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May 18, 1979

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**AN ABBREVIATED MACHINING SCHEDULE FOR
FABRICATING BERYLLIUM PARTS FREE OF SURFACE DAMAGE**

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U. S. DEPARTMENT OF ENERGY
CONTRACT DE-AC04-76DPO3533

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Printed in the United States of America
Available from the
National Technical Information Service
U. S. Department of Commerce
Springfield, Virginia 22161
Price: Printed Copy \$4.50 Microfiche \$3.00
Price Is Subject to Change Without Notice

Printed
May 18, 1979

RFP-2838
UC-25 MATERIALS
TID-4500-R66

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Albuquerque Operations Office
U.S. Department of Energy**

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RFP-2838

ACKNOWLEDGMENTS

The authors wish to thank J. E. Hanafée and W. K. Haslam of the University of California — Lawrence Livermore Laboratory for their encouragement, support, and guidance of this work. Other important contributors to this effort were Lynda Danio, A. G. Grimes, W. H. Schmalhorst, H. L. Stadtman, F. E. Adcock, K. R. Souply, and B. T. Cross — of the Rockwell International Rocky Flats Plant.

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AN ABBREVIATED MACHINING SCHEDULE FOR FABRICATING BERYLLIUM PARTS FREE OF SURFACE DAMAGE

S. Beitscher, J. F. Capes, W. W. Leslie, J. R. Luckow, and R. L. Riegel

Abstract. This study was performed to develop a more economical method of machining damage-free beryllium components at Rocky Flats. The present method involves a 9-pass schedule of lathe turning followed by a chemical etch. Prototype beryllium hemispherical shell parts and cylindrical tensile specimens machined to simulate the parts were utilized in this study. The main investigative methods used to evaluate the amount of machining damage were metallography and tensile tests.

It was found that damage-free parts could be produced by carefully controlled machining if the number of machining passes was reduced to 4 or even 3, if followed by the standard etching treatment. These findings were made on "Select S-65" grade beryllium, and probably apply to other common grades of powder source beryllium but not necessarily to ingot-source beryllium. It is recommended that the 4-pass schedule becomes the standard method to produce damage-free beryllium derived from powder. Significant savings in time, labor, and equipment can be realized by this change in method without decreasing the quality of the product.

INTRODUCTION

Certain beryllium components in nuclear weapons are subject to high stresses in their service application. When beryllium is machined by conventional methods (such as lathe cutting, milling or grinding), a layer of metallurgically altered metal forms on the surface. The layer is called the surface damage or machining damage layer. The layer always contains a dense network of intersecting twins, and sometimes contains cracks, altered crystallographic texture, cold work, and other potentially damaging structural features. The layer is only 0.001 to 0.020 in. (0.025 to 0.50 mm) deep, but can cause very detrimental effects to the mechanical properties of the components. Ductility can decrease by a factor

of 10, and ultimate tensile strength can decrease by 30 percent. Other mechanical properties, such as fatigue strength and impact resistance, can also be detrimentally affected by the machining damage layer. It is generally believed that the main damaging effect arises from the dense network of twins in the layer. It appears that cracks can readily initiate and propagate from these twins when the part is stressed in tension.

Prevention of the detrimental effects of surface damage in beryllium is important. Even in the damage-free condition, beryllium displays properties that are adequate only for some applications. For example, typical powder-source beryllium exhibits uniaxial tensile ductility when tested in the damage-free condition of only 3 to 5 percent. Any significant decrease in this ductility because of surface damage can cause the structure to crack when exposed to service stress. Therefore, structural components of beryllium are often fabricated to reduce or eliminate the surface damage they contain. Careful control of the machining practice is required to limit the depth and severity of the damage. This control includes all of the machining parameters such as tool composition, geometry, and wear; feed rate, surface speed, depth of cut, and sequence of cuts. For example, the recommended practice¹ for machining tensile specimens that are damage-free (an industry-wide practice for the preparation of structural components of beryllium does not yet exist) involves lathe turning with seven gradually decreasing depths of cuts ranging from 0.030 to 0.001 in. (0.76 mm to 0.025 mm). After the specimen is machined, it is etched in an acid solution to completely remove 0.002 to 0.004 in. (0.05 to 0.10 mm) from each surface. The purpose of the gradually decreasing depths of cuts is to minimize to a practical level the depth of damage after machining so that the etching treatment can completely remove it. The theory behind this is that each subsequent lighter cut totally

removes all previous damage and introduces another layer of thinner damage on the surface.

