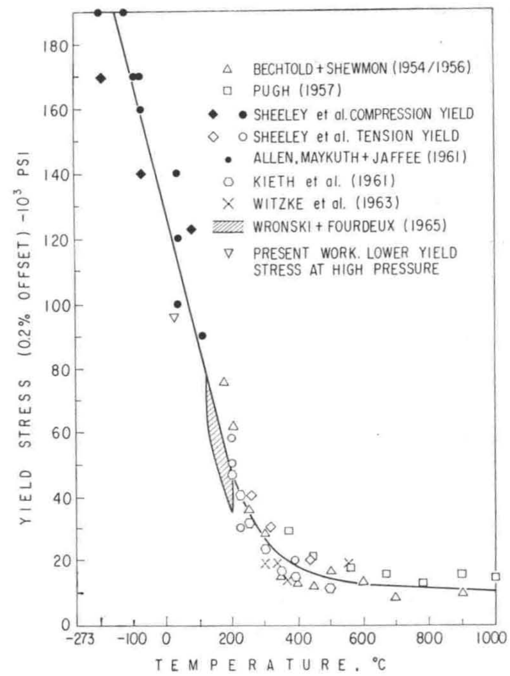

Fig. 7 Compilation of reported measurements of yield stress in tension and compression for recrystallised PM tungsten at atmospheric pressure.

smooth curve represents the mean of the scatter band (omitted for clarity) which encompasses the data points and it is seen that the temperature dependence appears continuous for both tension and compression yield data. The average tensile yield stress of 96000 psi obtained at high pressure and 25°C is also plotted on this figure and lies on the lower edge of the scatter band (which ranges from 96000 to 145000 at 25°C with a mean of 120000 psi). If the possible pressure dependence of the yield stress discussed above is assumed, the corresponding extrapolation to room pressure gives a value of some 83000 psi. However, although both these values of the tensile yield stress obtained from the

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(25) R. H. Schnitzel : J. Less-Common Metals, **8** (1965), 81.
(26) W. R. Witzke, E. C. Sutherland and G. K. Watson : Tech. Rept. TND-1707, National Aeronautics and Space Administration, 1963.

high pressure results are lower than those expected from the curve in Fig. 7, the scatter in the previously published data is unfortunately too large to conclude that there is a difference between the yield stress in tension and compression at room temperature.

In view of the well established fact that in most crystalline materials some plastic flow accompanies fracture and the several fracture theories which assume plastic strain as a pre-requisite for the initiation of fracture, it is of interest to compare the yield stress observed at high pressure with the fracture stress at atmospheric pressure. In Fig. 8, the reported data for

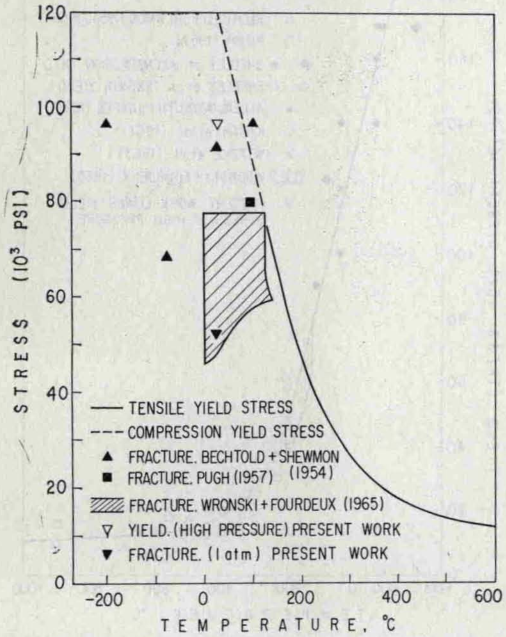

Fig. 8 Comparison of yield stress at high pressure with yield and fracture stresses reported for atmospheric pressure. Recrystallised PM tungsten.

the temperature dependence of the brittle fracture stress of recrystallized PM tungsten[14][21][22][24] are shown together with the yield stress curve from Fig. 7 and the average yield stress observed at high pressure. At 25°C, the latter is seen to be close to the upper limit of the values of the fracture stress measured at atmospheric pressure, as also is the yield stress of 83000 psi obtained by extrapolation from the high pressure data. Thus, these results are consistent with the initiation of fracture as a consequence of local plastic yielding at stress concentrations when the general stress level is below the macroscopic yield stress or, in the absence of stress concentrations, of general plastic yielding when that stress is reached i. e., it represents an upper limit for the fracture stress at room temperature. Examination of the prepolished surfaces of the fractured tensile specimens by optical microscopy and of the fracture surfaces by electron fractography established that the fractures occurred by a mixture of transgranular and intergranular cleavage over the complete range of pressure. For the specimens tested at all pressures up to 8 kilobars no evidence of cracking was found on the prepolished surfaces except for rare examples of grain boundary and transgranular cracks at the edge of the fracture surface. In contrast, the specimens fractured at 11 kilobars (8 % elongation) exhibited grain boundary cracks, occasionally with an associated transgranular crack, along the complete gage length. Most of the intergranular cracks were transverse to the tensile axis, but a number of instances of grain boundary separation in longitudinal and other directions were also noted. The transgranular cracks were not observed to propagate completely across the grains. In addition to the microcracks, occasional surface slip markings, usually associated with grain boundary junctions, were found. These various observations indicate that at pressures below 11 kilobars the principal effect of the imposed hydrostatic stress is to inhibit the formation of microcracks, but that once initiated—apparently by intergranular failure leading to transgranular cleavage—the initial crack propagates catastrophically. In contrast, at 11 kilobars the increased plastic deformation leads to the extensive development of intergranular separation and some transgranular cracks. However, the internal cracks formed in this way do not immediately lead to failure i. e. their rapid propagation and/or the initiation of catastrophic transgranular cleavage is inhibited. The fact that for a given increase in pressure the fracture stress does not increase by the same amount demonstrates that the effect of pressure cannot be attributed to a simple reduction in the applied stress normal to the crack.

The dislocation substructure observed by thin foil electron microscopy in the series of specimens strained to fracture showed a discontinuous change in dislocation density and distribution with increasing pressure. The structure of the as-recrystallized tungsten exhibited only large grains separated by high-angle boundaries and containing the low density of dislocations typical of a well annealed metal. No impurity particles were found either in the grains or at the boundaries, but voids of the type discussed earlier were present. Little change occurred in this structure after fracture at atmospheric pressure and 3 kilobars with the exception of isolated dislocations which appeared at boundaries more frequently at the higher pressure. Also at 3 kilobars, the development of internal elastic strains was evidenced by the presence of multiple diffraction contours. In contrast, the development of 2 % plastic strain before fracture at 5 kilobars (see Fig. 4) resulted in both increased numbers of dislocations at boundaries and a high dislocation density within the grains, as illustrated in Fig. 9(a). The dislocation arrays exhibit the dipoles, jogs and associated small loops characteristic of plastic deformation in the *bcc* transition metals. The nature of the dislocations at the grain boundaries is shown by the dark field micrograph in Fig. 9(b). The further strain (8 %) at 11 kilobars caused a considerable increase in the density of dislocations within the grains and the development of tangles—Fig. 10.

Occasional examples of grain boundary separation were seen in the foils and in one instance an associated transgranular cleavage crack penetrating partially across its grain was observed. The overall length of the crack lay in a single direction, but the detailed path was made up of short zig-zag segments parallel to