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LASER FABRICATION OF BERYLLIUM COMPONENTS

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Working with the beryllium industry on commercial applications and using prototype parts, we have found that the use of lasers provides a high-speed, low-cost method of cutting beryllium metal, beryllium alloys, and beryllium–beryllium oxide composites. In addition, we have developed laser welding processes for commercial structural grades of beryllium that do not need a filler metal; i.e., autogenous welds were made in commercial structural grades of beryllium by using lasers.

1. INTRODUCTION

Beryllium and beryllium alloys have several properties—low atomic number, good neutron reflection capability, low density, high modulus of elasticity, high mechanical damping capacity, and high frequency resonance—that make them ideal for a variety of applications. However, fabrication of this material can be difficult, especially machining and welding operations.

Even when care is used, conventional machining can damage these hard, low-ductility beryllium and beryllium alloys and significantly impair their mechanical performance.[1] The damage is in the form of microstructural changes that take place during the machining operation, and the mechanical properties can be seriously degraded. The microstructural changes are in the form of twinning, microcracks, residual stresses, and crystallographic texture.[1] Twinning and a highly worked surface layer can be seen in Figure 1. Evidence suggests that the loss in mechanical properties are primarily due to a strain-hardened oriented surface layer, and that while twinning is the most apparent microstructural feature, it does not play a dominant role.[1] Microcracks, of course, are harmful, but they can usually be detected by nondestructive test methods, and they are also indicative that the

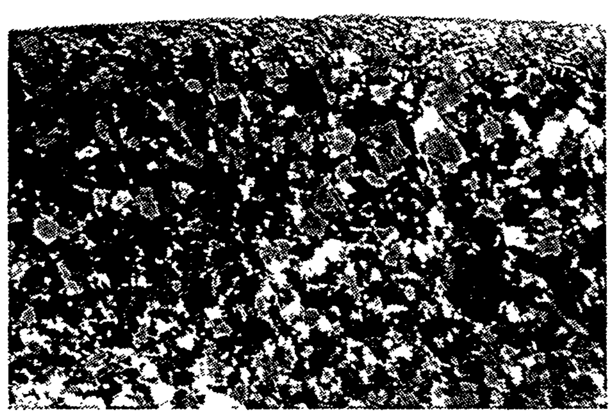

Figure 1. Machining damage in beryllium. Note the distorted grain morphology and twinning extending from the surface to a depth of about 100 μm (200×).

machining operation is out of control and corrective action should be taken. The decrease in mechanical properties is in the ultimate strength and ductility. Typical values are shown in Table 1.[1]

Welding this low-ductility metal and its alloys also presents problems. Conventional welding processes require use of a filler metal, i.e., a different alloy from the metal being welded. For beryllium, the most successful filler metal has been an aluminum–silicon alloy, and this process was developed over thirty years ago. Use of a filler alloy is not desirable for some applications, but autogenous welding—welding without a filler alloy—has been nearly impossible with beryllium.

We have found laser alternatives to the conventional methods of cutting and welding. Working with Brush Wellman, Inc. (BWI), on commercial applications and using prototype parts, we found that the use of lasers provides a high-speed, low-cost method of cutting beryllium metal, beryllium alloys, and beryllium–beryllium oxide composites. In a separate project with Nuclear Metals, Inc. (NMI), and Space Power, Inc. (SPI), we developed laser-welding processes for commercial structural grades of beryllium that do not need a filler metal; i.e., autogenous welds were made in commercial structural grades of beryllium by using lasers.

2. LASER CUTTING

For unique LLNL applications, we succeeded in cutting thin, high-purity beryllium foil using lasers long ago. However, there was no effort to explore cutting other beryllium based materials at that time. With recent new needs and applications, we saw that the use of lasers might provide a solution to some unique problems in fabricating beryllium base materials. We proposed that lasers be used to cut commercial structural grades of beryllium, beryllium alloys, and a beryllium–beryllium oxide composite. The beryllium alloy was AlBeMet 162, a 62% Be–38% Al alloy from BWI, and the beryllium–beryllium oxide composite was also from BWI. Of several lasers at LLNL approved for use with beryllium, we chose two for our initial study: a 400-W pulsed neodymium:yttrium–aluminum–garnet (Nd:YAG) laser and a 1000-W continuous-wave carbon dioxide (CO_2) laser.