Having no other evidence, a designer of a critical beryllium component would be tempted to specify the machining and etching practice recommended for tensile specimens. In fact, a machining procedure very similar to that has evolved as the standard method of machining beryllium at Rocky Flats when surface damage control is desired. If the component is large, much time is required to make the seven or more cuts. Considerable savings in time, manpower, and equipment could be realized if the number of cuts was reduced to two, three, or four.

This study was performed to develop a method of machining damage-free beryllium parts that is more economical than the "standard" (STD) method used at Rocky Flats. The STD method involved a 9-pass lathe-turning operation with progressively lighter cuts down to the final 0.001-in. (0.025 mm) cut. After machining, the parts are chemically etched to remove 0.004 in. (0.10 mm) off each surface. In this study, beryllium specimens were machined by a severely abbreviated (S/A) machining schedule (3-pass) designed to be about as severe a method as would ever be considered. In addition, a moderately abbreviated (M/A) schedule (4-pass) and the standard (STD) schedule (9-pass) were evaluated. Two types of specimens were studied; prototype hemispherical shells and tensile specimens. The primary methods used to evaluate the machining schedules were metallography and tensile tests. Every effort was made to machine the shells like a production part would be machined, and to machine the tensile specimens like the shells were machined. All tests were performed on specimens cut from the same log of beryllium.

EXPERIMENTAL METHOD

Material

The beryllium used in this study was a powder-source material termed "Select S-65." Select S-65 (or Lawrence Livermore Laboratory Specification MEL 76-001319A) is a variation of S-65; a comparison of some of the more important specification requirements for these two materials is given in

Table 1. The major differences between these two materials is the attritioning process, BeO content, Fe/Al ratio, and mechanical properties (particularly the yield strength).^{2,3} Select S-65 was used in this study because it represents a modern higher-strength grade of powder-source beryllium that is useful in a number of future applications.

Machining

It was recognized early in the planning of this program that great care would have to be taken if the results of the tensile tests were to be applicable to the machining of actual components. In the machining process, surface damage severity and depth is greatly influenced by cutting tool wear and tool breakdown.⁴ One of the most important factors in tool wear or breakdown is tool travel.⁴ There is a considerable difference in the tool travel-per-pass between the machining of a small tensile specimen, with a surface area of less than 1 in.² (6.5 cm²), and of a typical part with a surface area of perhaps 50 in.² (320 cm²) or greater. For this reason, the experimental plan involved the machining of tensile specimens with the same tools that were used to machine the parts that served as prototype components. The tools used for the tensile specimens were worn to the same extent that they were at the end of the final pass of the part machining. Therefore, the surface damage induced in the tensile specimens by the tool simulated, as far as the tool wear affects the machining damage, the surface damage at the end of the pass on the part.

A list of the machining parameters used on parts - approximately 6-in. (150 mm)-diameter hemishells of 0.5-in. (12 mm) wall thickness - and on specimens (Figure 1) is given in Table 2. Except for depth of cuts and number of passes (which were the primary variables in the investigation), the machining parameters used for the parts were the standard practice in machining beryllium at Rocky Flats. The machining of the tensile specimens was kept as similar as was possible to the machining of the parts. The tools used for each pass on the part were saved and used for the corresponding pass on the tensile specimen. A freshly ground tool was used for each finishing pass of the part. Surface

TABLE 1. Specification and Description of Select S-65 and S-65 Beryllium^{2,3}

	SELECT S-65	S-65
Chemical Composition (%)		
Be (min)	98.5	98.5
BeO (max)	1.2	1.0
Al (max)	0.06	0.06
C (max)	0.1	0.12
Fe (max)	0.1	0.12
Mg (max)	0.08	0.08
Si (max)	0.06	0.06
S (max)	0.04	—
U (max)	0.04	—
Other (each, max)	0.04	0.04
Fe/Al Ratio	controlled to approximately 2:1	not specified
Manufacture		
Powder attritioning	impact	not specified
Pressing	hot pressing or hot isostatic pressing	hot pressing
Mechanical Properties (Room Temperature)		
Ultimate tensile strength, ksi (min)	50	42
Yield tensile strength, ksi (min-max)	35-50	30
Elongation, %, (min)	3	3
Average grain size (μm)	≤15	≤15
Density, % of theoretical (min)	99	99

