TABLE 1

Fracture type	Initiation Mechanism	Initiation Requirement	Pressure effect	Propagation Mechanism	Propagation Requirement	Pressure effect
A-Brittle						
(1) Cleavage	Dislocation or twin intersection or dislocation pile-up	Shear strain	Nil	$\sigma^2 > \alpha \frac{\gamma_s E}{c}$	Normal tensile stress	Decrease σ
(2) Intergranular	Dislocation pile-up or twin intersection at grain boundary	Shear strain	Nil	$\sigma^2 > \alpha \frac{(\gamma_s - \gamma_B)E}{c}$	Normal tensile stress	Decrease σ
B-High temperature rupture						
	Cavitation due to grain boundary sliding	Shear strain	Nil	Cavity growth and link-up	Shear strain	Retard cavity growth
C-Ductile						
(1) Fibrous	Void formation in deformation bands	Shear strain	Nil	Void extension in deformation bands	Shear strain + normal tensile stress	Retard void growth and extension, decrease σ
(2) Shear	Void formation in deformation bands	Shear strain	Nil	Void sheet formation in deformation bands	Shear strain	Nil

if not negligible effect upon dislocation formation and motion.

Consider the propagation stage: in the case of cleavage and intergranular fracture, propagation occurs when the strain energy released due to crack extension equals the increase in energy associated with the formation of new crack surfaces. This energy balance results in the basic Griffith relationships shown in Table 1 where σ is the applied normal tensile stress and γ_s and γ_B the surface and grain boundary energies respectively, and "c" the crack size. The effect of a superposed pressure then will be to decrease the normal tensile stress by the magnitude of the pressure, thus impairing, if not preventing, crack propagation by cleavage or intergranular modes.

The propagation stage of high-temperature rupture and fibrous fractures involves the growth and extension of voids requiring shear strain in combination with some normal tensile stress and, in the former case, vacancy diffusion at low strain rates. The effect of pressure then will be to reduce any normal tensile stress contribution and to resist the growth of voids.

One can estimate the effect of pressure on retarding void growth by considering the parallel case of the yielding of a hollow sphere of infinite wall thickness under an external pressure.[10] From elasticity theory and assuming either a maximum shear stress or the Von Mises–Hencky yield criteria, collapse of the sphere will occur at a pressure equal to two-thirds the yield stress. Thus, one would not expect to see spherical void growth at pressures above two-thirds the yield stress at the test condition. Similar elastic solutions are also available for the ellipsoidal cavity case.[11]

Ductile shear fracture propagation is by means of void-sheet formation in severe deformation basis. Being primarily a shear-strain process, it is relatively unaffected by pressure.

In summary then, the proposed model is that pressure has little or no effect upon the initiation stage of fracture; its principal effect is in the propagation stage where it retards those mechanisms requiring normal tensile stresses or the growth and extension of large voids. Its effect then will be to retard those propagation mechanisms associated with brittle or low ductility type fractures, thus favoring those involving shear strain and high ductility.

EXPERIMENTAL PROCEDURE

Apparatus

The 30-kb Bridgman–Birch type hydrostatic pressure system used in this work has been previously described in detail.[7] It will suffice to say that this system is a piston–cylinder device having a high pressure cavity of 0.75-in. dia. with an 8-in. working length and 4-in. piston stroke. Pressure measurement is by means of a manganin wire transducer used in conjunction with a Foxboro recorder. The estimated error in pressure measurement is ± 2 per cent.

The fixture utilized for the conduct of the tensile tests under pressures to 23 kb is shown in Fig. 1 along with a typical specimen. This fixture consists of 4 segments or legs, two of which are stationary and bear against the bottom closure of the pressure cavity. The remaining pair of legs are movable and are driven downward by the advance of the main piston into the pressure cavity, thus inducing a tensile force in the specimen.

