JOURNAL OF MATERIALS SCIENCE 9 (1974) 569–575

Grinding induced machining damage in beryllium

W. TAYLOR
Kawecki Billiton (UK) Ltd, Slough, Bucks, UK

J. S. WHITE
Atomic Weapons Research Establishment, Aldermaston, Berks, UK

An investigation has been made of the machining damage induced in beryllium by surface grinding. A series of damage free specimens was prepared from a bar extruded from a block of hot-pressed beryllium powder. Each specimen was then ground on one large surface using a different set of grinding conditions, as dictated by the requirements of a quarter-replicate factorial experiment which involved eight grinding parameters each taken at two levels. The damage induced by the surface grinding was evaluated by testing each specimen in a four point bending mode. The tests were conducted so that the maximum tensile strain due to bending occurred at the experimentally ground surfaces. A statistical analysis of the results enabled the grinding conditions giving rise to the least and the greatest amount of machining damage to be predicted. In a second series of experiments, these predictions were found to correlate with the metallographically observable damage and the mechanical test data obtained from a further series of bend test specimens.

1. Introduction

The susceptibility of beryllium to machining damage has been known for some time. This manifests itself by its deleterious effect upon the mechanical properties of the metal. For example, a damaged tensile test piece shows a marked reduction in both its ultimate tensile strength and percentage elongation to fracture, as compared with an undamaged specimen. The exact nature of the damage in beryllium has not been established. However, machining is known to be responsible for several effects which may play a part in the nucleation and/or propagation of brittle cracks, thus leading to the premature failure of test specimens. The known effects are deformation twinning [1-3], microcrack formation [1, 2] and internal stress [1, 3].

Jacobson *et al* [2] studied the damage produced by surface grinding. They concluded that the presence of deformation twinning was more detrimental to the mechanical properties of beryllium, than the surface microcracking induced by the grinding. This conclusion was based upon their observation of fracture nucleation occurring at twin intersections and twin/matrix interfaces. In addition, Bonfield *et al* [3] concluded that on straining machined beryllium, plastic deformation was initiated by the high stress fields around the twin tips in the surface layers. Presumably this could lead to basal dislocation pile-ups and the subsequent nucleation of basal cleavage cracks.

The magnitudes of the compressive stresses generated by surface grinding operations have been measured and values of 11.9 and 15.4 kg mm^{-2} have been reported [1, 3]. Presumably, such compressive stresses could account for the observations of Jacobson *et al* [2] since they would obviously impede the propagation of surface microcracks. However, the balancing tensile stresses within the body of the machined material would be expected to assist the propagation of cracks, once nucleation had occurred in the highly stressed regions associated with the subsurface deformation twinning.

A number of investigations have been made of the effects of post-machining treatments on the mechanical properties of various grades of beryllium [1, 2, 4]. In general, the suggested method of alleviating machining damage is to anneal machined parts at a temperature sufficient to recrystallize the deformation twinning and/or etch away the surface to a depth of 0.12 to 0.25 mm [2, 4]. Intuitively, neither machining damage or post-machining treatments would be expected to affect the proof stress of beryllium since they mainly influence surface behaviour. Nevertheless, Hill [4] showed that the 0.2% proof stresses of tensile test pieces made from hot-pressed powder sheet, were lower after 0.2 mm had been etched from their damaged surfaces as compared with the values given by similar specimens in the as-machined condition.

In order to try and minimize or eliminate the machining damage in beryllium caused by drilling or lathe turning, work has been done in an effort to try and establish the optimum machining parameters for these two operations [5]. The extent of the machining damage was assessed qualitatively from a metallographic examination of the depth and intensity of the deformation twinning produced by the machining operations. It was found that the amount of surface deformation twinning could be considerably reduced by optimizing the machining parameters. However, no attempt was made to show that the use of the optimum machining conditions in the production of test pieces, had a beneficial effect upon their mechanical properties.

2. Experimental materials and methods

2.1. Materials and specimen preparation

The majority of the work was done using four point bend test specimens taken from a bar extruded from a hot-pressed block of −250 mesh beryllium powder. The experimental material was not analysed but the manufacturer's analytical specification for the powder is given in Table I. The extrusion was carried out at 1050° C with the block sheathed in a mild steel can. After fabrication, the material had a mean grain size of 20 μm.

