193
8-30
RFP-1816

221
RFP-1816
July 6, 1972

MASTER

ISOTROPIC HIGH STRENGTH BERYLLIUM

Dennis R. Floyd

THIS DOCUMENT CONFIRMED AS
UNCLASSIFIED
DIVISION OF CLASSIFICATION
BY JH/Kahn/amb
DATE 8/9/72

DOW CHEMICAL U.S.A.
ROCKY FLATS DIVISION
P. O. BOX 888
GOLDEN, COLORADO 80401

U. S. ATOMIC ENERGY COMMISSION
CONTRACT AT(29-1)-1106

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Printed in the United States of America

Available from the

National Technical Information Service

U. S. Department of Commerce

Springfield, Virginia 22151

Price: Printed Copy \$3.00; Microfiche \$0.95

Publication Date
July 6, 1972

RFP-1816
UC-25 METALS, CERAMICS,
AND MATERIALS
TID-4500 (56th Ed.)

ISOTROPIC HIGH STRENGTH BERYLLIUM

Dennis R. Floyd

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DOW CHEMICAL U.S.A.
ROCKY FLATS DIVISION
P O BOX 888
GOLDEN, COLORADO 80401

Prepared under Contract AT(29-1)-1106
for the
Albuquerque Operations Office
U. S. Atomic Energy Commission

R5915

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

CONTENTS

Abstract	1
Introduction	1
Experimental	1
Results	3
Hot Pressing	3
Extrusion	4
Forging	5
Sub-Scale Samples	5
Full-Scale Pieces	7
Discussion	7
Conclusions	10
References	10

ACKNOWLEDGMENTS

This project involved the services of people at several different facilities. The majority of the work was done at Brush-Wellman Company by Brush personnel. The Brush-Wellman work was very ably directed by Mr. Richard O'Rourke, and he was aided at times by Dr. Ray Foos, Dr. Ken Walsh, and Mr. Jerome Mang. To these gentlemen, especially Mr. O'Rourke, I extend not only my gratitude but also my congratulations for achieving the goals of this project.

The valuable assistance and technical discussions of Mr. Arthur F. Hayes of the Ladish Company, Cudahy, Wisconsin are appreciated. Thanks are also extended to Mr. Edgar P. Stein of the Los Alamos Scientific Laboratory, who originated the program and remained interested and helpful throughout its course.

The experimental work at Rocky Flats was ably done by Mr. Richard M. Simmons, and testing services were provided by Mr. D. V. Miley and Mr. R. P. Brugger. Mr. Charles Maak of the Sandia Corporation, Albuquerque originally recommended to us the manufacturing route that was finally used. My thanks to all.

ISOTROPIC HIGH STRENGTH BERYLLIUM

Dennis R. Floyd

Abstract. A process for making high strength beryllium by a hot pressing, extrusion, and upset-forging route is described. Isotropic compressive yield strengths of greater than 100,000 psi were achieved by forward-extruding to a 4 to 1 reduction in area at 1300°F followed by upset-forging at temperatures between 1000° and 1200°F and reductions in height between 40 and 60%. Both tensile and compressive data for hot pressed, hot pressed and extruded, and hot pressed, extruded, and forged beryllium are presented and discussed.

INTRODUCTION

This work was originally initiated to determine if a process could be established for producing high strength beryllium parts. The size of these parts required, as machining stock, a solid right-circular cylinder 5.25-in. diameter by 3.25-in. thick. The desired room temperature compressive yield strength was 100,000 psi in 3 orthogonal test directions. The purpose of this report is to describe the experimental work that led to achieving these goals, to present the results of this work, and to discuss the significance of these results.

Earlier work at Brush-Wellman, and Ladish, had shown the feasibility of making a fine grain size, hot-pressed block material which was amenable to extrusion and forging.^{1,2} Tensile yield strengths in the neighborhood of 100,000 psi were observed in some of the material but the yield behavior was anisotropic. Also the extrusion and forging temperatures were close to the recrystallization temperature for beryllium, and thus the optimum amount of cold work was probably not achieved. Some of the higher strength data reported came from pieces that had cracked in the forging operation. No data on the room temperature compressive strength of this material were reported. Since we were unable to find a comparison of tensile properties to compressive properties in the literature, we could not accurately predict the compressive properties of the Brush and Ladish material from the available tensile data. A limited amount of compression test data from Sandia (Albuquerque) on some of the Brush-Wellman material that had been extruded and forged at Ladish, showed that the 0.2% offset

compressive yield strength varied from 75,000 to 122,000 psi.³ The fabrication parameters for the material tested were not available.