FIGURE 1. Tensile Specimen for Evaluating Machining Damage in Beryllium

TABLE 2. Machining Parameters

1. Tool:
T-304, grade 999 carbide (10° primary; 18° secondary, 0.030-inch radius, 0° top rake).
2. Coolant:
Mist spray trichloroethane.
3. Surface Speed:
Parts; 356-surface-feet per minute from waist of part to diameter where machine reached maximum speed of 1100 rpm (1.4 inches), then decreasing surface speed at constant (1100) rpm to zero at pole, corresponding to 72 feet per minute at 1/2-inch radius.
Tensile Specimens; at finish dimensions (0.132-inch diameter) - 52-surface-feet per minute (1500 rpm, maximum speed).
4. Feed:
Parts; 0.002-0.003-inch per revolution to 1.4-inch diameter, then 3.3-inch per minute to pole.
Tensile Specimens; 3.3-inch per minute across gage length.
5. Depth of Cut:
Standard (STD) Method; 0.050-inch maximum roughing cut, 0.050, 0.020, 0.010, 0.010, 0.005, 0.002, 0.002, 0.001, 0.001-inch finishing cuts.
"Moderately Abbreviated" (M/A) Method; 0.050-inch maximum roughing cut, 0.050, 0.020, 0.010, 0.005-inch.
"Severely Abbreviated" (S/A) Method; 0.050-inch maximum roughing cut, 0.050, 0.030, 0.005-inch.
6. Machine:
Parts; roughing - conventional tracer lathe, finishing - air bearing, tape controlled EXCELLO lathe.
Tensile Specimens; roughing/+ finishing - air bearing computer controlled Heald lathe.

speed and feed rate necessarily varied between parts and specimens because of the large differences in the diameters of these pieces and the limited rotational speed (1500 rpm) of the lathe used to machine the tensile specimens.

As Table 2 shows, three machining-pass schedules were investigated: (1) the standard 9-pass schedule (STD), (2) a moderately abbreviated 4-pass schedule (M/A), and (3) a severely abbreviated 3-pass schedule (S/A). The S/A cutting depth schedule represents a limit in the machining of tensile specimens. Deep cuts cause large tool forces that can break a beryllium tensile specimen, particularly when these passes are performed when the specimen is at a small diameter. The next-to-last pass of 0.030-in. (0.76 mm) depth of the S/A schedule represents the deepest cut that can be made at that diameter without risking fracture of the specimen. Deeper cuts can probably be made on parts without fracture, but even on parts the S/A schedule is about as severe a machining schedule that would ever be considered for a part requiring the control of surface damage.

Testing

Four hemishells were fabricated; two were machined by the STD machining schedule, one by the M/A schedule, and one by the S/A schedule. Figure 2 shows the sequence of treatments and tests performed on each of the parts. One of the STD parts was etched as in the current practice, and the other STD part was heat treated after machining to determine how much distortion results from this alternative method of removing surface damage. The M/A and S/A parts were both heat treated after machining to provide data on the effects of machining schedule on distortion.

After being machined, the parts were dimensionally inspected and ultrasonically tested for surface flaws. As Figure 2 shows, two of the parts were then metallographically sampled near the pole (where each machining pass ends, and where the amount of surface damage should be the greatest). The parts were then either chemically etched or heat treated by the procedures listed in Table 3.

The parts were then again dimensionally inspected and ultrasonically tested. As the final operation, metallographic sections were taken from the pole, 45°, and near the equator of each shell.

The cutting tools used to machine the parts were used for machining the tensile specimens. Three groups of tensile specimens were machined; one group for each of the three machining schedules investigated. Each group of specimens was split into thirds – one-third were etched and then (all but one) were tensile tested, one-third were heat treated and then (all but one) were tensile tested, and one-third (all but one) were tested in the as-machined condition. The specimen from each third of the group that was not tensile tested was metallographically examined for surface damage.

The metallographic procedure was a specially developed (attack-polish) method to clearly reveal twins and cracks, and is outlined in Table 4. The dimensional inspection method involved the use of a Sheffield Roto-Con gage sensitive to less than 0.0002 in. (0.005 mm). The tensile tests were performed in a universal testing machine of 10,000-pound capacity operated at a crosshead speed of 0.02 in./min. (0.5 mm/min.) corresponding to a nominal strain rate of 0.04/min., and an actual strain rate at yield of the specimen of approximately 0.004/min. Strain was measured directly off the gage section of the specimen with a 1/2-in. (12.7 mm) extensometer that had a sensitivity of 1 in. (25.4 mm) of chart travel per 1 percent strain.

