STRENGTH OF ALUMINIUM NITRIDE WHISKERS

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ANALYSIS of the strength of materials, from an atomistic point of view, predicts that the ratio, α, of fracture stress (σ) to initial strain (ε) in atomic bonds will be of the order of 10 per cent E (E = Young's modulus). A value of α of this magnitude should be obtainable for perfect crystals. Whereas in practice yielding occurs in high-strength structural materials when α is about 1 per cent E, it has been known for a long time that whiskers or fibres of almost all materials, with diameters of $\sim 10^{-4}$ cm, and large length/diameter ratios show values of α near to the ideal value. Non-metallic whiskers having mixed ionic/covalent bonding with low specific densities and high melting-points have been examined as strengthening media for fibre-reinforced materials[1]. Analysis of fibre-reinforced systems have recently been made by Cottrell[2] and Kelly[3].

Aluminium nitride is a refractory material which may be considered suitable as a fibre-reinforcing material. Whiskers of this material were prepared by heating aluminium nitride powder (contained in an alumina crucible), at temperatures up to 1,820° C in an alumina tube in a flowing atmosphere of high-purity nitrogen diluted with high-purity argon. Chemical and X-ray analysis of the whisker product confirmed that the whiskers were aluminium nitride. The whiskers formed on cooler sections of the container. It is suggested that the whiskers grow by a process of dissociation of aluminium nitride powder at the operating temperature with subsequent growth of whiskers, from a vapour phase, at a cooler substrate. Straight whiskers, about 18–20 mm long, were formed after 15 h at temperature, giving an average growth rate of about 1·5 mm/h. Some of the whiskers with good morphological symmetry had 'kinks' and 'branches' (Fig. 1) and it was also observed that a whisker changed its axial growth direction by about 2° (minimum) to 20° (maximum) over its length. Platelets formed at slightly higher temperatures showed surface striations (Fig. 2); under oblique illumination these striations appeared to be growth steps and not slip planes perpendicular to the major growth axis. The results of bend and tensile strength determinations on whiskers are given in Tables 1 and 2.

Bend-strength tests. The whiskers were subjected to bending on a Reichart microscope stage. Fig. 3 shows a typical bend in a whisker before fracture. All these tests were conducted with the whisker lying in a film of oil.

For perfectly elastic bending, the tensile stress in the outer surface of a fibre can be expressed as:

$$\sigma = \frac{Er}{p}$$

where σ = tensile stress in outer fibre; E = Young's modulus; r = radius of fibre; p = radius of curvature. It was observed that fracture occurred most frequently in whiskers containing common types of structural imperfections, that is, low-angle kinks, whiskers with twists of about 10° along their length and whiskers with surface growth steps.

The majority of whiskers were extremely flexible and it was sometimes difficult to obtain a sufficiently small

Table 1. Bend Strength of Aluminium Nitride Whiskers ($E = 50 \times 10^6$ lb./in.^{2})

No.	Length ($\mu \times 10^3$)	Cross-section (μ)	p (μ)	$\sigma = \frac{Er}{p}$ (lb./in.^{2})	$\frac{\sigma}{E}$ (%)
1	7·3	2·5 × 4·0	60	$1·04 \times 10^6$	2·08
2	4·2	2·5 × 3·0	58	$1·08 \times 10^6$	2·16
3	5·0	2·8 × 3·5	72	$0·97 \times 10^6$	1·93
4	7·5	7·2 (hex)	1,820	$9·9 \times 10^4$	0·02
5	5·2	6·5 (hex)	1,720	$9·5 \times 10^4$	0·19
6	5·0	5·5 (hex)	1,900	$7·25 \times 10^4$	0·02
7	8·2	3·0 × 8·0	75	$1·0 \times 10^6$	2·00
8	8·3	$8·0 \times 10^2 \times 2·5 \times 10^2$ (platelet)	10^4	$1·25 \times 10^4$	—
9	4·7	3·5 × 2·5	78	$0·8 \times 10^6$	1·60
10	4·2	3·7 × 2·8	82	$0·88 \times 10^6$	1·75
11	5·0	4·0 × 2·2	2,500	$2·2 \times 10^4$	—
12	5·2	8·0 × 2·5	10^4	$6·7 \times 10^3$	—