Therefore, this work was started with the intention to cold-work a forgeable grade of fine grain, high strength beryllium, hot-pressed block to increase its yield strength. The isotropic properties would be induced by extruding at 1300°F to a 4 to 1 area reduction followed by upset forging at a temperature and reduction in height which would be established with sub-scale forging specimens. Although the earlier work at Ladish and Brush had shown that the 4 to 1 extrusion at 1300°F was feasible, we did not know if we could forge at temperatures below 1300°F. We felt that a forging temperature somewhere in the range of 1000°F to 1300°F was needed to achieve the 100,000 psi strength level. We also specified a 0.2% offset tensile yield strength of 70,000 psi in the as-hot-pressed material so that only about a 50% increase in yield strength due to cold-working operations would be needed to reach 100,000 psi.

EXPERIMENTAL

The program was divided into three phases:

1. Fabrication of four hot pressings, 8.4-in. diameter by 12-in. long, using minus 20 micron input powder with chemistry selected to produce optimum hot-working characteristics. One of these pressings was to be shipped to Rocky Flats Division (Dow Chemical U.S.A.) for evaluation and three were to be held for subsequent extrusion.
2. Forward-extrusion of one of the hot-pressed billets to 4.2-in. diameter (4:1 area reduction) at 1300°F. Determine tensile and compressive properties as-extruded, and machine sixteen 1.4-in-diameter forging samples, half to be 3-in. long and half 2-in. long. Upset forge to 1.167 in. two samples of each size at each of the following temperatures: 1000°F, 1100°F, 1200°F, and 1300°F. Three full-size pieces would then be upset-forged using conditions based upon the strength and soundness of the sub-scale samples.

- Extrusion of the remaining two hot pressings followed by upset forging of as many full scale pieces as could be obtained from these extrusions.

The majority of this work was done by Brush-Wellman Company in production facilities at Cleveland, Ohio, and Elmore, Ohio. Details of their powder manufacturing and hot-pressing operations were not in their completion report.⁴ The equipment used for powder production and hot-pressing is known to have been production type.

The extrusion operation was done by Brush-Wellman on their 3000-ton horizontal press using the jacketed-billet design shown in Figure 1. Extrusion parameters were:

Billet temperature:	1300°F ±20°F
Soak time:	4 hours
Tooling temperature:	750°F
Breakaway tonnage:	2850 tons
Area reduction:	4 to 1
Ram speed:	40 in. per min.

Forging of the sub-scale samples was done on a 150-ton hydraulic press at the Brush-Wellman Research and Development facility in Cleveland. Stop-blocks

were used to control the upset height. Samples were heated to the forging temperature and held for one hour. Platens were torch-heated prior to forging and then coated with a hot die lubricant prior to each test. Mild steel tubes were available to encapsulate the beryllium in the event that it could not be successfully upset-forged bare in the desired temperature and reduction ranges. The load required to upset the samples varied between 70 to 90 tons depending upon the forging temperature. Strain rates were about 20-40 in./in. per minute. Some of the samples were air cooled and the others were returned to the furnace and slow cooled after forging.

Forging of the full-scale pieces was done at the Ladish Company, Cudahy, Wisconsin on a 3000-ton vertical hydraulic press. Forging billets that had been machined from one extrusion, and four ½-in.-thick mild steel tubes were placed side by side in a small muffle furnace 3 hours prior to forging the first piece. Temperature of the billets was measured with Tempil* sticks immediately after forging. The platens of the press were not heated, but 1-in.-thick steel plates were heated to about 1400°F in a separate furnace.

*Registered tradename of the Tempil Corp., 132 W. 32nd St., New York, New York.