RESULTS

Figure 3 shows the photomicrographs of the part machined by the STD schedule and then etched. Figure 4 shows the photomicrographs of a similarly machined part that was heat treated after machining. Figure 5 shows the surface damage in a part machined by M/A schedule, and Figure 6 by the S/A schedule. Figures 3 and 5 also show metallographic sections from the pole of parts machined by the STD and M/A methods that are in the as-machined condition (before etching or heat treating). Figures 7, 8, and 9 show the surface damage in untested tensile specimens machined by the STD, M/A, and S/A

FIGURE 2. Processing Sequence for Parts Used in Beryllium Machining Study

TABLE 3. Surface Damage Removal Methods

A. Chemical Etching

1. Solution:

- 750 (± 15) ml H_3PO_4 (85%)
 71 (± 2) g CrO_3 (99%)
 200 (± 5) ml H_2O distilled or deionized
 30 (± 2) ml H_2SO_4 (95 to 98%)

2. Specific Gravity:

- 1.598 at 25 °C
 1.560 at 70 °C

3. Temperature: 70 °C (± 2 °C)4. Time to remove 0.004-inch per surface:
13 minutes 20 seconds

5. Technique:

- Tensile Specimens - simple immersion
 Part - immersion with rotation

B. Annealing

- 800 °C for 2 hours in vacuum, furnace cool.

The quantities measured were 0.2 percent offset yield strength, ultimate tensile strength, and percent elongation at fracture for each of the 3 machining schedules and 3 surface conditions (as-machined, etched, and heat treated). Each tabulated quantity is the average of 4 independent measurements (from 4 tensile specimens). Standard deviations of the individual results are also tabulated.

The dimensional inspection data are summarized in Table 6 for a STD part and the S/A part. Measurements (radial deviation from nominal) are given for two positions of each part before and after heat treatment. The differences relate to the distortion of the part that resulted from the heat treatment.

Results from the ultrasonic tests are summarized in Table 7.

DISCUSSION

Metallographic Analysis

One of the key objectives of this program was to obtain tensile data that could be applied to parts. The tensile tests were merely a way of evaluating the surface damage that a machining treatment produced in parts. An analysis of the metallography of parts and tensile specimens will indicate whether the tensile specimens simulate the parts with respect to surface damages, and whether the results of the tensile tests can be applied with confidence to the machining of parts. The best of the possible comparisons between parts and tensile specimens is on the metallography of samples in the as-machined condition. The comparison can be made for the STD schedule (Figure 3 vs. Figure 7) and for the M/A schedule (Figure 5 vs. Figure 8). It appears, at least on a qualitative basis, that the amount (depth and severity) of the surface damage in the tensile specimens is equal to or perhaps slightly greater than that in the parts for both machining schedules. Further comparison of the etched and of the heat-treated conditions confirms a similarity of the amount of surface damage in parts and specimens. These are favorable and important results because they indicate that the surface damage effects deduced by the properties measured in the tensile tests are indicative (and perhaps

TABLE 4. Metallographic Procedure
for Revealing Surface Damage

1. Section with silicon carbide cut-off wheel with water mist spray.
2. Mount in black, hard thermosetting resin for good edge retention and to reduce scattered light.
3. Grind with water lubricant on silicon carbide paper:
 - a. Coarse - 60 grit, remove at least 1.5 mm.
 - b. Intermediate - 180, 240, 320, 400, and 600 grit.
4. Final polish on vibratory polisher with kerosene lubricant:
 - a. 1-micron diamond paste on silk for 8 hours.
 - b. 0.5% HF in distilled water and 0.05- μ m gamma alumina for 2 to 15 minutes (attack polish) on a worn, short-napped cloth.

schedules. Each figure shows longitudinal and transverse (with respect to the longitudinal axis of the specimen) sections of specimens in the as-machined, etched, and heat-treated conditions.

The tensile test results are listed in Table 5. These results are in the form of a 3-quantity 3 X 3 matrix.

FIGURE 3. Micrographs of Sections From Part Machined by the Standard (STD) Schedule Followed by Etching

0.001 in.

a. pole section, as machined

b. pole section, etched

c. 45° section, etched

500X, polarized light
attack polished

d. waist section, etched

FIGURE 4. Micrographs of Sections From Part Machined by the Standard (STD) Schedule Followed by Heat Treating

a. pole section, heat treated

b. 45° section, heat treated

c. waist section, heat treated

0.001 in.