Both the pulsed Nd:YAG and the CO_2 laser penetrated beryllium and AlBeMet sheet. Parameters were developed that cut beryllium sheet and the AlBeMet 162 alloy sheet at thicknesses from 0.5 mm to about 2.5 mm. Table 2 shows typical laser parameters for cutting. The 0.5-mm beryllium sheet was cut at speeds up to 40 mm/s, and 2.0-mm-thick sheet was cut at speeds up to 6 mm/s. The 0.5-mm AlBeMet sheet was also cut at speeds up to 40 mm/s, and

Table 1. Tensile properties of machine-damaged beryllium.

Grade	Condition	UTS MPA (ksi)	YS MPA (ksi)	Elongation (%)	Machining damage
S200E	As-machined	263 (38)	216 (31)	0.7	100 μm deep
	Annealed	343 (50)	230 (33)	3.1	None
	Etched	342 (50)	239 (35)	3.3	None
1319	As-machined	282 (41)	277 (40)	0.7	100 μm deep
	Annealed	381 (54)	235 (34)	3.8	None
	Etched	372 (54)	270 (39)	4.0	None

the maximum cutting speed for the AlBeMet 2.0-mm-thick sheet was 4 mm/s.

Both lasers easily produced acceptable surface finishes of the cut edges (Figure 2). A generic prototype part cut from a large, 0.5-mm-thick beryllium sheet is shown in Figure 3. The part's outline and six holes were cut in 18 s. Most of this time was spent on relocating the part for cutting the holes, rather than the cutting itself. On a microscopic scale, the cut edges were acceptable, and the part easily met tolerance requirements. In laser cutting, the beam size determines the minimum radius possible, which is in the range of 25 μm for our equipment. The smallest holes in the part shown have 1.0-mm radii.

Table 2. Typical beryllium cutting development parameters with a 400-W pulsed Nd:YAG laser.

Thickness of sheet mm (in.)	Cutting speed mm/min (in./min)	Power (W)	Power density (W/mm^2)	Pulse rate (Hz)
0.5 (0.020)	1270 (50)	390	6400	100
0.5 (0.020)	1900 (75)	350	5500	200
0.5 (0.020)	2540 (100)	400	5500	150
2.0 (0.080)	250 (10)	410	6700	50
2.0 (0.080)	380 (15)	410	6700	50
6.4 (0.250)[a]	250 (10)	410	6700	50

[a] Full penetration not achieved.

(a) (b)