Figure 1. Drawing of the Extrusion Can and Billet. R. G. O'Rourke, "Final Report—High Strength Beryllium," Technical Report 468 for Purchase Order 57094, Brush-Wellman Company, Cleveland, Ohio, October 15, 1971.

and placed on top and beneath the billets prior to forging. A hot die lubricant was used between these heated platens and the billets. The force required to upset the beryllium was not measured. Strain rates were estimated to be about 40-60 in./in. per minute. Forged pieces were slowly cooled by placing them in a bed of vermiculite immediately after forging. Tensile and compression specimens used for the sub-scale pieces are shown in Figure 2. Some additional testing of a full-scale piece was done with the specimens shown in Figure 3. All specimens were etched in a HF-HNO₃-distilled water solution to remove 0.010-in. from the diameter prior to testing. A 20,000 lb Instron machine was used for all testing, and extensometers were used for strain determination in tensile testing. Cross-head travel data and measurement of fractured specimens were used to estimate strain in compression testing.

Figure 2. Tension a) and Compression, b) Specimen Designs Used to Test the Sub-Scale Extruded and Forged High Strength Beryllium.

Figure 3. Tension (a), and Compression (b) Specimen Designs Used to Test Full-Size Extruded and Forged High Strength Beryllium. The tensile bar is the standard ASTM round threaded design.

RESULTS

Hot Pressing

Although only four hot pressings were ordered, enough powder was generated to make five. The chemical analyses of the input powder and four hot pressings are listed in Table 1. The fifth hot pressing was found to be cracked upon removal from the hot pressing die. Brush feels this pressing probably cracked because the maximum temperature reached during hot pressing was too low. As seen in Table 2, the tensile yield strength was close to the target of 70,000 psi in the as-hot-pressed condition. The material exhibited a yield point in tension but not in compression. The magnitude of the difference between upper and

Table 1. Chemical Analyses of Beryllium Materials.

	Powder Blend	Pressing 8084	Pressing 8113	Pressing 8114	Pressing 8409
BeO %	3.57	3.57	3.41	3.46	4.09
C %	0.070	0.085	0.072	0.070	0.102
Fe (ppm)	1355	1360	1340	1390	1325
Al (ppm)	95	80	100	100	120
Si (ppm)	250	290	320	360	330
Mn (ppm)	35	30	20	20	40
Mg (ppm)	70	20	20	20	20
Cr (ppm)	65	80	60	60	95
Ni (ppm)	210	260	210	200	240
Ti (ppm)	60	60	60	60	95
Zn (ppm)	<55	<100	<100	<100	<55
Ag (ppm)	<3	<3	4	4	<3
Ca (ppm)	<55	<100	<100	<100	<85
Co (ppm)	8	10	10	10	12
Cu (ppm)	55	80	60	60	70
Mo (ppm)	10	20	20	10	20
Pb (ppm)	<6	<6	<6	<6	<6

Notes: BeO by bromine methanol method

lower yield strengths, $\Delta\sigma$, varied with test direction as is evident in Table 2; axial having the lowest $\Delta\sigma$ and transverse the largest. Also note in Table 2 that the 0.2% offset yield strength in compression is consistently less than the lower yield strength in tension.

Extrusion

As planned, three extrusions were made at a 4 to 1 area reduction and 1300°F preheat temperature. The first extrusion was made using a mild steel following-block. When the following-block was being removed

by sawing through the tubular tail of beryllium that is normally present in cylindrical extrusions, the extrusion was heard to crack.

The crack was radially oriented, and it started at the back end and extended down $\frac{1}{4}$ the length of the piece. The next two extrusions were made with graphite following-blocks because previous Brush experience had shown that the graphite would crush and release the hoop stress in the tubular beryllium section. However a radially oriented crack extending along the entire length of the extrusion was noted in each case upon removal of the sheath.

A fourth extrusion was made successfully, using the 8-in.-long section remaining from Pressing No. 8084 that had been tested at Rocky Flats. The hollow tail was not present in this extrusion because, following a practice established by Ladish,⁵ the extrusion operation was stopped before the back-end of the beryllium entered the throat of the die. The extrusion was extracted from the die by pulling it back through the throat and removing it from the entry side.

The tensile and compressive yield properties of material in the extruded condition are listed in Table 3. The metal was very brittle in both tension and compression in all test directions. The axial tensile yield is probably close to the true upper yield strength, but the radial and transverse specimens probably failed before reaching the true upper yield

Table 2. Average Tensile and Compression Properties of Brush Pressing 8084 in the As Hot-Pressed Condition. Rocky Flats Data are the averages of 3 tests; Brush-Wellman data are averages of 2 tests.