500X polarized light
attack polished

FIGURE 5. Micrographs of Sections From Part Machined by the Moderately Abbreviated (M/A) Schedule

0.001 in.

a. pole section, as machined

b. pole section, heat treated

c. 45° section, heat treated

d. waist section, heat treated

500X, polarized light
attack polished

FIGURE 6. Micrographs of Sections From Part Machined by the Severely Abbreviated (S/A) Schedule

a. pole section, heat treated

b. 45° section, heat treated

c. waist section, heat treated

500X, polarized light
attack polished

FIGURE 7. Micrographs of Untested Tensile Specimens Machined by the Standard (STD) Schedule

a. as machined

b. etched

c. heat treated

500X, polarized light
attack polished

FIGURE 8. Micrographs of Untested Tensile Specimens Machined by the Moderately Abbreviated (M/A) Schedule

FIGURE 9. Micrographs of Untested Tensile Specimens Machined by the Severely Abbreviated (S/A) Schedule

b. etched

c. heat treated

500X, polarized light
attack polished

TABLE 5. Tensile Data From Short Term Machining Damage Study

		MACHINING SCHEDULE								
		Standard (STD)			Moderately Abbreviated (M/A)			Severely Abbreviated (S/A)		
		0.2% YS (ksi)	UTS (ksi)	%E	0.2% YS (ksi)	UTS (ksi)	%E	0.2% YS (ksi)	UTS (ksi)	%E
As-machined	avg.	37.1	58.9	5.2	37.6	59.4	5.6	37.9	59.4	5.1
	s.d.	0.8	0.8	0.2	0.7	1.4	0.3	0.1	0.4	0.2
Etched (0.004 in./surface)	avg.	37.1	59.6	6.4	37.0	59.1	6.1	36.9	59.1	5.9
	s.d.	0.2	0.4	0.2	0.1	0.6	0.3	0.0	0.7	0.5
Heat Treated (800 °C, 2 hr, furnace cooled)	avg.	33.5	59.0	5.5	33.3	58.3	5.1	33.4	58.4	5.3
	s.d.	0.3	0.4	0.4	0.5	0.4	0.5	0.3	0.4	0.3

TABLE 6. Summary of Dimensional Inspection Results

		MACHINING SCHEDULE					
		Standard (STD)			Severely Abbreviated (S/A)		
		Before HT	After HT	Distortion	Before HT	After HT	Distortion
Deviation from Nominal at Pole		+0.0007	+0.0002	0.0005*	+0.0004	-0.0002	0.0006*
Out-of-Round at 70°		0.0003	0.0004	+0.0001**	0.0005	0.0004	-0.0001**

*decrease in pole height (sag) as a result of heat treatment.

**increase in out-of-roundness as a result of heat treatment.

TABLE 7. Nondestructive Evaluation Results

Results	No measurable surface damage was detected in the as-machined state, and no measurable change in surface condition was observed as a result of subsequent heat-treating or etching processes.
Method	15 MHz ultrasonic surface wave pulse echo test, 11° incident angle and immersion.
Sensitivity	Electro-discharged machined notches of 0.001- and 0.003-inch depth were readily measured in reference specimens as notch signal amplitudes 30 to 50 times greater than background.

slightly conservative or more severe) of the effects of surface damage in parts. Consider, in contrast, the hypothetical situation where much less damage occurred in the tensile specimens than in the parts. Then, in the limit (no machining damage in the tensile specimens), any machining treatment would appear on the basis of the tensile tests to be suitable for producing damage-free parts. This would clearly lead to erroneous conclusions of what machining schedule is recommended. Instead, *equal or greater* machining damage was observed on tensile specimens than on parts; a favorable result for the application of the results of this study to the machining of parts.

An important result from the metallography is the comparison of the amount of machining damage resulting from different machining schedules. Intuition indicates that the deeper the final cuts, the greater the amount of damage. From the metallography of the tensile specimens in the as-machined condition, (Figures 7-9) no such effect can be observed: the amount of damage was no greater in specimens machined by the M/A schedule than in the STD schedule, or by the S/A schedule compared to the M/A schedule. Furthermore, the amount of damage at sections near the pole of parts removed after the parts were machined (Figures 3 and 5) revealed no greater damage by the M/A schedule than by the STD schedule. This leads to an interesting and unexpected observation: the abbreviated machining schedules (M/A and S/A) produce no greater machining damage than the standard (STD) schedule.