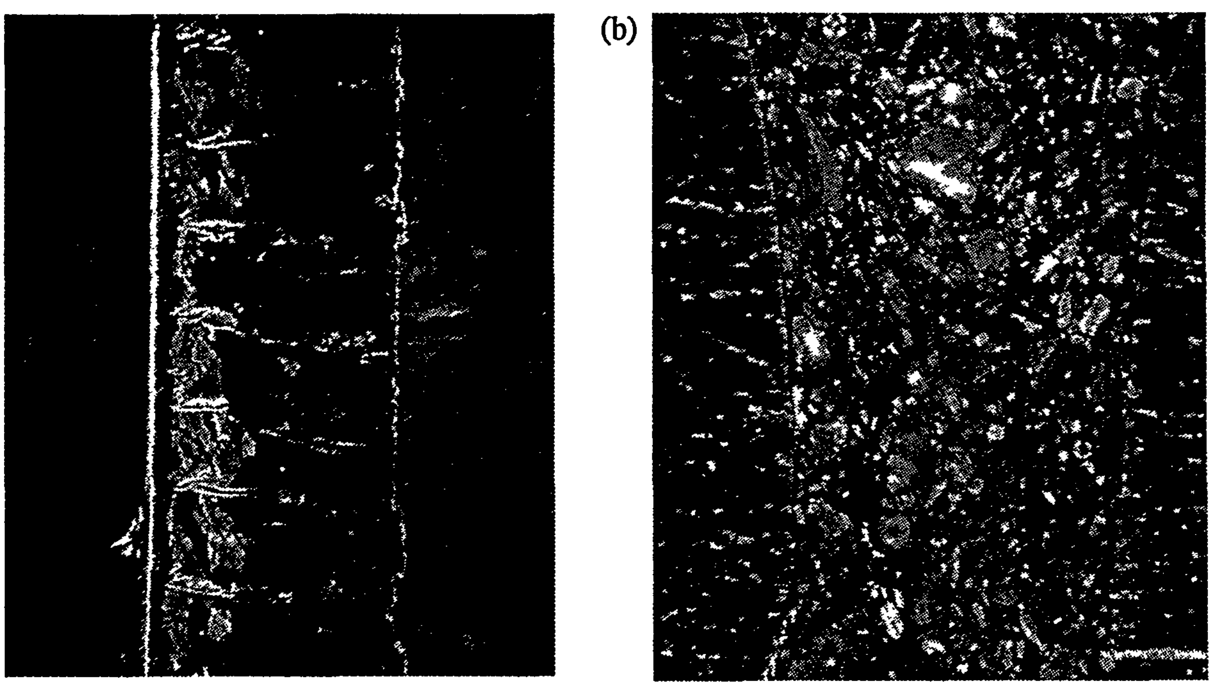

Figure 2. Edge and cross section of pulsed Nd:YAG-laser–cut beryllium sheet. (a) Edge; note evidence of individual laser pulses (60×). (b) Cross section showing grain structure on each side of the laser cut; note absence of machining damage (160×).

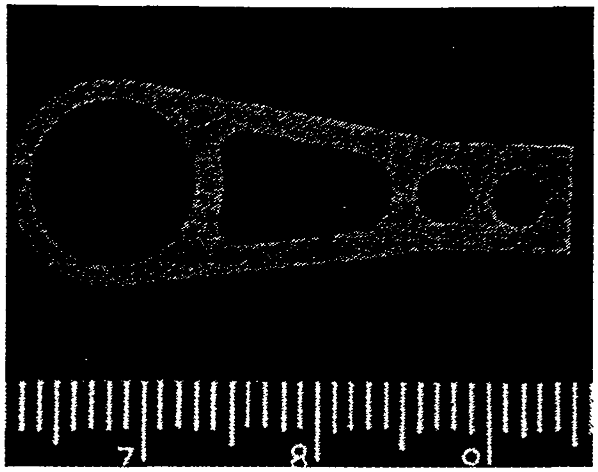

Figure 3. Generic beryllium disk-drive component cut by laser from 0.5-mm sheet in less than 20 seconds. Scale is in centimeters.

The pulsed Nd:YAG laser did not produce acceptable results in cutting the beryllium–beryllium oxide composite, while the CO_2 laser was successful. As expected, the cutting speeds were slower than for the metals, and the maximum speed achieved for the 1.6-mm-thick sheet was 4 mm/s.

There are additional advantages to laser cutting. First, the kerf is small and the parts can be laid out in a very efficient fashion on the sheet. Thus, more parts can be made from a sheet of a given size, and just as important, there is less beryllium waste for disposal. Second, there is no machining damage. This microscopic damage can harm mechanical properties and ordinarily would require additional steps to ensure that it is not a problem. For the laser-cut edges, from microscopic examination, we did not observe any machining damage. We also cut tensile specimens from the same structural beryllium sheet and, without any further treatment after the laser cutting, pulled the tensile specimens to failure. The mechanical properties easily met the mechanical properties expected for powder-origin beryllium sheet, specifically elongation to failure and ultimate strength (Table 3). This confirmed our microscopic observations of no machining damage. Third, for large-scale production, a more powerful laser can be used and the beam split to cut several parts from a sheet at the same time. Fourth, it may be useful to pipe the laser beam into a single designated room for beryllium-cutting operations. This would reduce the possible exposure of personnel to beryllium particulate and reduce the number of formal beryllium workers.