Description and Test Direction	Ultimate (kpsi)		Yield (kpsi)			Fracture Strain (%)	
	Tension	Compression	Tension U.Y.S.*	Tension L.Y.S.**	Compression 0.2% Offset	Tension	Compression
Brush Data							
Axial	74.6	ND	ND	68.9	ND	1.34	ND
Transverse	76.1	ND	ND	72.0	ND	1.05	ND
Rocky Flats Data, One End							
Axial	64.3	226.7	64.7	62.8	62.6	1.0	12.3
Radial	73.2	204.1	69.9	64.7	60.6	2.3	11.4
Transverse	88.7	230.5	89.4	77.2	64.2	1.8	12.1
Rocky Flats Data, Opposite End							
Axial	70.1	215.6	69.5	66.2	63.4	1.3	11.5
Radial	82.1	206.1	77.7	68.3	60.0	2.1	11.7
Transverse	88.2	213.8	81.3	72.1	60.7	3.4	11.8

*U.Y.S. = upper yield strength.

ND = No data

L.Y.S. = lower yield strain.

**L.Y.S. = lower yield strain.

Table 3. Tensile and Compressive Yield Properties of Hot Pressed and Extruded Beryllium from Brush Pressing 8113. Data are the averages of three tests per direction, except as noted.

Description	Tensile Yield, Upper (kpsi)	Compression Yield		
		Upper	Lower	0.2% Offset
Brush Data				
Axial	119.8	118.4	110.0	111.4
Radial	75.3 ^a	117.1	115.6	116.1
Transverse	75.0 ^a	114.8	114.2	114.3
Rocky Flats data				
Axial	127.4 ^b	83.7 ^d	d	d
Radial	93.6 ^c	105.5 ^d	d	d
Transverse	e	e	e	e

^a May be premature failures.

^b Data from 2 tests only, 2 others failed prematurely.

^c Data from 4 tests, all probably premature failures.

^d All samples failed in the elastic portion of the curve.

^e No tests were made in this direction.

strength. All tensile bars failed in the elastic portion of the stress strain curve. Brush observed a yield point phenomenon in compression and, in this case, the axial test direction exhibited the greatest $\Delta\sigma$.

Forging

SUB-SCALE SAMPLES--

This aspect of the program was quite successful. The minimum temperatures and maximum reductions in height which could be used without cracking the forging samples were determined as shown in Figure 4. The compressive yield strengths of these same samples were determined at room temperature after forging, and the results are included in Figure 4. As can be seen in the figure, there is a range in which the desired 100,000 psi compressive yield strength can be obtained without cracking the material during forging.

The compressive yield strength, for each condition of forging that was attempted, is listed in Table 4. A photograph of some of the forged sub-scale samples is shown in Figure 5. Generally two samples were forged for each condition, and one was slowly cooled whereas the other was fast-cooled. No obvious differences were noted as a result of the changes in cooling rate.

Figure 4. Summary of Results of Sub-Scale Beryllium Upset Forging Tests. Numbers next to the data points refer to the compressive yield strengths in kpsi that resulted from the indicated forging conditions. Open circles indicate that the forging sample did not crack for those forging conditions, whereas closed circles mean that the samples did crack.

Table 4. Room Temperature Compressive Yield Strength of Beryllium as a Function of Percent Reduction in Forging, Temperature of Forging, and Direction of Testing. Data are in kpsi and are the averages of two tests per condition. The average strength for all 3 directions is also listed.

Forging Temp (°F)	Reduction (%)	Axial Compressive YS	Radial Compressive YS	Tangential Compressive YS	Average of 3 Directions
1000	40	117.0	112.9	115.1	115.0
1000	50	111.2 ^a	121.5 ^a	121.8 ^a	118.1
1000	60	111.1 ^a	117.6	ND ^c	114.3
1100	40	106.7	108.8	115.8 ^a	110.4
1100	50	111.4 ^b	112.5 ^b	ND	112.0
1100	60	105.4 ^a	112.4 ^a	121.0 ^a	113.0
1200	40	98.4	99.5 ^a	102.0 ^b	99.9
1200	50	95.2 ^b	101.9 ^b	ND	98.5
1200	60	88.7 ^a	100.5 ^a	ND	94.6
1300	40	86.6	91.4	92.7	90.2
1300	50	83.6 ^b	85.1	ND	84.3
1300	60	75.6 ^a	87.8 ^a	ND	81.7

^a Crack present at 2% strain.

