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Metallurgical viewpoints on the brittleness of beryllium

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Summary:

At present the development and use of beryllium metal for structural applications is severely hampered by its brittleness. Reasons for this lack of ductility are reviewed in discussing the deformation behaviour of beryllium in relation to other hexagonal metals. The ease of fracturing in beryllium is assumed to be a consequence of a limited number of deformation modes in combination with high deformation resistance. Models for the nucleation of fracture are suggested. The relation of ductility to elastic constants as well as to grain size, texture and alloying additions is discussed.

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Introduction.

Beryllium has many attractive properties for structural applications, as light weight, high tensile strenght, high modulus of elasticity and high melting point. Among its drawbacks brittleness, toxicity, scarcity and cost are usually mentioned. Brittleness in particular seems to have set the limit for the development and use of beryllium as a structural material. This paper will be concerned with some facts and speculations regarding the reasons for this brittleness.

In general it is assumed that brittleness in metals is favoured if there are few possible deformation modes and if the resistance to deformation is high. Hence, deformation modes and deformation resistance of beryllium in relation to the corresponding properties of other hexagonal metals will first be discussed. Then some ideas presented in the literature[17] on the relation between ductility and elastic constants are examined. Finally the effects of grain size, texture and alloying additions on the deformation behaviour are considered.

For ease of reference Fig. 1 shows some planes and directions of the hexagonal close-packed lattice.

1. Crystallography of deformation and fracture.

As far as is known[1, 2, 3] the only slip direction in beryllium is $\langle 11\bar{2}0\rangle$. Slip planes are (0001), $\{1\bar{1}00\}$ and $\{1\bar{1}0X\}$ -basal, prism and pyramid planes respectively. At room temperature the critical shear stress for prismatic slip is about five times as high as for basal slip. With increasing temperature the critical shear stress decreases rather rapidly for prismatic slip but remains about constant for basal slip. Pyramidal slip is postulated to occur at high temperatures only[2].

The twinning plane has been established as $\{10\bar{1}2\}$ and the twinning occurs by shear in the $\langle 10\bar{1}1\rangle$ direction[1]. Russian work[3] has also disclosed the twinning planes $\{10\bar{1}1\}$ and $\{10\bar{1}3\}$ above 400 °C.

Cleavage occurs primarily along the basal plane (0001) and along secondary prism planes $\{1\bar{1}20\}$. Cleavage along twinning planes has also been observed[2].

The deformation modes observed at room temperature for some hexagonal close packed metals are listed in Table I. As compared to the ductile metals magnesium, zirconium and titanium, also with low c/a ratios, the number of deformation modes in beryllium is low. On the other hand cadmium and zinc with high c/a ratios also display few deformation modes. In spite of this they are ductile, probably owing to low deformation resistance as will be discussed below.

There has been some speculation regarding the significance of the c/a ratio for the slip mechanisms of hexagonal metals. Thus, Hauser, Landon and Dorn[4] found that the addition of lithium to magnesium lowered the c/a ratio and increased the tendency to prismatic slip. They therefore suggested that basal slip should predominate at high c/a ratios as for zinc and cadmium and that prismatic slip should become increasingly important at decreasing c/a as found in magnesium, zirconium and beryllium. Moore and Martin[5] pointed out, however, that beryllium does not fit into this series as its critical resolved shear stress is greater on the prism plane than on the basal plane. This is evident from Table I. The pronounced influence of temperature and impurities on critical shear stress obviously obscures correlations of this kind. Consequently nothing definite could be stated about the significance of the value of c/a for beryllium in relation to its deformation characteristics.

Besides in beryllium and in zinc cleavage planes have not been identified with certainly in the hexagonal metals considered. Basal cleavage is observed in zinc and might very well be a consequence of the limited number of deformation modes in this metal.

Table I.

Deformation modes of hexagonal close-packed metals at room temperature.