The extruded bar was acid desheathed using concentrated nitric acid and the specimen blanks, 3.8 cm × 0.75 cm × 0.32 cm, were machined transversely from it with their large faces perpendicular to the extrusion axis. At this stage all the machining damage introduced into the material during the preparation of the blanks was removed by etching away 0.37 mm of each surface, using a 10% sulphuric acid solution. Subsequently, 0.25 mm was ground off one of the large surfaces of each blank, parallel to the major axis, using one of the experimental sets of grinding conditions.

TABLE I Analytical data for the experimental materials

	Total Be (wt %)	O	Al	C	Fe	Si
Ingot material	99.8	1000	350	200	300	150
Powder material*	98 min	12800 max	1600 max	1500 max	1800 max	850 max

ppm by weight.
*Manufacturer's specification.

In order to facilitate metallographic studies of the machining damage, a limited number of experiments was carried out using specimens cut from sheet which had been prepared by rolling a cast ingot. The rolling was carried out at 700° C, with the ingot sheathed in a mild steel can. In the as-rolled condition, the ingot sheet had a mean grain size of 80 μm and a partially recrystallized grain structure. The analysis of this material is given in Table I.

2.2. Methods

2.2.1. Four point bend testing

The machining damage induced into the specimens by the surface grinding, was evaluated by testing the specimens in a four point bend test. The bend test jig was located in a compression cage mounted on a hard testing machine. The applied load and the chord height during the bending was continuously measured on an X-Y recorder. For all tests the rate of crosshead movement was maintained at 0.5 mm min^{-1}. Each specimen was set up in the bending jig so that the maximum tensile strain on bending occurred in the experimentally ground surface.

The four point bend test arrangement is shown diagrammatically in Fig. 1, together with the corresponding shearing force and bending moment diagrams. As can be seen, for purely elastic bending, the shearing force on that part of the specimen between the inner anvils is zero while the bending moment, M, is constant where

$$M = nLP/2\,, \qquad (1)$$

L = the separation between the outer anvils, P = the load applied to the test specimen and n = a constant such that the separation between an inner and an adjacent outer anvil = nL. In

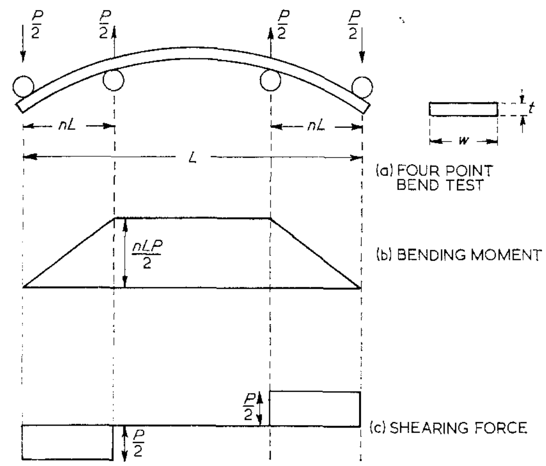

Figure 1 The schematic arrangement of the four point bend test.

simple bending, the maximum elastic stress in the outer fibres of a specimen equals

$$\sigma = Mt/2I \quad (2)$$

where t = specimen thickness and I = the moment of inertia of the specimen about its neutral axis. In the case of the rectangular section specimen under consideration,

$$I = wt^3/12 \quad (3)$$

where w = the specimen width. Substituting the values for M and I from Equations 1 and 3 respectively, into Equation 2 gives

$$\sigma = 3nLP/wt^2 = P \times \text{const.} \quad (4)$$

This means that in four point bending, the specimen length between the inner anvils, is subject to a constant stress at all points a constant distance from the neutral axis.

When P is the load at fracture, σ is termed the modulus of rupture. In the present work this parameter was used to compare the bend test specimens and hence the damage induced by the surface grinding. Although the above considerations apply only to elastic bending, the modulus of rupture can, in the present work, be regarded as a pseudo-elastic parameter. This arises due to the fact that beryllium is a brittle anisotropic material. The extrusion of the hot-pressed powder block produced a highly textured bar. The specimens were taken in relation to the axis of the bar so that they had only a very limited capacity for plastic deformation in bending. Failure occurred, therefore, shortly after the elastic limit had been exceeded, at the point between the inner anvils where the machining damage had the most deleterious effect on the properties of the beryllium.

