Femtosecond Laser Manufacturing Experiments

Federal Manufacturing & Technologies

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Contents

Section

Abstract

Summary

Discussion

Scope and Purpose

Activity

Burst Disc Scribe Lines

Burst Disc Pressure Study

PZT Ceramic Cutting

Accomplishments

Future Work

Reference

Bibliography

Illustrations

Figure

- 1 Femtosecond Laser Pulse Is Shorter Than Material Lattice Dimensions.
- 2 Typical Laser Pulse for Conventional Lasers
- 3 Cross Sections Show No Change in Grain Structure in Side Walls of Hole. (LLNL photo)
- 4 Holes Drilled in Stainless Steel Using Femtosecond Lasers Show No Distortion of Remaining Material. (LLNL photo)
- 5 Entrance and Exit Surfaces Are Equally Unaffected by Femtosecond Laser Pulses.
- 6 Geometry of Sample A
- 7 SEM Photo of Femtosecond Laser Grooves in Stainless Steel
- 8a Topology of Line A at Low Magnification
- 8b Topology of Line A at 1000x Magnification
- 8c Topology of Line A at 3000x Magnification
- 8d EDS Spectrum of Line A
- 9a Penetration of the Laser Completely Through the Burst Disc Material
- 9b Topology of Line B at Low Magnification
- 9c Topology of Line B at High Magnification
- 9d EDS Spectrum of Line B
- 10a Cross Section Through Line A (Unetched)
- 10b Cross Section Through Line A (Etched)

- 11a Cross Section Through Line B (Unetched)
- 11b Cross Section Through Line B (Etched)
- 11c High Magnification View of the Right Side of Line B
- 11d High Magnification View of Left Side of Line B.
- 12 Measurement Locations for Sample B
- 13 Power x Time Vs Groove Depth
- 14 Power Vs Groove Width
- 15 Burst Pressure Vs Groove Depth

Tables

Number

- 1 Test Conditions for Sample B
- 2 Groove Dimensions From Sample #2 Tests
- 3 Average and Standard Deviation of Sample #2 Grooves (from Table 2 Data)
- 4 Burst Pressure Study Results
- 5 Repeatability of Groove After 40 Passes
- 6 Results of Traversing the Beam Only 36 Times

Abstract

The femtosecond laser utilizes an unusually short laser pulse that results in little, if any, metallurgical damage in stainless steel and other materials. Studies of the process demonstrated high quality wall contours (metallurgically "clean") when the laser was used to cut grooves in stainless steel discs. This study did prove the feasibility of the process as an alternate potential for the existing process for making burst discs. Significant additional work is required to increase groove reproducibility and produce three-dimensional cuts, requiring development of appropriate tooling and controllers.

Summary

The femtosecond laser was shown to produce exceptionally high quality metallography and to provide the kind of action necessary to produce burst disc scores. Brief tests provided some measure of laser depth repeatability and burst pressures. While the tests were on flat discs, and not quite representative of

a production need, the results indicate that further work could lead to a manufacturable process.

The high quality of edges produced clearly has many production applications beyond the application studied. Additional work would be required to provide laser controls and tooling for manufacturing, but such work is not difficult to do.

Despite the success of this project, the project was closed a year early due to other priorities and lack of funds and key personnel to carry on the work.

Discussion

Scope and Purpose

This project explored the ability of a femtosecond laser to cut stainless steel and ceramic parts to specific sizes, shapes, and tolerances. The project was to provide early capability data at a minimum of effort to determine if broader effort was justified.

Activity

In 1997 Los Alamos National Laboratory (LANL) engineers requested that Honeywell develop a backup process for fabricating burst discs. The process in use worked, but there was a concern that the existing product might change over time, the vendor might lose interest or ability in producing the part, and some unknown issue might turn up later that would cause a need for other processes.

Several potential approaches were considered. When news of the Lawrence Livermore National Laboratory (LLNL) femtosecond laser surfaced, it appeared to be the type of process that might meet all the requirements of this product. Because there was no data on actual manufacturing abilities, a process development project was initiated to provide some preliminary information about this laser as a manufacturing tool.