^b Crack occurred at $\leq 0.5\%$ strain.

^c No Data.

Figure 5. The Sub-Scale Samples after Forging at the Conditions Shown. The 60% reduction at 1000° F was done in a mild steel can and the sample is crack free.

The compression testing of the sub-scale material was terminated after nominally 2% strain, and samples were examined for signs of cracking. The presence of cracking is noted in Table 4 with asterisks. The cracks originate in most samples at the outer edge of one of the faces in contact with the platens of the testing machine. An example is shown in Figure 6. Occasionally, the operator heard a crack during testing before 0.5% strain had occurred. In such cases the test was stopped immediately.

FULL-SCALE PIECES -

Four pieces, 4.2-in. diameter by 5.5-in. long, were machined from the sound portion of the first extrusion and sent to Ladish for upset forging at 1100°F to 40% reduction in height. The first piece failed catastrophically at the instant the press platen made contact with it. Two factors contributed to this failure:

- a. The workpiece probably had not come to an equilibrium temperature after only 3 hours in the 1100°F furnace.

Figure 6. Photomicrograph Showing the Typical Cracking Present at 2% or Less Plastic Axial Compressive Strain. 8X.

- b. The press operator brought the platen down on the workpiece at a very fast rate.

Since the full-scale pieces were in such short supply, we decided to increase the furnace temperature to 1200°F and hold for 2 more hours. The sub-scale work showed that a 40% reduction at 1200°F should have resulted in compressive yield strengths close to 100,000 psi. The operator was asked to make gentle contact with the work prior to increasing the tonnage, and the next piece was placed in the mild steel can prior to forging. This piece forged successfully, so the third one was attempted without the steel can. Since the third piece was also sound, the final piece was also forged bare. It, too, was sound. The three sound pieces are shown in Figure 7.

One of the bare-forged pieces was sectioned for testing purposes to see if the desired strength levels were reached. Both the tensile and compressive data are presented in Table 5. Although the compressive yield strength is isotropic, the strength falls about 6% short of 100,000 psi. The ductility is improved over the as-extruded values shown in Table 4. The tensile ductility is poor, however. Note that there is a strong yield point present in some tensile tests, and the upper yield strength exceeds 100,000 psi in the axial direction. This yield point phenomenon was not observed in the compressive tests, at Rocky Flats, in either the extruded or the extruded-and-forged material, but Brush observed it in their compression testing of extruded material.

DISCUSSION

The results indicate that it is possible to achieve an isotropic compressive strength of 100,000 psi in beryllium by a hot pressing-extrusion-forging route. Our approach was to obtain hot-pressed block with a high isotropic yield strength in the as-pressed condition and cold work this material to increase the yield strength. The high strength in the as-pressed condition was achieved by using very fine input powder (less than 20 micron particles) and controlling the impurity levels. The extrusion conditions of 4 to 1 area reduction and 1300°F preheat were chosen from the earlier Brush work.⁶ Since extrusion would impart a preferred texture to the material, the upset forging operation was needed to revert the material to a more random texture and thereby achieve the desired isotropy. Various forging temperatures were examined to maximize the strength, and various reductions-in-height were chosen to optimize the isotropy.

Figure 7. Three Full-Scale Pieces of Extruded and Forged High Strength Beryllium. Only the piece on the left was jacketed during forging.

Table 5. Tensile and Compression Data on a Full Size Beryllium Block which Had Been Extruded 4 to 1 at 1300°F and Upset-Forged 42% at 1200°F. Two compression and four tension tests per direction.

Test Direction and Type	Ultimate (kpsi)	Yield (kpsi)		Fracture Strain (%)
		Upper	0.2% Offset	
Axial				
Tension	102.4	100.3	94.6	2.4
Compression	305.0 ^a	b	90.8	35.8 ^a
Radial				
Tension	98.2 ^c	86.6 ^c	85 ^c	2.1 ^c
Compression	232.5	b	93.7	17.7
Tangential				
Tension	d	d	d	d
Compression	258.7	b	94.4	21.6

^a Samples had not failed at the load capacity of the testing machine.