In contrast, in three point bending tests which have been used by other workers to assess machining damage [2], the bending moment varies from zero at the end supports, to a maximum at the centre loading point. This means that the tensile stress at the outer surface of a test piece is always a maximum at its centre. In three point bending, therefore, the specimens generally fail at the centre irrespective of the machining damage in the material at that point. For this reason, such a testing technique was not considered suitable for the present investigation.

2.2.2. Metallography

Metallographic specimens were prepared using conventional hand grinding and diamond polishing techniques. The final polishing was done on a selvyt cloth impregnated with an aqueous suspension of gamma alumina. During the course of the final polishing operation, the specimens were periodically etched in a 2% hydrofluoric acid solution. Finally the specimens were examined and photographed under polarized light.

3. The design of the factorial experiment

The grinding parameters studied in the investigation are listed in Table II. The eight variables examined, were each taken at two levels. giving a total of 2^8 possible sets of grinding conditions. Thus one complete replication would have required 256 specimens and this number would have been impracticable within the limitations imposed by the availability of the experimental material and the time scale of the investigation. As a result, a $\frac{1}{4}$ replicate factorial experiment was performed. Since this only involved sixty-four sets of grinding conditions, it was possible to obtain all the specimens needed for the work from a single bar. In order to minimize the effect of any material variations along the length of the bar, the sixty-four experiments were arranged in a randomized block design. The bar was cut up to give eight blocks and each block was then subdivided to give eight test specimens. Within each group of eight specimens, each parameter was represented four times at its higher level and four

TABLE II The surface grinding parameters examined in the factorial experiment

Parameter	Level	
	Low	High
Abrasive	Alumina (B)	Silicon carbide (W)
Grit size	−46 mesh (B)	−180 mesh (W)
Crossfeed (motion perpendicular to the grinding wheel)	0.175 mm per pass (B)	1.5 mm per pass (W)
Coolant	No coolant (W)	Oil-water emulsion (B)
Bond strength	Soft bond (B)	Hard bond (W)
Wheel speed	15.25 m sec^{-1} (B)	30.5 m sec^{-1} (W)
Traverse speed (motion parallel to the grinding wheel)	9.7 mm sec^{-1} (B)	30.5 mm sec^{-1} (W)
Depth of cut	0.0125 mm (W)	0.050 mm (B)

(B) indicates the parameter level for the best grinding conditions.
(W) indicates the parameter level for the worst grinding conditions.

at its lower level. The experimental layout was of a conventional pattern for a $\frac{1}{4}$ replication of a 2^8 system and, in fact, was that quoted by Kempthorne [6].

One variable omitted from consideration in the experiment, was the structure of the grinding wheel. That is, the proportion and arrangement of the abrasive and bond in the wheel. This was done primarily in order to reduce the number of separate grinding experiments required. It was considered acceptable to omit this variable since all previous experience in surface grinding beryllium, qualitatively suggested that what manufacturers term a medium spaced structure, gave optimum results for the rate of stock removal in relation to the surface finish achieved. As a consequence, all the grinding wheels used in the factorial experiment had this type of structure. Similarly, the type of bond used in the wheels was not treated as a variable. The majority of wheels used for surface grinding metals have a vitreous bond and this type of bond was standardized in the present investigation.

4. Experimental results

4.1. Four point bend testing

The analysis of variance of the rupture moduli values was carried out using standard statistical techniques. This showed that two first order interactions displayed a degree of significance but then only at the very low level of 20%. These interactions were: crossfeed-traverse rate and wheel speed-depth of cut. In addition, three primary effects were found to have some significance, these being abrasive, crossfeed and bond strength. Again the significance was found to be at the 20% level. Since the crossfeed was found to be involved in a first order interaction, a separate analysis was carried out to establish the significance of this variable at a constant traverse rate. It was found that on holding the traverse rate at its lower level the crossfeed assumed a 5% significance. In view of their first order interactions, wheel speed and depth of cut were also re-examined but were found to be without significance.

From these data, two sets of machining conditions were defined, one of which was designed to provide the best mechanical properties and the other the worst, as determined by the four point bend test. The levels of the parameters for each set of machining conditions are given in Table II. In constructing this table, the indications given by the factorial survey were accepted even when they were without statistical significance.