The slip systems are listed in order of increasing critical shear stress.

	c/a	slip systems			Twinning planes
Cd	1.886	(0001)	$\langle 11\bar{2}0\rangle$	basal	$\{10\bar{1}2\}$
Zn	1.856	(0001)	$\langle 11\bar{2}0\rangle$	basal	$\{10\bar{1}2\}$
		$(11\bar{2}2)$	$\langle 11\bar{2}3\rangle$	pyramidal	
Mg	1.624	(0001)	$\langle 11\bar{2}0\rangle$	basal	
		$\{10\bar{1}1\}$	$\langle 11\bar{2}0\rangle$	pyramidal	$\{10\bar{1}2\}$, $\{10\bar{1}1\}$, $\{30\bar{3}4\}$
		$\{10\bar{1}0\}$	$\langle 11\bar{2}0\rangle$	prism	
Zr	1.593	$\{10\bar{1}0\}$	$\langle 11\bar{2}0\rangle$	prism	$\{10\bar{1}2\}$, $\{11\bar{2}1\}$, $\{11\bar{2}2\}$ $\{11\bar{2}3\}$
Ti	1.587	$\{10\bar{1}0\}$	$\langle 11\bar{2}0\rangle$	prism	
		$\{10\bar{1}1\}$	$\langle 11\bar{2}0\rangle$	pyramidal	$\{10\bar{1}2\}$, $\{11\bar{2}1\}$, $\{11\bar{2}2\}$
		(0001)	$\langle 11\bar{2}0\rangle$	basal	$\{11\bar{2}3\}$, $\{11\bar{2}4\}$
Be	1.568	(0001)	$\langle 11\bar{2}0\rangle$	basal	$\{10\bar{1}2\}$
		$\{10\bar{1}0\}$	$\langle 11\bar{2}0\rangle$	prism	

2. Deformation resistance.

As indicated in the previous section the difference in ductility between beryllium on the one hand and zinc and cadmium on the other must be sought for in a corresponding difference in deformation resistance.

The critical shear stress for basal slip in beryllium (the slip system having the lowest critical shear stress) is about 1. 4 kg/mm^2 [2] as compared to the corresponding values for cadmium and zinc that are considerably below 0. 1 kg/mm^2 [6]. This implies a much higher friction stress for the motion of dislocations on the basal plane in beryllium then on the same plane in cadmium or zinc. The friction stress is due to lattice defects, impurity atoms, precipitates, and the Peierls-Nabarro force of the lattice itself[7]. A high Peierls-Nabarro force would mean inherent high slip resistance. On the other hand, if impurities in solid solution or as precipitates were responsible for the high friction stress it should be possible to decrease the slip resistance by purification of the metal. This situation is possibly born out for beryllium according to Russian work[8] on purification by condensation on heated surfaces. This process was reported to reduce the hardness by 50 %. Simultaneously the metallic impurities were substantially removed. Oxygen contents before and after purification were not given.

It is not unlikely that dissolved oxygen is the main reason for a high friction stress. Evidence in support of this theory has been summarized by Ellis[9]. The strongest argument is given by the fact that all beryllium analyzed to date has been found to contain at least 0. 2 % of oxygen which has not been microscopically identified. (This oxygen content is known to seriously impair the ductility of titanium and zirconium). A high modulus of elasticity and a low Poisson's ratio might also be taken as indications of solid solution hardening[9]. Further evidence of a solute in beryllium has been inferred from anomalous changes taking place at higher temperatures, in hot hardness[10] in lattice parameters[11] and in elongation of polycrystalline metal[9].

3. Nucleation of fracture.

For fracture to occur a crack nucleus must form that is capable to produce a running crack at the applied stress. According to Cottrell[7,12] the crack nucleus might form by dislocations merging together to form a cavity. The energy of the stress field surrounding dislocations that are brought together must not be dispersed by starting secondary flow in preference to the formation of the cavity when instead the energy is expended for rupturing the bonds between atoms and converted to surface energy. High deformation resistance and a limited number of deformation modes probably prevent appreciable secondary flow in beryllium.

The easiest fracture process in beryllium is cleavage along the basal plane (which is also a slip plane). Such cleavage is often associated with $\{11\bar{2}0\}$ bend planes and with intersections of kink bands and twins[2]. Friedel[13] has proposed a dislocation model for crack nucleation in crystals that slip and cleave on the same lattice plane. Slip dislocations are passing a low angle boundary as shown in Fig. 2 and in doing so their Burgers vectors slightly change direction. The vector components necessary to produce the direction change will form a cavity constituting the crack nucleus. This process applies very well to basal cleavage in beryllium and it has been observed in zinc[14].