Liu and Mourou¹ describe some characteristics and operation of an ultra-short laser pulse machine. In essence the concept behind this laser is that the wavelength is shorter than the lattice dimensions of a material and as such it can cut without visible distortion (see Figures 1 and 2). Stated differently, the pulse duration is so short that it does not couple energy to deform the metal lattice. It is shorter than the lattice vibration. Absorption of these ultra-short laser pulses occurs on such a short time scale that the material is ablated with virtually no heat transfer to the surrounding material, resulting in a "cold" laser cut. In contrast, laser cutting techniques that use laser pulses longer than 10 ps first melt, then vaporize, the material with significant heat transfer to material outside the cutting region.

Figures 3, 4, and 5 are examples of some early LLNL work that shows the lack of metallurgical damage when small holes were drilled with this device. The lack of surface damage is critical to some applications and this ability makes the femto laser stand out as a viable future manufacturing tool. More than just viable, the results shown in Figures 3-5 represent an exciting advance in laser cutting.

The name "femto" refers to the laser pulse width – i.e., 10^{-15} seconds (one quadrillionth of a second). The LANL laser on which this work was done has a pulse length of 125 fs, a wavelength of $0.825\text{ }\mu\text{m}$, a 1-kHz pulse rate, and 5 mJ/pulse.

Figure 1. Femtosecond Laser Pulse Is Shorter Than Material Lattice Dimensions

Figure 2. Typical Laser Pulse for Conventional Lasers

- 750 μm SS304 at 45° angle of incidence
- 8 J/cm² (150 μm spot at 1.0 W).

Cross section

Entrance surface

Exit surface

- The grain structure at the surface is preserved to the edge of the hole.

In addition to the need for work on stainless steel, a need also existed to enhance the cutting of ceramic parts for piezoelectric motors. Some preliminary work involved drilling 0.006-inch diameter holes in stainless steel. This project explored both capabilities in a very abbreviated manner in order to capture some essence of process ability.

The femtosecond laser at the time of the work being performed was the only laser of its kind in the Department of Energy (DOE) complex. It was built to assess its performance as a laser. It was an experimental laser, not designed for production work, and one of the team members had to procure means to move the part under the laser beam. The system had no tooling, and was a research instrument, not a production tool. Early work was focused on simple ways to move the part under the beam.

The laser had a power capability of 5 megajoules (33 terawatts) per pulse. It had a wavelength of 800 nm and pulse width of 150 fs.

LLNL, the owner of the laser, was interested in knowing more of its abilities and gaining additional supporters for its efforts with this device, so a natural teaming occurred. The work occurred with the support of LANL's High Explosives Applications Facility (HEAF) staff, who were very helpful in providing time and knowledge in conducting Federal Manufacturing & Technologies (FM&T) studies and understanding the laser operation.

Burst Disc Scribe Lines

The burst disc of interest is a 316L stainless steel disc, 0.007 inch in thickness and, for these tests, 1.0 inch in diameter. For these studies the parts were flat and were blanked out with a die. The samples were taken from special stock used for burst discs.

Sample A

For the first sample parallel lines identified as #1 and #2 were cut on the disc (Figure 6). The intent is to cut a channel in the disc about 0.003 inch deep, but not break through. The laser was set to a power of 0.3 W, and the motor stage was set to move the lens at 1 mm/sec. Cut #1 was run for 3 minutes, 30 seconds, and light could be seen through the cut at both ends. This was a deeper cut than desired. It was 230 microns wide by 120 microns deep.

Cut # 2 was performed with the lens moved away from the chamber and the time of cut was 2 minutes and 20 seconds. No light could be seen through the groove. This groove was 380 microns wide by 70 microns deep.

These two laser scribed lines were analyzed with scanning electron microscopy (SEM), energy dispersive X-ray analysis (EDS), and metallography.

Figure 6. Geometry of Sample A

In Figure 7, a SEM image is shown of the disc with the two lines scribed by the laser. Line A was formed with the lower power setting of the laser. The length of this line is 0.0272 inch while the width is 0.0112 inch. In the case of line B, the length is 0.270 inch while the width is 0.0079 inch.

In Figure 8a, a SEM image is shown of line A. This image displays the surface topology in this area. This topology can be seen at higher magnifications in the SEM images in Figures 8b and 8c. In Figure 8d, the EDS spectrum of line A is displayed. Only the components of the stainless steel were found.