4.2. Post-factorial surface grinding experiments

4.2.1. Metallographic examination

Bend test specimens were ground using the best and worst sets of grinding conditions detailed in Table II. The ground surfaces were examined using optical microscopy and the results are shown in Fig. 2. These photographs show that the worst grinding conditions have produced surface cracking which is absent in the specimen ground using the best conditions. As can be seen, the cracks are regularly spaced and are normal to the grinding direction. A metallographic examination of the structure of these

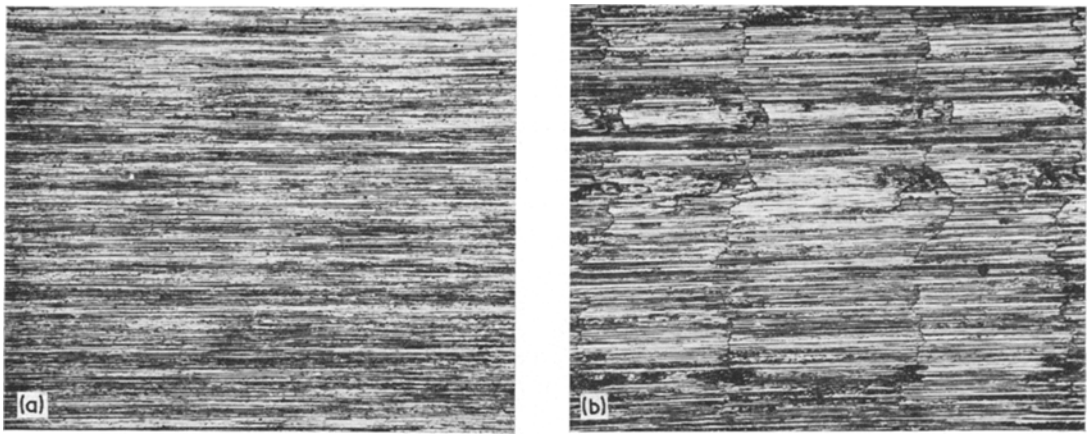

Figure 2 The surfaces of four point bend test specimens ground using the best and worst conditions (×60). (a) best, (b) worst.

specimens showed that the worst conditions produced extensive deformation twinning which was largely absent in the specimen ground using the best conditions.

In order to facilitate an investigation of the deformation twinning, a sample of relatively large grained rolled ingot sheet was ground on one surface using the worst and on the opposite face, the best conditions. The metallographic structures shown by this sample are given in Fig. 3. It is apparent that the worst conditions have produced a large amount of deformation twinning, together with some subsurface cracking. On the other hand, the best conditions have produced twinning in only a few isolated grains which were presumably favourably oriented for this deformation mode.

4.2.2. Four point bend test specimen grinding

Ten bend test specimens were prepared from similar damage free blanks to those used in the factorial experiment. Each blank was then ground on one large surface, parallel to its major axis. Five specimens were ground using the best and five the worst conditions, as defined by Table II. In every case, the specimen thickness was reduced by 0.25 mm by the surface grinding.

The specimens were then tested in a four

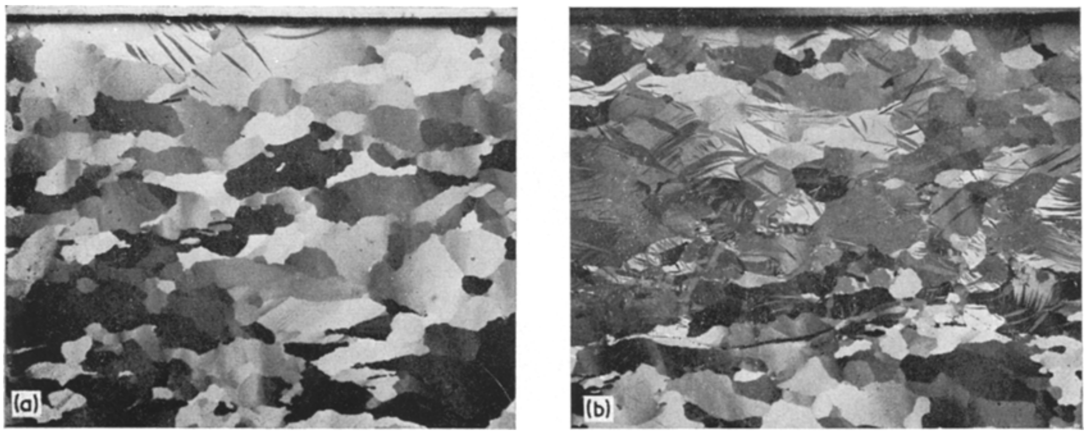

Figure 3 The machining damage produced in rolled ingot beryllium samples ground using the best and worst conditions (×60). (a) best, (b) worst.