All specimens except No. 6 were immersed in oil during testing. All specimens except Nos. 11 and 12 were bent about an axis parallel to the longest side of the cross-section; Nos. 11 and 12 were bent about the shorter cross-sectional axis. Specimens 4, 5 and 6 were produced in the image furnace[4]; for these specimens with a hexagonal cross-section the mean diameter is given.

Table 2. Tensile Measurements (Gauge Length 1·0 cm)

No.	Whisker section (μ)	Load at fracture (g)	Fracture stress (σ) (per lb./in.^{2})
1	10 × 38	272	$1·02 \times 10^6$
2	17 × 22	188	$0·72 \times 10^6$
3	9 × 42	260	$0·98 \times 10^6$
4	11 × 37	268	$0·94 \times 10^6$
5	10 × 39	272	$0·99 \times 10^6$
6	8 × 45	268	$1·06 \times 10^6$
7	26·3 mean diam. (hex)	52	$0·14 \times 10^6$
8	28·6 mean diam. (hex)	53	$0·13 \times 10^6$

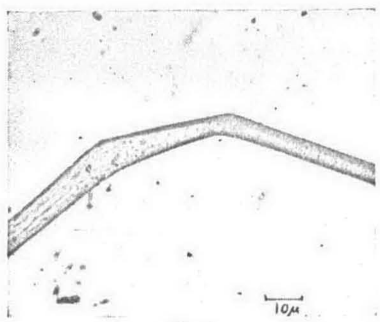

Fig. 1

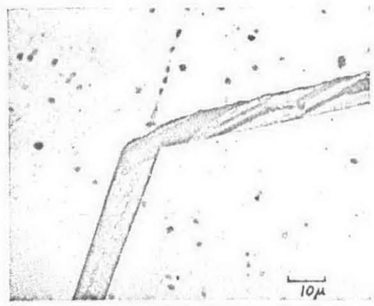

Fig. 2

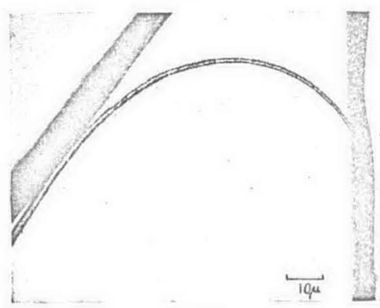

Fig. 3

radius of curvature to induce fracture. Where fracture did not occur the bent whiskers reverted to the initial shape when the constraint was removed. The results of bend tests on whiskers of different cross-section are given in Table 1.

From direct observations of the whiskers during bending and from the results of Table 1 it was concluded that:

(a) The maximum strength and flexibility were associated with whiskers of small cross-section and large length : diameter ratios. These whiskers also possessed smooth and apparently defect-free surfaces.

(b) Whiskers with an hexagonal cross-section had poor strength.

(c) When the bending moment was applied on the shortest side of a whisker section the whisker showed low strength.

(d) The presence of an oil film appeared to improve the strength of the whiskers, possibly by reducing the chance of surface damage.

(e) All whiskers fractured within the elastic limit.

Tensile testing. The tensile strength of whiskers was measured with an 'Instron' tensile testing machine with a load cell giving full-scale deflexion for 400 g. The whiskers were mounted on a reinforced cardboard holder with an accurately punched gauge length of 1 cm. Some of the whiskers tested had a taper of about 2° over the gauge-length; for these the cross-sectional area was taken as the average of the minimum and maximum measured. Although more than 50 specimens were mounted and tested, only 8 of these fractured within the gauge-length; a large percentage of fractures occurred at the base of the mounting resin. The results are given in Table 2.

