Table 3.6
Incipient spall strengths

Material	Spall strength GPa*	Impactor thickness mm	Character of damage	Method**	Remarks	Reference
Aluminum and alloys						
Aluminum	1.0	1.58	ductile voids	M	Annealed	[71S1]
1145	0.5–1.1	1.14–5.84	ductile voids	M	NAG parameters given	[70B1, 71S1, 72B1]
2024-T4	1.25	3.8	blunt cracks	M	30% weaker at 541 K	[70B5]
2024-T81	0.6	3.36	blunt cracks	M	NAG parameters given	[71S1]
2024-T86	2.0–1.8	0.3–1.0		V, PB	e-beam data on 4 metals	[78S1]
6061-T6	1.5–0.8	0.25–1.75	blunt cracks	M		[64B4]
6061-T6	1.0	3.17	blunt cracks	M	No effect of precompression	[71S2]
6061-T6	2.0–1.3	0.25–4.0	blunt cracks	M, PB	Broad investigation	[71C4]
6061-T6	2.3–0.8	0.25–6.35	blunt cracks	M		[63B1]
2014–T6	1.76–1.47	0.61–1.57	blunt cracks	M		[71B2]
AMg-6	2.14–1.36	3.0–5.0	blunt cracks	M, V		[73T2]
Beryllium						
a-cut crystal	1.0	1.27 (quartz)	prism cleavage	M		[73P1]
c-cut crystal	1.15	0.76 (quartz)	basal cleavage	M		[73P1]
HP-10	0.92	1.02 (quartz)	cleavage	M, PB		[73S5]
HP wrought ingot	0.54–0.36	1.27–5.08	cleavage	M	35% stronger at 533 K	[70C1]
S-200	1.3–0.78	0.64–2.54			Stronger hot	[68W2]
N50A	0.9–0.5	0.25–5.08	irregular crack	M		[68W1]
Brass, 60/40	1.4	6.35		M		[70S2]
Copper						
OFHC	0.95–0.75	1.5–3.2	blunt cracks	M	Cold rolled	[63S1]
OFHC	2.5–1.8	0.5–3.0	voids and cracks	M	Half hard	[71C3]
OFHC	2.3–0.62	0.4–1.6	voids and cracks	M	Believed annealed (NAG)	[71S1, 72B1]
Graphite, ATJ-S	0.062–0.047	0.79–3.18	irregular crack	M	Independent of temperature	[68W2]
Plastics						
Lucite	0.1	0.25–6.35	fine cracks	V		[63B1, 63K1]
Lexan	0.16		plane cracks	V	Polycarbonate plastic (NAG)	[73C8]
Epon 828 Epoxy	0.076	5.08	plane crack	V	Single crack	[68G6]
Plexiglas	0.15–0.14	1.0–2.8	plane cracks	M, V		[73T2]
PMMA		1.0–2.0	plane cracks	M, V	80 to 333 K	[73T1]
ABS	0.1–0.06	0.55–4.5	fine crazing	V		[72T1]
Iron and steel						
Fe (99.99%)	1.9	1.16	brittle cracks		Light damage	[71S1]
Armco iron	3.5–1.7	0.51–2.36	brittle cracks	M	NAG	[70B1, 71S1, 72B1]
1020	1.6	3.17	brittle cracks	M	No effect of precompression	[71S1]
4340 Rc 15	2.5	6.35			Annealed	[67B4]
Rc 54	4.1	6.35			Quench to max. hardness	[67B4]
Rc 52	5.3	6.35			Quenched and tempered	[67B4]
Armco 21-6-9	3.7	3.2–12.8		PB		[69G3]
AM 363	4.5–2.1			PB		[71D1]
Titanium	3.9–2.1	0.22–4.09	blunt cracks	PB	25% stronger at 533 K	[72C3]
	3.7–2.2	0.4–6.0	voids, cracks	M	Cracks at grain boundaries	[78S3]
Uranium	2.4	0.77–3.01		PB	Also Cu, Ta, two steels	[77C1]
Rock***						
Oil shale	0.017–0.023			PB	Strength increases with kerogen content	[76S1]
Quartzite	0.04		plane cracks	V, M	Arkansas novaculite	[73S2, 74S3]

* All values inferred from plate-impact experiments done with thickness ratios approximately 2 to 4. Values are measured at room temperature (~ 20°C).