Cleavage along $\{11\bar{2}0\}$ in beryllium occurs after slight bending around $\langle 1\bar{1}00\rangle$. The crack nucleus can be imagined to form by the coalescence of slip dislocations on prism planes with differently directed Burgers vectors as illustrated in Fig. 3. Such a process has been suggested for $\{100\}$ cleavage in iron by Cottrell[7] and some experimental evidence exists for this[15]. Direct observation of crack nucleation by dislocation reactions has also been made in MgO[16].

4. Relation between elastic moduli and brittleness.

Pugh[17] has developed a theory according to which the plastic properties of polycrystalline pure metals are related to their elastic moduli. Hence he predicts that metals with a low Poisson's ratio should display low values of plastic strain at fracture and vice versa. With a few exceptions this correlation seems to be in accordance with experimental facts. Cherkasov[18] has also demonstrated correlation between Poisson's ratio on the one hand and hardness, tensile strength and reduction of area on the other for many metals.

According to Pugh a very low value of Poisson's ratio would indicate inherent brittleness and this should be the situation for beryllium with its exceptionally low Poisson's ratio of less than 0.1 as compared to 0.25 to 0.50 for most metals. The argument presupposes that Poisson's ratio is not a function of the purity of the metal. This assumption stands in contradiction to Ellis'[9] statement that a low Poisson's ratio could be indicative of a solute impurity.

In general impurities do not seem to affect elastic moduli very much but the situation could be different in the case of interstitially dissolved oxygen in beryllium if the bonding forces in the lattice are changed considerably by oxygen. Cherkasov[18] states that lattice strains introduced by coldwork change Poisson's ratio.

To check the validity of Pugh's theory it would be of interest to know the Poisson's ratio for purified beryllium, e.g. the beryllium produced by vacuum distillation which resulted in a 50 % hardness reduction[8] as referred to above.

5. Effect of grain size on ductility.

Stress concentrations initiating fracture become larger the larger the grain size. This is because the stresses set up in front of a dislocation pile are directly proportional to the number of dislocations in the pile and a larger grain will permit more dislocations to be generated from a given Frank-Read source. By this model it is possible to explain why fracture stress varies inversely proportional to the square root of the grain diameter[19]. This law holds for many metals and has also been found to apply to the hexagonal metals zinc[20] and magnesium[21].

Cast beryllium is extremely coarse grained and brittle and a primary requirement to achieve ductility is to reduce the grain size. So far attempts to do this by alloying[22] or by means of ultrasonic vibration during solidification[23] have not been successful. One reason for the ineffectiveness of alloying is that the hexagonal phase is nucleated at a high temperature (somewhat below 1250 °C). Moore and Martin[11] have recently established the existence of a body centered cubic modification that is stable between 1250 °C and the melting point 1283 °C. If an alloying element that lowers the transformation point could be found, it would probably also produce grain refinement.

Fine grained beryllium is obtained by means of powder metallurgy. It is impossible to avoid an oxide coating of the powder particles used as starting material and hence the metal produced will contain intergranular films or particles of beryllium oxide. This oxide acts as a barrier against grain growth and does not seem to cause embrittlement since fracture is observed to be predominantly transcrystalline.

6. Effect of texture on ductility.

The anisotropy of the single crystal is the reason for strong texture dependence of the mechanical properties of polycrystalline beryllium. The development of a fiber texture with $\langle 10\bar{1}0 \rangle$ parallell to the working direction is rather well understood[2]. This texture permits duplex prismatic slip and there seems to exist a good correlation between degree of texture and elongation[24, 25]. In hot pressed textureless powder the elongation amounts to 2 to 3 % only, since many grains will deform by basal slip leading to kink bands and consequent basal cleavage. Extruded rod exhibits an elongation of 15 to 20 % in the longitudinal direction. In this case the slip is mainly of the duplex prismatic type and the elongation is probably limited by the required contraction which cannot take place in directions perpendicular to the basal planes of the crystals. In transverse directions of extruded rod the same conditions as in textureless metal prevail and consequently the elongation is of the order of 2 to 3 %. In cross rolled sheet the basal planes become aligned parallell to the plane of the sheet and the elongation amounts to 40 % in directions in this plane. This condition is usually referred to as two-dimensional ductility.