^b A yield point was not observed in compression.

^c One test only, other three broke in threads.

^d All four samples broke in threads.

Figure 8. Typical Microstructure of the As Hot-Pressed Beryllium. The average grain size is 5.6 microns. Polarized Light 500X.

The hot-pressed material behaved predictably both in testing and in mechanical working. The 70,000 psi yield strength target was achieved, principally because of the fine grain size as shown in Figure 8. The high iron content probably contributed to the strength by the precipitation of FeBe_{11} , but this was not verified. The mechanical working success was due probably to the low aluminum content which prevented hot shortness, and to the low BeO content

(<3.5 wt%). The BeO content of very fine grain size powder product often runs 4 to 6% and the elevated temperature ductility suffers.⁷

In reviewing the room temperature properties of the as-hot-pressed material in Table 2, it is interesting to note that the fracture strain is 3.5 to 12.3 times greater in compression than in tension. This results in more strain hardening and a higher fracture stress in compression than in tension. The ultimate compressive-strength values given in Tables 2 through 5 have not been adjusted for the increased cross-sectional area during testing. The true compressive fracture stresses will be less than those listed by approximately the same percentage as the compressive strain at fracture.

The data for the as-hot-pressed material in Table 2 also reveal that although there is up to 25% variation in the lower tensile yield strength with testing direction, there is only 6% variation in compressive yield strength. Tests in the transverse direction are mainly responsible for the large variation in the tensile results, and this direction also has the largest $\Delta\sigma$. It is possible that the mechanism responsible for the yield point increases both the upper and lower yield strengths. Hauber has suggested that the apparent orientation dependence of the yield point may be due to an orientation-dependent precipitation of FeBe_{11} on a certain habit plane.⁸ If so, this precipitate may preferentially strengthen certain test directions.

The Brush data on the extruded material given in Table 3 show a yield point in compression testing. The tests at Rocky Flats were stopped because of minor cracks, but we were unable to observe a yield point in compression testing of as-hot-pressed material that had a strong tensile yield point. The reason for the discrepancy is not known, but theoretically the yield point should be present; therefore the problem may be in our testing procedures.

The Brush compressive lower yield strength data are surprisingly isotropic for extruded material. Both Brush and Rocky Flats tensile data were affected by the exceptional brittleness of the beryllium in the as-extruded condition resulting in premature test failures.

The difficulty with cracking during extrusion was circumvented by the partial extrusion technique; but Brush feels that the problem could be solved by further experimental extrusion work or by lowering the

iron content in the raw material. The reason for the cracking must involve the hollow tube which naturally results when the complete billet is pushed through the extrusion die. It is not clear whether the crack occurs during cooling or in decanning operations.

The data on extruded and forged sub-scale samples reveal that, for the conditions studied, the working temperature has a much greater effect on compressive yield strength than does the percent reduction in height. For example in the axial orientation at 40% reduction the compressive yield strength increases from 86,000 psi at 1300°F to 117,000 psi at 1000°F forging temperature. This is a 36% increase. On the other hand there does not appear to be any consistent increase in compressive yield strength as a result of an increase in percent reduction in height. In fact, several cases show a decreasing strength with increasing reduction. However, while increased reduction does not significantly affect yield strength in the range 40% to 60%, an effect can be expected at some lower range of reduction; for example, 10% to 30%. The higher reductions are necessary to revert the as-extruded texture to a more random texture. The data in Table 5 indicate, since the axial tests exhibit more ductility than radial and transverse, that the random texture was not completely achieved at 40% reduction.

The successful forging of the full-size pieces at 1200°F, after one had broken at 1100°F, may have been due to the 100°F increase in temperature. But, since three sub-scale samples were successfully forged at 1100°F, it is more likely that the one failure was caused by inadequate soak time prior to forging, or by impacting the work piece with the moving platen of the press.