TABLE III The post-factorial four point bend test data

Machining condition	Rupture modulus (x) (kg mm^{-2})	Mean rupture modulus ($\bar{x}$)	$(x - \bar{x})$	$(x - \bar{x})^2$	Sample variance $\frac{\Sigma(x - \bar{x})^2}{5}$
	67.9		−4.8	23.04	
	77.7		5.0	25.00	
Best	74.2	72.7	1.5	2.25	10.86
	70.7		−2.0	4.00	
	72.8		0.1	0.01	
	65.8		−0.7	0.49	
	72.8		6.3	39.69	
Worst	61.6	66.5	−4.9	24.01	12.94
	66.5		0.0	0.00	
	65.8		−0.7	0.49	

point bending mode and the results obtained are given in Table III. The significance level of the difference between the mean rupture modulus values for the specimens ground according to the best and worst conditions has been calculated. This was done by determining the Student's "t" values for the two mean modulus values using the appropriate small sample statistics incorporating Bessel's correction [7]. A "t" value of 2.53 was obtained and from statistical tables it was found that his value corresponds to a significance level of between 2 and 2.5%. Usually a significance level of 5% is taken to represent the demarcation level between the "probably significant" and "probably not significant" situations. Thus, the present data can be interpreted on the basis that the mean rupture modulus values for the best and worst grinding conditions are probably significantly different. That is the best and worst grinding conditions do produce a real difference in the mechanical properties as determined in four point bending.

5. Discussion

The factorial experiment shows that when surface grinding beryllium, the choice of machining parameters markedly affects the amount of damage induced into the material, as assessed by four point bend testing. However, of all the parameters involved in the factorial experiment, only the crossfeed could be shown to have a statistically significant effect. The reason for this is not apparent and intuitively the damage might be expected to correlate with a factor such as the rate of metal removal which would involve parameters other than the crossfeed.

The post-factorial experiments indicate that the rupture modulus of four point bend test specimens, can be increased by about 10% on going from the worst to the best grinding conditions. In addition, it has been shown for the first time that the damage, as assessed by the bending tests, is qualitatively related to the metallographically observable features of the microstructure such as the intensity of the deformation twinning and the incidence of microcracking. However, as shown by Fig. 3, grinding induced deformation twinning, unlike microcracking, was only reduced in its intensity and not completely eliminated by the use of the best grinding conditions. Therefore the present investigation does not support the findings of Jacobson *et al* [2], who claimed that deformation twinning was more detrimental to themechanical properties of beryllium than surface microcracking. However, the present findings appear more logical since a pre-existing crack should be a more effective nucleus for catastrophic brittle fracture than deformation twins even if there is a mechanism by which they can cause the nucleation of cracks.

Acknowledgements

The authors are indebted to the United States Air Force Materials and Propulsion Laboratories and the Ministry of Defence for financial support for this work. They would also like to thank Mr J. H. Dingle for carrying out the metallographic work and Mr W. M. Long for many helpful discussions on the design of the factorial experiment.

References

1. W. V. WARD, M. I. JACOBSON and C. O. MATTHEWS, *Trans. ASM* **54** (1961) 84.
2. M. I. JACOBSON, F. M. ALMETER and E. C. BURKE, *ibid* **55** (1962) 492.
3. W. BONFIELD, J. A. SARTELL and C. H. LI, *Trans. Met. Soc. AIME* **227** (1963) 669.
4. N. A. HILL, "The Metallurgy of Beryllium" (Chapman and Hall, London, 1963) p. 84.
5. F. MORROW, J. S. WHITE and A. H. WILLIAMS, Conférence Internationale sur la Métallurgie du Béryllium (Presses Universitaires de France, Paris, 1966) p. 615.
6. O. KEMPTHORNE, "Design and Analysis of Factorial Experiments" (Wiley, New York, 1952) p. 404.
7. M. J. MORONEY, "Facts from Figures" (Penguin, Harmondsworth, 1951) p. 227.

Received 21 August and accepted 9 October 1973.