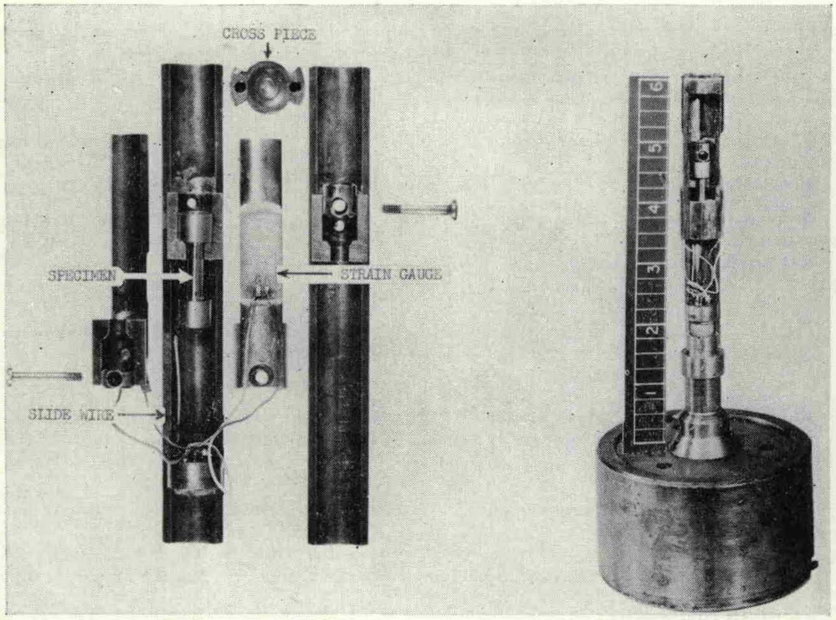

FIG. 1. High-pressure tensile specimen holder.

Materials and specimen configuration

The following materials and material conditions were utilized in this investigation:

Material	Purity %	Condition	Grain size (mm)
Magnesium	99.98	Hot extruded	0.08
Zinc	99.99	Hot drawn	0.08
Cobalt	99.9	Hot swaged	0.03
Tungsten	99.9	Pressed and sintered	0.09
1045 Steel	Alloy	Water quenched from 843°C. 61 R_c	0.07

In the pressure range of this investigation, these metals do not undergo any abrupt changes in electrical resistance nor in volume indicative of an allotropic transformation.[12]

The specimen configuration, as can be seen in Fig. 1, has a length of 9/16 in. as measured between the shoulders and section diameters of 0.160 in. for magnesium, zinc and cobalt, and 0.070 in. for the 1045 steel and tungsten.

Procedure

Since the actual straining of the specimen while under pressure was accomplished by the motion of the main piston, an increase in pressure occurred during the conduct of the test. The actual pressure change observed during the conduct of a test depends upon the ductility of the material being tested. For materials in their brittle form, little displacement of the piston is required and the pressure increase is quite small. In the case of ductile materials, or at pressures above brittle–ductile transition where the ductility can be quite high, the pressure variations during testing can be large. However, in the initial stages of the brittle–ductile transition, which is of principal concern in this investigation, the pressure change during the test is relatively small viz. 0.5 kb for magnesium at 4 kb, and 0.1 kb for steel at 18.5 kb. The fact that large changes occur above the transition pressure, particularly in the case of magnesium and zinc, has little bearing on the results or on the conclusions drawn therefrom since it is beyond the pressure region of major concern. For the purpose of reporting the data, only the final pressure, i.e. the pressure at fracture, is plotted.

The strain rate used throughout this investigation, as measured from the displacement rate of the high-pressure piston, was maintained at 0.05 in/min.

The tests for all materials except magnesium were conducted at ambient temperature. For the studies on magnesium at elevated temperatures, i.e. 100°C and 175°C, the outer restraining jacket of the pressure system was removed and the entire high-pressure cylinder was wrapped with a heating tape. For the tests conducted at —55°C, the high pressure cylinder was immersed in a dry ice–acetone bath.

Temperatures within the high-pressure cylinder were measured by the calibrated resistance change of an annealed platinum wire. The estimated error in the temperature measurement was ± 3 per cent.