Table 3. Mechanical properties of beryllium sheet.

Condition	**UTS MPA (ksi)**	**YS MPA (ksi)**	**Elongation (%)**	**Orientation in sheet**
As-laser cut	450 (65.5)	270 (39.4)	13.9	Transverse
As-laser cut	510 (74.0)	330 (47.8)	17.4	Longitudinal
As-laser cut	485 (70.5)	355 (51.4)	20.2	45°
BW S200E spec.	480 (70)	345 (50)	10	—

3. AUTOGENOUS LASER WELDING

Autogenous welding of metals (i.e., no filler metal) is usually preferred. It is a simpler process and would result in a more homogenous part across the junction of the two pieces being welded. In addition, operating temperatures may militate against the use of a lower melting point filler metal. However, many metals and alloys do not lend themselves to autogenous welding; which is basically a complicated high-speed casting process.

The low-strength ingot grade of beryllium can be welded in an autogenous manner, and it has been welded with no filler metal for the past thirty-plus years. For specialized applications in which the welding metallurgist had freedom in the details of the weld design, we have autogenously laser welded thin sheets of ingot beryllium and; in one case, autogenously electron beam welded the structural grade of beryllium. However, generally the more useful high strength powder-origin structural beryllium grades have not been amenable to autogenous welding, with severe cracking prevalent.

Several times over the past few years, we have been asked to make or design specialized beryllium parts for satellites. The various parts have been for such applications as detection of signals from deep space or operation of the satellite. The common requirement for these parts was no foreign material; viz., no filler material in the form of a weld or braze alloy. In the past, we have responded by making very thin braze joints, usually with aluminum or an aluminum alloy. Recently, an application came to our attention in which even a thin braze line with a minimum of non-beryllium material was not satisfactory.

Through NMI, we learned that SPI needed beryllium caps joined to beryllium cylinders to encapsulate a nontoxic hydride. The cylinder would eventually be a component in a power source for a satellite, and the beryllium had to be the higher-strength structural grade. The reason for no filler metal in the weld (i.e., autogenous) was due to two requirements. First, a higher atomic weight element than beryllium would harm the performance of the unit. Second, the cylinder operating temperature was above 600°C, which is above the melting temperature of virtually all welding filler alloys for beryllium. Any filler metal would violate one or both of these requirements.

With our experience in autogenously welding beryllium, albeit very limited, we offered to try laser welding the components. We knew this would be difficult because the application was a circumferential weld, which results in substantial residual stress problems, and beryllium is a low-ductility material that is not amenable to residual stresses.

After considerable experimentation on the exact weld design and laser parameters, we were successful in autogenously welding the cap on the 25-mm-diam cylindrical component. We preferred the pulsed Nd:YAG laser; however, the CO_2 continuous-wave laser is promising. Table 4 shows typical laser parameters for welding. The typical appearance of the laser weld

Table 4. Typical beryllium welding development parameters with a 400-W pulsed Nd:YAG laser.

Thickness of sheet mm (in.)	Cutting speed mm/min (in./min)	Power (W)	Power density (W/mm^2)	Pulse rate (Hz)	Comments
0.35 (0.014)	200 (8)	210	260	10	Good weld
0.30 (0.012)	200 (8)	170	210	10	Poor weld
0.30 (0.012)	200 (8)	135	165	10	Poor weld
0.25 (0.010)	200 (8)	95	115	10	Poor weld

fusion zone is shown in Figure 4. The approach is, in a sense, the opposite of the laser cutting. For the welding, a small amount of energy, gently applied, is necessary to avoid high residual stresses, especially at the weld start and stop. Laser welding does have the advantage that, compared to electron beam welding, the depth of the weld can be more precisely controlled. The individual ridges on the fusion zone reflect the individual laser pulses. There is some columnar epitaxial grain growth in the fusion zone (Figure 4). This is not desired, and we believe we can improve upon the microstructure with refinement of the welding parameters and slightly modifying the weld design.