The tensile and compression properties of the full-scale hot pressed, extruded, and upset forged beryllium, presented in Table 5, show improvement over similar properties of the as-hot-pressed beryllium in Table 2. The tensile ultimate and yield increased by about 40% in the axial and radial direction, but data in the transverse directions were lost because of poor ductility and notch sensitivity in the worked material. Tensile ductility was more isotropic in the as-hot-pressed condition. The compressive ultimate and yield increased by about 50% in all test directions. Ductility in compression was more isotropic in the as-hot-pressed condition, but the ductility in the worked condition was greater than in the as-pressed condition. This latter result may have been due to the

squat compression sample (Figure 3b) which was used to test the worked material. This design would tend to produce a more compressive stress-state throughout the sample than the design used for the as-hot pressed tests (Figure 2b), because of the surface friction effects. A more compressive stress state would inhibit fracture and therefore improve ductility.

The direction for any future work on this program is clear. The partial extrusion should be sectioned into full-scale forging pieces and should be forged bare at 1100°F using a sufficient hold time and making certain to prevent impact of the workpiece with the press platen. Improvements could be realized by investigating the following areas:

- Prevent cracking of the extrusions by lowering the iron content in the input powder, preventing the formation of the hollow tube at the end of the extrusion, or using a beryllium following-block. The beryllium following-block would prevent stresses resulting from differential thermal expansion.
- Further increase the strength by extruding at lower temperatures, or by canning followed by forging at lower temperatures.
- Improve the ductility and yield-strength isotropy by using heat treatments designed to eliminate the yield point.

At its present stage of development, however, the process described results in a high strength isotropic product that is an addition to the inventory of beryllium products available to designers and users of this specialty metal. As is the case for any engineering material, the designer must recognize and account for the limitations of the material. In this case the penalty that must be paid for increased strength is increased brittleness. The brittle behavior will result in poor resistance to impact loading and increased notch sensitivity. Also, the size of a crack that will promote catastrophic failure will decrease because of the high yield strength and presumably lower fracture toughness. On the other hand, the yield strength of this material exceeds the 30,000 psi guaranteed minimum yield strength associated with conventional hot-pressed block by 200%. Certain applications, such as the compression critical structure that prompted this work, will benefit from the availability of this isotropic high strength beryllium.

CONCLUSIONS

1. A process has been established that will produce beryllium with an isotropic compressive yield strength of 100,000 psi. This process was developed on production-type equipment. Although more development work is needed to improve the extrusion technique, the process can be used for large quantity production.
2. The acceptable forging range, for achieving greater than 100,000 psi yield strength in hot pressed and extruded beryllium, is between 1100°F to 1200°F preheat temperature and 40% to 50% reduction in height. The range can be increased to include 1000°F and 60% reduction if the forging billets are canned in mild steel.
3. For the range of forging conditions studied, temperature has a much greater effect on the room temperature yield strength than does the percent reduction in height.
4. A combination of extrusion to 4 to 1 area reduction at 1300°F and upset forging to 40% reduction in height at 1100°F increases the room temperature yield strength of beryllium by 40% to 50%.
5. The room temperature compressive yield strength of hot-pressed beryllium and of hot pressed, extruded, and forged beryllium is 6 to 10% less than the corresponding tensile yield strength.
6. The room temperature ductility of hot-pressed beryllium or hot pressed, extruded, and forged beryllium is from 3.5 to 12.3 times greater in compression than in tension, depending upon the testing direction.

REFERENCES

1. A. F. Hayes, "Production of Forged Beryllium Conical Structural Shapes," Air Force Materials Laboratory, Wright-Patterson AFB, Ohio, AFML-TR-69, 168, p. 163.
2. R. G. O'Rourke and W. W. Beaver, "A Study to Characterize a Fully Forgeable Grade of Fine Grained High Strength Beryllium Powder," Air Force Materials Laboratory, Wright-Patterson AFB, Ohio, AFML-TR-69-61 AFML-54-69-61, November 1969.

3. C. H. Maak, unpublished data, Report of Compression Test Data, Materials Property Test Section 5165, Sandia Corporation, Albuquerque, New Mexico, June 8, 1970.
4. R. G. O'Rourke, "Final Report - High Strength Beryllium," Technical Report 468 for Purchase Order 57094, Brush-Wellman Company, Cleveland, Ohio, October 15, 1971.
5. A. F. Hayes, op. cit., p. 63.
6. R. G. O'Rourke and W. W. Beaver, op. cit., p. 44.
7. R. G. O'Rourke and W. W. Beaver, op. cit., p. 62.
8. J. R. Hauber, private communication, University of California, Lawrence Livermore Laboratory, Livermore, California, October 25, 1971.