Further useful observations can be made from the metallography. The depth of machining damage measured on as-machined samples is 0.001 in. (0.025 mm) ± 100 percent. Therefore, if the surfaces are etched 0.004 in. (0.10 mm) all surface damage should be removed. Inspection of the metallography on the part machined by the STD method and then etched (Figure 3) and on the etched tensile specimens (Figures 7, 8, and 9) indicates that the etching indeed results in surfaces that are essentially damage-free. Tails of twins remain in one grain of the part at the waist section, and this cannot be easily explained. Some twins are apparent in other sections of parts and specimens below the surface and are the result of polishing rather than of machining damage as deduced by their distribution

with distance from the surface (machining damage twins should be most frequent at the surface, and their frequency should decrease with the distance from the surface).

Heat treating after machining resulted in surfaces that for some of the machining schedules were not free of twinning damage (See Figures 4a and 5b for parts, and Figure 7c for tensile specimen). The metallography indicated that heat treatment removed virtually all the surface twinning in parts and specimens machined by the S/A and M/A methods, but not in the STD method. If the previous observation that the amount of machining damage is the same for all three machining methods is correct, one would expect that the effectiveness of a similar heat treatment on all three schedules would be the same. This was obviously not observed, and may indicate that there are subtle differences in the amount of machining damage produced by the different machining schedules, and that these differences are not easily detected by metallography of the as-machined samples.

Tensile Data

One of the questions remaining after the analysis of the metallography is the one dealing with the effect of the machining schedule on the amount of surface damage. If the schedule truly has an effect on the amount of damage, the ductility and ultimate tensile strength of the specimens tested in the as-machined condition might show it. Analysis of these data in Table 5 failed to reveal any significant difference between any of the machining schedules. Neither the yield strength, ultimate strength, nor the elongation displayed any significant effect of machining schedule.

Only relatively small (10 to 20 percent) increases in ductility were observed after the specimens were etched. There were no concurrent increases in ultimate tensile strength. Yield strength decreased slightly (by 2 to 3 percent) in the S/A specimens and possibly in the M/A specimens after etching.

Somewhat larger increases in ductility and ultimate strength are usually observed when as-machined beryllium tensile specimens are etched. In ingot-sheet beryllium the elongation increases by a factor

of about 10, the ultimate tensile strength increases by about 30 percent, and the yield strength decreases by about 10 percent.⁵ Powder-source specimens such as those tested in this study usually exhibit smaller changes in tensile properties after etching.

Hanafee⁶ found that in similar (Select S-65) material, etching after careful machining had essentially no effect upon the tensile properties. However, in roughly machined specimens, etching increased the ductility by a factor of 5, increased the ultimate strength by 20 percent, and had an inconsistent effect upon the yield strength.

It appears that surface damage effects in uniaxial tensile specimens of powder-source material can be quite small and variable. Careful machining, even with heavy cuts, leads to only small (less than 20 percent) reductions in ductility. Heavy cuts with dull tools (corresponding to rough machining in Hanafee's study)⁶ can cause large decreases in ductility and ultimate strength.

Heat treatment was less effective than etching in increasing the ductility of the samples. In the STD and S/A specimens, the elongations increased by about 5 percent which was probably not statistically significant. In the M/A specimens, the elongation appeared to decrease by about 10 percent after heat treating.

A significant decrease in the yield strength occurred as a result of heat treating. The yield strength decreased by 10 percent [from 37-38 ksi (259 MPa)] to below the specification limit of 35 ksi (242 MPa) in all three machining conditions after heat treating.

Stress-strain curves that are typical of all the specimens tested in the as-machined, in the etched, and in the heat-treated conditions are shown in Figure 10. The reduction in the yield strength by heat treating was the result of the disappearance of the yield point displayed by the as-machined specimens. It may be observed that etching does not cause the removal of the yield point. The removal of the yield point by heat treatment indicates that heat treatment causes a general effect on the structure, and does not alter merely the surface where the machining damage is located.

Floyd⁷ explained yield points in beryllium by a dislocation pinning reaction of Al-Fe-Be₄ precipitate. Such pinning probably occurred during a proprietary heat treatment (intended to increase the yield strength) after hot isostatic pressing and was eliminated by the damage-removing heat treatment performed in this study (probably by rapid cooling from the heat-treating temperature of 800 °C).