In Figure 9a, a SEM image of line B is shown. This line was formed at the higher power setting on the laser. The hole observed is at one end of the line. At this point, a reciprocating table that held the disc changed directions. The laser beam spent more time at this point because of the change in direction resulting in the hole. In Figures 9b and 9c, SEM images are shown to display the surface topology in line B. The image in Figure 9c is comparable to the image of line A in Figure 8c. The topologies are quite different, with line B exhibiting much finer surface features. In Figure 9d, the EDS spectrum of line B is displayed. Only the components of the stainless were found.

Figure 7. SEM Photo of Femtosecond Laser Grooves in Stainless Steel

These lines were cross-sectioned transversely to determine the profiles from laser scoring. In Figure 10a, an image of the cross section through line A is shown. This line has a very shallow profile. This same image is shown in Figure 10b, but the stainless steel has been etched to bring out the grain structure. The penetration of the line into the stainless steel is 0.0011 inch.

In Figure 11a, an image is shown of the cross section through line B. The profile is quite different from that of line A. In Figure 11b, the same image is displayed but the stainless steel has been etched to bring out the grain structure. Higher magnification views of this profile are shown in Figures 11c and 11d. Each side of the profile was examined for a heat-affect zone. No heat-affected zone was found at this magnification.

Figure 8a. Topology of Line A at Low Magnification

Figure 8b. Topology of Line A at 1000x Magnification

Figure 8c. Topology of Line A at 3000x Magnification

Figure 8d. EDS Spectrum of Line A

Figure 9a. Penetration of the Laser Completely Through the Burst Disc Material

Figure 9b. Topology of Line B at Low Magnification

Figure 9c. Topology of Line B at High Magnification

Figure 9d. EDS Spectrum of Line B

Figure 10a. Cross Section Through Line A (Unetched)

Figure 10b. Cross Section Through Line A (Etched)

Figure 11a. Cross Section Through Line B (Unetched)

Figure 11b. Cross Section Through Line B (Etched)

Figure 11c. High Magnification View of the Right Side of Line B

Figure 11d. High Magnification View of Left Side of Line B

In summary, the metallography of this cut is similar to the photos shown earlier and in line with that needed for burst disc applications. Groove dimensions are not consistent with need, but this was a first attempt to cut grooves.

Sample B

The second sample was scribed with four lines. The lens was moved horizontally +/- 6 mm at a rate of 1 mm/sec. The settings used were as shown in Table 1.

Table 1. Test Conditions for Sample B

Line #	Power (Watts)	Beam on Time (Seconds)
1	0.25	60
2	0.25	30
3	0.125	30
4	0.125	60

The resulting groove dimensions are shown in Table 2. Figure 12 illustrates the location of measurements for Sample #2.

Table 2. Groove Dimensions from Sample #2 Tests

Measurement Location	Depth Micron (Inch)	Width (Inch)
LE1	9.7 (0.00038)	460 (0.0181)
LE2	5.0 (0.00020)	320 (0.0126)
LE3	3.7 (0.00015)	332 (0.0131)
LE4	9.2 (0.00036)	388 (0.0153)
A1	10.3 (0.00043)	484 (0.0191)
A2	9.9 (0.00039)	432 (0.0170)
A3	5.8 (0.00023)	484 (0.0191)
A4	7.2 (0.0028)	376 (0.0148)
B1	9.2 (0.00037)	368 (0.0147)
B2	8.6 (0.00034)	448 (0.0179)
B3	6.9 (0.00028)	328 (0.0131)
B4	9.4 (0.00038)	356 (0.0142)
RE1	8.7 (0.00034)	400 (0.0157)
RE2	8.6 (0.00034)	496 (0.0195)
RE3	6.8 (0.00027)	404 (0.0159)
RE4	6.8 (0.00027)	388 (0.0153)
C1	12.1 (0.00048)	440 (0.0176)
C2	7.4 (0.00030)	436 (0.0174)
C3	3.9 (0.00016)	368 (0.0147)
C4	8.6 (0.00034)	360 (0.0144)

Figure 12. Measurement Locations for Sample B

Table 3. Average and Standard Deviation of Sample #2 Grooves (from Table 2 data)

Groove Number	Depth {micron} (inch)		Width {micron} (inch)	
	Avg.	Std Dev	Avg.	Std Dev
1	9.6 (0.00038)	0.66 (0.00003)	428 (0.0171)	53 (0.0021)
2	8.0 (0.00032)	2.1 (0.00008)	424 (0.0170)	74 (0.0030)
3	5.8 (0.00023)	1.5 (0.00006)	387 (0.0155)	74 (0.0030)
4	8.2 (0.00033)	1.3 (0.00005)	377 (0.0151)	15 (0.0006)

As seen from these measurements and from Figures 13 and 14, the groove depth is linearly related to the product of power and time (energy), and groove width is directly proportional to power. Groove repeatability is not as consistent as deemed necessary for production, but this data is from early evaluations.