The sealed cylinder containing the hydride was delivered to SPI, and they reported that the cylinder provided excellent results and there was no leaking above 600°C. This is the first successful application of autogenous laser welding of structural grades of beryllium.

4. SUMMARY

Lasers can be used to cut components to size from beryllium sheet, beryllium alloy sheet, and beryllium–beryllium oxide composite sheet. The cutting can be done at high speeds with tight tolerances and small radii without introducing machining damage. The small size of the laser beam and the use of CNC machines result in high material efficiencies. Lasers can be used to autogenously weld commercial structural grades of beryllium.

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(a) (b)

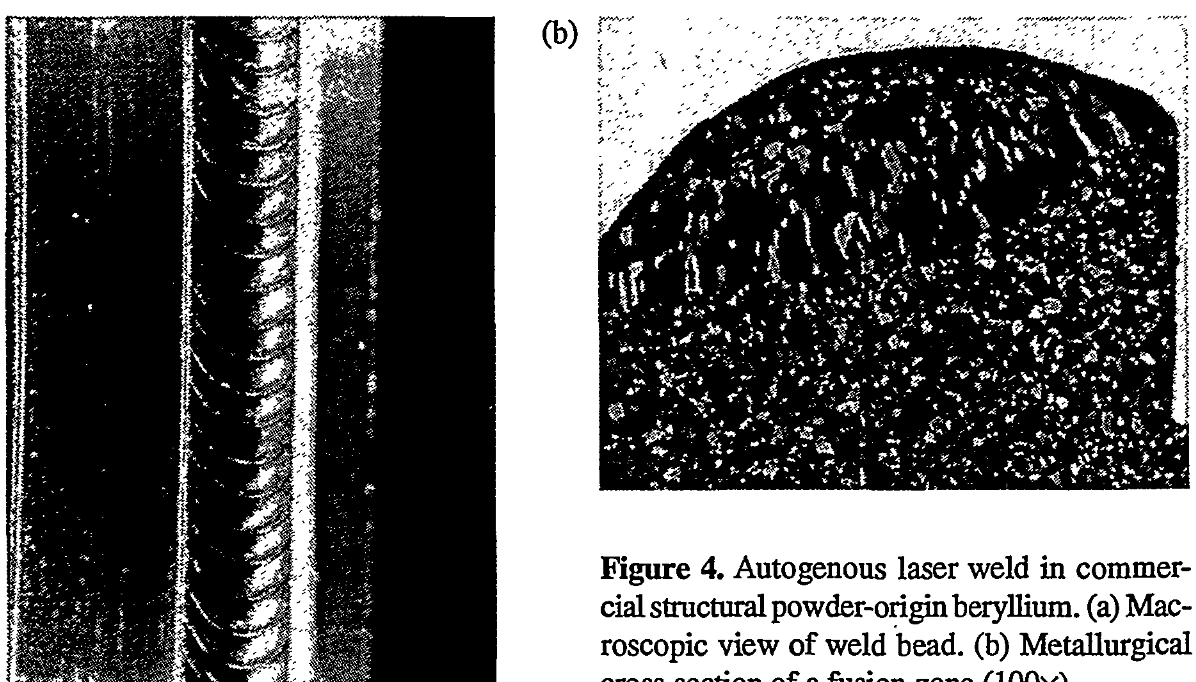

Figure 4. Autogenous laser weld in commercial structural powder-origin beryllium. (a) Macroscopic view of weld bead. (b) Metallurgical cross section of a fusion zone (100×).