It would be desirable to obtain ductility in three dimensions since a material for structural applications should be able to stand triaxial stresses. The lack of three-dimensional ductility in beryllium is illustrated by the fact that a specimen with fiber texture will not show localized contraction in uniaxial tension parallell to the fiber axis. Biaxial tension tests involving some bending on sheet produced in various ways as recently reported by Muvdi[26)], show, however, that beryllium could stand complicated deformation to a limited extent, provided that the proper fabrication process is selected.

7. Effect of alloying on ductility.

The effect of small alloying additions on the ductility of preferentially oriented sheet has been studied by Yans, Donaldson and Kaufmann[27)] who claim that the critical shear stress for prismatic slip is increased by alloying and the more the lower the atomic number of the solute. Thus copper has no effect on elongation whereas iron reduces it drastically. In both cases the tensile strength is increased. By extrapolation of these results the authors suggested that alloying with zinc might improve the tensile strength still more without reducing the ductility of beryllium. The present lack of good solubility data for most elements in beryllium is embarassing for a fruitful study of the effect of alloying additions. Reliable solubility data for iron and nickel by studing diffusion couples with an X-ray absorbtion technique have recently been reported[28)], however.

8. Conclusions.

The present views on the brittleness of beryllium may be summarized as follows:

1. Fracture in beryllium is facilitated by comparatively high deformation resistance in combination with limited number of defor-

mation modes. If the deformation resistance could be decreased the tendency to fracture would probably also decrease.

2. The deformation resistance may be inherent or caused by impurities. Comparison with deformation modes in other hexagonal metals in relation to c/a ratio gives no information on this point. It is not unlikely that dissolved oxygen causes the high deformation resistance.
3. It remains to be proved whether the low Poisson's ratio of beryllium is indicative of inherent brittleness.
4. Fine grained metal with suitable texture exhibits ductility in certain directions but will not be able to withstand complicated stress systems. Hence, to a limited extent the production method may be adjusted to meet the strength requirements of constructional parts.
5. Alloying seems to improve tensile strength in general whereas ductility remains unchanged or is reduced. Further development along this line is likely.

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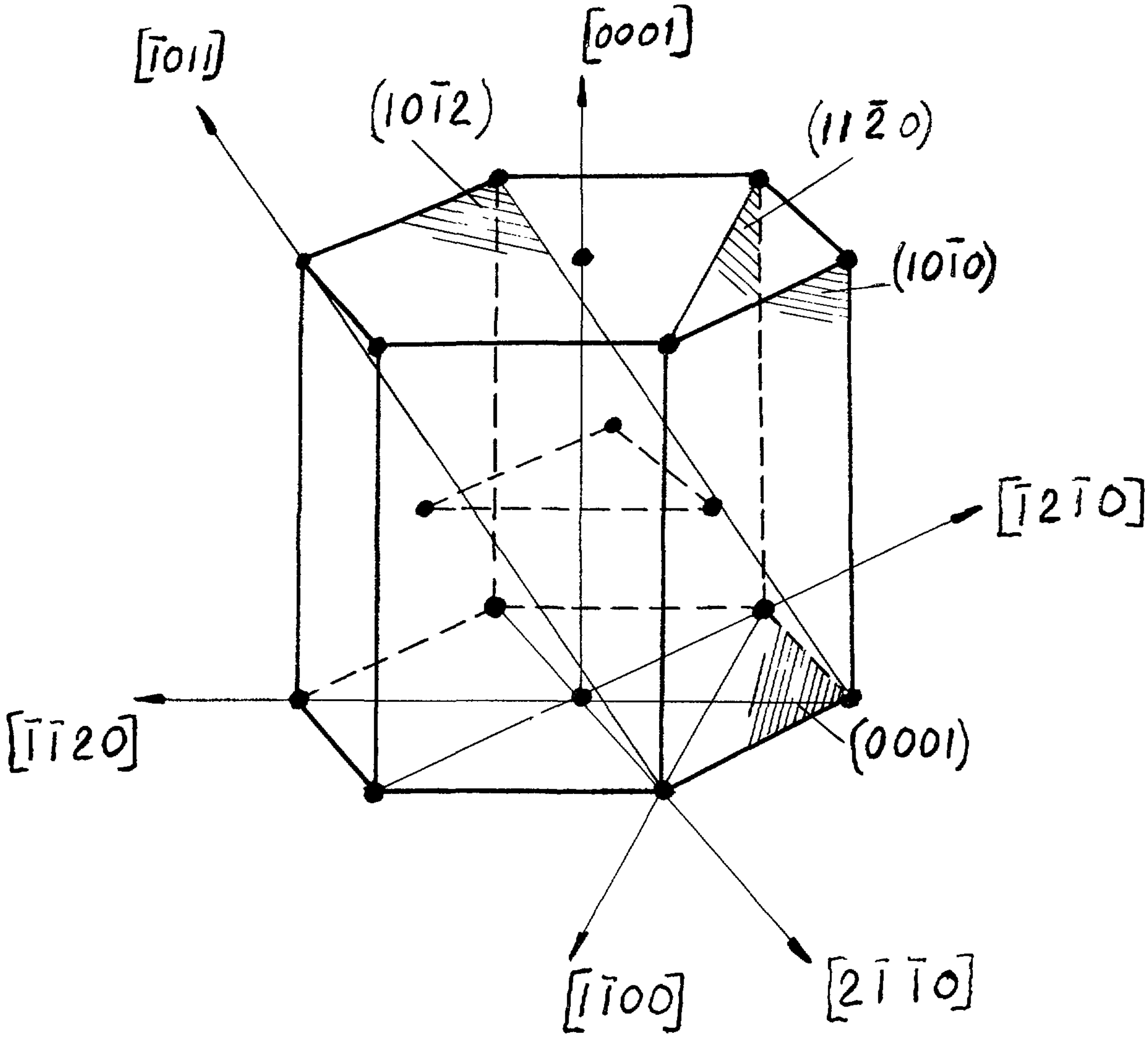