** V - visual inspection, M - microscopic examination, PB - inferred from free-surface velocity history.

*** See also the recent measurements on 21 rocks by Grady and Hollenbach [79G3].

is found in an investigation of Stevens et al. [72S2, 73S4] in which spall damage in high-purity aluminum monocrystals took the form of octahedral voids with {111} planes of the fcc crystal as faces. This observation was explained as a consequence of volume being transported into the void by edge dislocations moving into it in response to the surrounding stress concentration. A model developed on this basis indicates that, at constant stress, the volume of a void increases at a rate proportional to its current value, i.e., exponentially in time. This result is consistent with the law previously discovered empirically by Barbee et al. [72B1] and since shown to hold rather generally for the early phase of the growth process.

Formation of well-defined plane cracks has been noted in iron, beryllium, poly(methyl methacrylate), and polycarbonate. The work on iron [71C8, 72B1, 73S1], which is quite detailed as to the statistical properties of the crack distribution, indicates a 50 per cent higher strength for Armco iron over that of a similar but more nearly pure material, and notes a transition to ductile behavior at high temperatures. At temperatures where brittle fracture is observed, the cracks are randomly oriented, probably lying on {100} planes of the various grains comprising the polycrystalline sample [61E1, 68B1]. Experiments [73P1] on beryllium monocrystals showed that impact along the *a* axis produced cleavage along type-II prism planes, while impact along the *c* axis produced cracks along basal planes. In each case the spall plane was that subjected to the greatest tension. Impact of a crystal cut at 45° to the *c* axis produced a spall fracture surface comprising elements of basal and pyramidal planes, and perhaps other planes, of micrometre diameter. Spall damage nucleated at grain boundaries in polycrystalline samples of beryllium is observed to propagate in both inter- and intragranular modes. The work on poly(methyl methacrylate) [73T1] and polycarbonate [73C8] plastics shows that damage results from stress activation of pre-existing flaws. The cracks, which are circular and lie perpendicular to the direction of maximum principal stress, grow in a complicated way that involves dynamic phenomena associated with the individual cracks and also seems to include coalescence of large cracks with small cracks forming in the path of their advance.

In technical materials, where damage is most frequently nucleated at gross defects, the distinction between ductile and brittle response is often blurred with "blunted cracks" being observed in most materials. There is a large, but not very definitive, literature describing such observations and the matter is discussed in most of the work listed in table 3.6.

The effect on spallation of variations in metallurgical characteristics of aluminum alloys and beryllium can be inferred from existing work, and Jones and Dawson [73J2] have surveyed the effects of varying dislocation density, stacking-fault energy, and state of second-phase precipitation in several materials. Unfortunately, metallurgical changes that influence fracture phenomena influence propagated waveforms as well, and this effect must be taken into account if data are to be interpreted with assurance.

Most research on spallation has been directed toward finding a criterion for its occurrence [72D1]. Several criteria have been proposed, all sharing a number of serious shortcomings among which is that the concept of spall damage itself is not given a quantitative interpretation. In modern work, spall damage is quantified by the number density and size distribution of the cracks or voids in the material. At low damage levels these might typically be $10^4/\text{mm}^3$ and 1 to 100 μm radius, respectively. Experimental investigations have concentrated on measuring these quantities in samples subjected to various histories of load application. Theoretical interpretation of the results has been in terms of equations relating the rate of nucleation and growth of cracks or voids to the stress.