Figure 13. Power x Time Vs Groove Depth

Figure 14. Power Vs Groove Width

Burst Disc Pressure Study

Several discs were scored with the femtolaser, with one straight scribe line (score) each. The sample material was the same 0.007-inch thick sheet used to produce production burst discs. Table 4 presents the inspection data taken from a Tencor Profiler. These discs were then burst in a setup simulating normal burst disc operation using FM&T LTR 3576. Sample #21 was tested twice. In the first instance a supply of 1040 to 1500 psig gas was used, but it did not burst at that low a pressure. The pressure supply was increased to 2050 and it burst. The burst pressures and time are indicated in Table 4. Two measurements of groove depth are recorded for sample #20. We cannot at this time determine which is

correct, but they were recorded within five minutes of each other in November 1998.

Table 4. Burst Pressure Study Results

Serial Number	Groove Width (μm)	Groove Length (mm)	Groove Depth (μm)	Burst Pressure (psig)	Time to Burst (sec)	Supply Pressure (psig)
17	285.5	15.773	70.56	822	127	2100
18	208.1	15.773	66.84	871	133	2050
19	210.1	15.770	71.62	812	125	2050
20*	214.1	15.804	68.36	944	144	2050
21	202.1	15.802	72.59	1135	173	2050
22	207.1	15.810	62.49	1041	156	2050
23	217.1	15.754	65.47	1162	172	2050

*Sample #20 had a second depth measurement of 74.25

As shown in Figure 15, burst pressure was roughly proportional to remaining material below the groove. With additional study by making a groove slightly deeper at the center of the part, a more consistent burst pressure probably could be achieved.

Table 5 illustrates the results of another study on the flat disc. The disc was cut with a 220-micron diameter beam at 0.15 watts, with a velocity of 5 micron/second. The beam was moved back and forth over the cut 40 times under a vacuum of 14 mtorr. The third column illustrates the difference in value of the depth from the average of the entire run.

When the beam was traversed only 36 times under the same vacuum level, the values in Table 6 were obtained.

Figure 15. Burst Pressure Vs Groove Depth

Table 5. Repeatability of Groove After 40 Passes

ID Number	Depth (μ m)	Delta Average Depth	Depth (inch)	Width (μ m)	Width (inch)
17-1	69	0.22	2.72	230	9.06
17-2	73	4.22	2.87	230	9.06
18-1	66.5	-2.28	2.62	220	8.66
18-2	69	0.22	2.72	225	8.86
19-1	70	1.22	2.76	235	9.25
19-2	71	2.22	2.80	225	9.86
20-1	64	-4.78	2.52	220	8.66
20-2	67	-1.78	2.64	220	8.66
21-1	67.5	-1.28	2.66	225	8.86
21-2	70.8	2.02	2.79	225	8.86
Average	68.78				

Table 6. Results of Traversing the Beam Only 36 Times

ID Number	Depth (μ m)	Delta Average Depth	Depth (Inch)	Width (μ m)	Width (Inch)
22	58.7	-2.4	2.31	225	8.86
23	63.5	2.4	2.50	220	8.66
Average	61.1				

As seen in Table 6, a 10% reduction in traverse passes reduced depth by 11%, implying an almost linear rate of removal per pass.

PZT Ceramic Cutting

Some brief experiments were made of cutting of PZT ceramic for piezomotor applications. There was little of the edge quality benefit found on the stainless steel samples. Further testing was discontinued.

Accomplishments

This project demonstrated that the femtosecond laser produces grooves with little visible metallography damage. The general shape of the grooves produced is similar to that produced by pressworking operations and thus is a desirable shape. The necessary depth was not produced in the few samples studied, but the femtolaser appears to be one of the few processes available that might, with more development, reproduce the desired properties of commercial burst discs.

Future Work

Despite the relative success of this development, further work is not planned due to funding limitations and other priorities. Future studies are appropriate for reproducibility from part to part, obtaining deeper grooves, and providing more reproducible burst results.

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