Fig. 1. Crystallographic planes and directions in hexagonal close-packed metals.

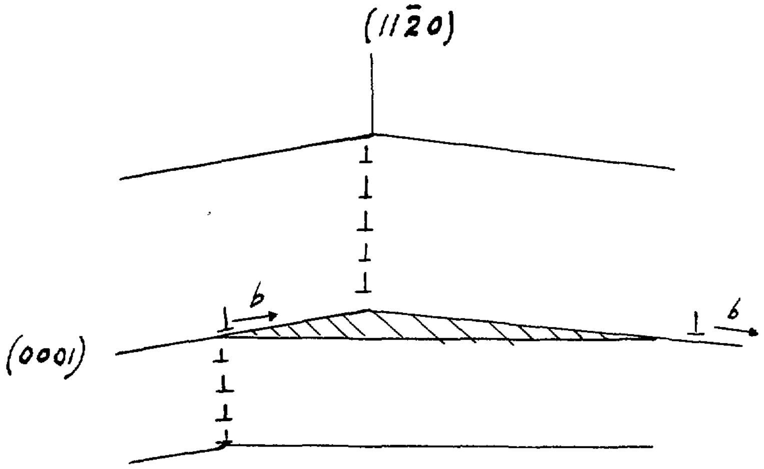

Fig. 2. Model for crack nucleation along (0001).

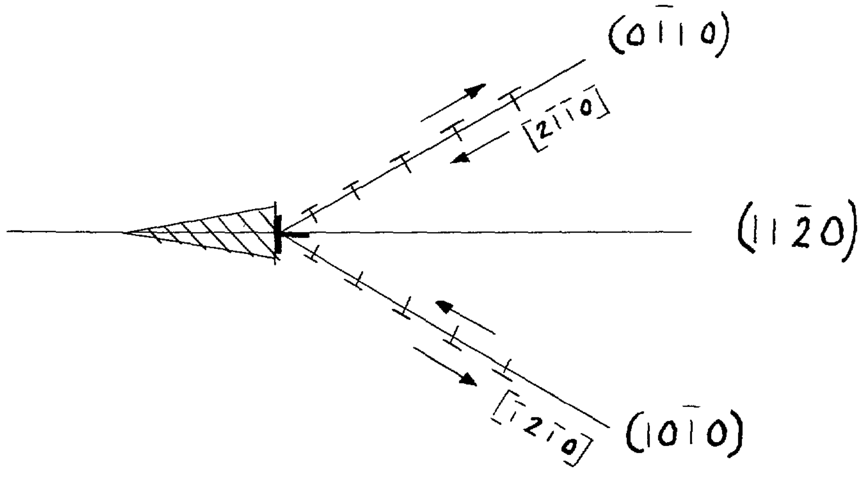

Fig. 3. Model for crack nucleation along $\{11\bar{2}0\}$.

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