The application of the findings of this study, or of any study involving the application of tensile data to the fabrication of beryllium components, is not without some risk. Tensile tests are probably not conservative in evaluating the effects of machining damage in complex parts. Tensile tests are essentially low strain rate tests in uniaxial stress, and structural members are rarely loaded in uniaxial stress but often in multiaxial stress such as biaxial tension, and often at high rates. Biaxial tension and high strain rates are likely to increase the apparent detrimental effects of surface damage. It is conceivable that in a biaxial stress state, a structure with a given state of surface damage might be detrimentally effected by that damage, whereas in uniaxial tension no effect would occur. Recent testing⁸ at Rocky Flats indicates that large effects of surface damage in powder source beryllium are observed by impact tests.* Average impact energies increased by over a factor of 6 after specimens were etched or heat treated at 600 to 900 °C for 4 hours. Room temperature tensile properties were only slightly affected by surface damage. The effects of stress state and strain rate on the behavior of surface-damaged beryllium clearly requires further study.

One last point concerning the effects of heat treating on the removal of machining damage should be made. As previously mentioned, heat treating appeared to eliminate more of the machining twins in the S/A tensile specimens than in the STD specimens. This would be consistent with the concept that a more complete recrystallization occurred because the more heavily machined material is more heavily cold worked. The temperature at which complete recrystallization occurs decreases with increased amounts of deformation or, alternatively, the amount of recrystallization from a given treatment increases with increasing deformation. One

*Subsequent tensile tests indicate large effects of surface damage at high strain rates.

FIGURE 10. Stress-Strain Curves of Specimens With Three Different Surface Conditions

interesting implication of this observation is a method of increasing the effectiveness of surface damage removal by heat treating. The method is to increase the surface deformation in a machined part by some scheme that compressively cold works the surface; for example, by sand blasting or shot peening. Then the subsequent heat treatment will be more likely to totally recrystallize the surface and result in a twin-free surface. Sand blasting or shot peening are possible methods for introducing compressive cold work on the surface without risking the introduction of cracks. This method may allow the removal of surface damage twins at lower temperatures than conventionally used and make heat treatment more attractive than etching for certain applications.

Another possibly useful idea to eliminate surface damage in beryllium parts is by laser heating. Two of the benefits of laser heating of beryllium parts are that only the surface is heated, and the risks of thermal distortion and reduction of strength by elimination of the yield point (as occurs in Select S-65) are reduced. Furthermore, the laser process can be used only on critical sections and, therefore, be more time efficient and energy conservative than conventional heat treatment (heating of the entire component).

Ultrasonic and Dimensional Tests

The ultrasonic tests were performed to evaluate the method as a technique for detecting surface damage. It was reasoned that twins and cracks would somehow perturb the passage of an ultrasonic wave along the surface and an indication of the damage would be obtained. As the results in Table 7 indicate, the technique was not able to detect damage even in as-machined specimens.

The dimensional inspection data were obtained to determine if the heat treatment would distort the parts. As shown in Table 6 small amounts of increased out-of-roundness and sag were observed after heat treatment. However, both these measures of distortion were significantly below the 0.001 in. (0.025 mm) normally allowed for dimensional tolerance. It is indicated, therefore, that distortion

from heat treating at 800 °C for 2 hours is not a problem.

CONCLUSIONS

The results of this study have indicated that a beryllium surface, as free of machining damage as that produced by the standard method (9-pass finish followed by a chemical etch) can be obtained by an abbreviated machining schedule (either 4- or 3-pass) followed by an etch. This conclusion is based on a study of the metallography of the machined and machined-and-etched surfaces, and by a study of the behavior of tensile specimens fabricated to simulate the machining of a typical hemispherical beryllium shell.

RECOMMENDATIONS

It is recommended that the 4-pass abbreviated machining schedule (M/A) be used as a substitute for the standard 9-pass method (STD) previously used to fabricate damage-free beryllium components that serve as critical structural members from powder-source beryllium. The 3-pass severely abbreviated schedule (S/A) appeared to be equal to the M/A schedule, but conservatism would indicate that it be used only for less-than-critical components until further evaluation is performed. Ingot-source beryllium is more sensitive to machining damage than is powder-source, and the application of the findings of this study to that material is discouraged.

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