All fractures occurred without plastic deformation taking place. The fracture surfaces showed that all the fractures were conchoidal. The lower strength of the whiskers of hexagonal cross-section is not completely understood and, although these may contain axial voids, examination of the fracture surfaces did not reveal this phenomenon. Excluding specimen number 2, the mean value of the experimental tensile fracture stress of the first six specimens is $1 \cdot 0 \times 10^6$ lb./in.^{2}, that is, about 2 per cent E. Transmission electron microscope examination of a large number of thin whiskers and platelets has not, so far, provided conclusive evidence of the presence of dislocation.

[1] Sutton, W. H., and Chorne, J., *Met. Eng. Quart. Amer. Soc. Met.*, **3**, 44 (1963).

[2] Cottrell, A. H., *Proc. Roy. Soc.*, A, **282**, 2 (1964).

[3] Kelly, A., *Proc. Roy. Soc.*, A, **282**, 63 (1964).

[4] Evans, P. E., and Davies, T. J., *Nature*, **197**, 597 (1963).

OPENING ELECTRICAL CONTACT: BOILING METAL OR HIGH-DENSITY PLASMA?

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THE processes occurring at the opening of a low-voltage (~4 V) electrical contact have considerable fundamental physical interest as well as having practical importance in the field of electronic and communication engineering. It is well known[1] that, starting with the electrodes closely pressed together in the fully closed position, the opening process leads to a constriction of the current stream lines, which can produce intense local heating and melting of the penultimate microscopic region of contact. The maximum temperature in the contact is related to the potential difference by the ψ, θ theorem:

$$\psi = \left[2 \int_0^{\theta m} \frac{\lambda}{\varkappa} \, d\theta \right]^{1/2} \quad (1)$$

where ψ = a generalized potential equal to the electrical potential in the absence of thermo-electric effects, θ = temperature, λ = thermal conductivity and $\varkappa$ = electrical conductivity. Thus, on gradual separation of the electrodes the constriction resistance increases and the temperature rises up to and past the melting-point of the metal. On continuing the withdrawal the molten volume thus increases and gets drawn out into a microscopic bridge of molten metal joining the solid electrodes; the contacts finally separate and the circuit opens only when the bridge is broken. The rupture process, however, can be very complicated and lead to transfer of metal from one electrode to the other, a process which, when continually repeated, can lead to the 'pip' and 'crater' formation which renders the contacts useless after some time. There is evidence[1,2] to show that the matter transferred per operation ($\sim 10^{-12}$ cm^3 in a 5-amp circuit) is related to the size of the molten metal bridge (width $\sim 10^{-4}$ cm/amp), so that the stability, growth and final rupture of the bridge are a matter of importance, not only from practical considerations, but also from the point of view of the physical properties of metals in the molten state and at high temperatures.

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In the first place, an important condition of equilibrium, at least in the earlier stages, is that which depends on the application of surface tension forces. The shapes of the bridges would then be surfaces of revolution satisfying the equation:

$$\Delta p = T\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \quad (2)$$

and these are unduloids, catenoids or nodoids according as Δp is positive, zero or negative respectively[3]. Photographs of static microscopic bridges have indeed confirmed that these stable shapes can be attained[1]. In the later stages of opening Δp will be negative, and experiment has established that the final stable shape is usually the nodoid. The ψ, θ theorem shows that the hottest region of the microscopic molten metal bridge between like electrodes will probably be the narrow neck and, at first sight, it might appear that this is the region at which the bridge is most likely to break. However, detailed investigation of this final process raises some important problems in the physics of metals at high temperatures, and, in particular, near their boiling points.

Mechanisms of Break

It can be seen at once from the ψ, θ theorem that the mechanism of rupture of the molten metal bridge involves the physical properties of the metal, not at any one temperature, but over a wide range of temperatures up to boiling-point, and a number of different processes of rupture are possible.

In the first place, continued separation of the electrodes and the drawing out of the bridge increases the contact resistance R_c; consequently, the contact voltage V_c ($= R_c I_c$) for a given circuit current I_c continually rises.