Evaluation of Waterjet-Machined Metal Matrix Composite Tensile Specimens

**C. A. Lavender
M. T. Smith**

April 1986

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ABSTRACT

The Pacific Northwest Laboratory, in support of the Close Combat Armaments Center of the U.S. Army Armament Research and Development Center/Production Base Modernization (ARDEC/PBM), evaluated four magnesium/boron carbide metal matrix composite (MMC) tensile specimens that were fabricated using the waterjet machining method. The objective of the evaluation was to determine the effects of the waterjet material removal process on the composite material surface structure and properties. These results were then compared with data generated from material that had been conventionally machined (using polycrystalline diamond tooling) and that exhibited the same matrix and reinforcement.

Results of the tests showed that while waterjet cutting produces a rough surface finish and does not meet specified dimensional tolerances, the technique appears to be suitable for sectioning and rough machining of metal matrix composites.

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INTRODUCTION

The Pacific Northwest Laboratory (PNL),^(a) in support of the Close Combat Armaments Center, U.S. Army Armament Research and Development Center/Production Base Modernization (ARDEC/PBM), evaluated four magnesium/boron carbide (B_4C) metal matrix composite (MMC) tensile specimens that were fabricated using the waterjet machining method. The objective of the evaluation was to determine the effects of the waterjet material removal process on the composite material surface structure and properties. These results were then compared with data generated from material that had been conventionally machined (using polycrystalline diamond tooling) and that exhibited the same matrix and reinforcement.

The characterization of the waterjet-machined specimens comprised four phases: 1) dimensional inspection, 2) analysis of mechanical properties effects, 3) surface characterization, and 4) analysis of microstructural damage. Dimensional inspection was performed using an optical comparator and a Talysurf-4 surface finish measuring system. Mechanical property effects were determined by comparison of conventional/(polycrystalline diamond) machining to waterjet machining using a standard tensile test procedure. Surface roughness was characterized using optical and scanning electron microscopes. Metallographic specimens were used to examine surface profiles and microstructural damage. Microhardness values also were used to determine microstructural damage.

(a) Operated for the U.S. Department of Energy (DOE) by Battelle Memorial Institute.

SPECIMEN EVALUATION

Material for the waterjet machining effort was supplied in the form of 1.50-in.-diameter extruded rod. Representative of current magnesium MMC materials, the extrusion consisted of a ZK60A matrix reinforced with nominally 15 vol.% B_4C particulate. To provide a basis for comparison of mechanical properties, a modified 0.250-in.-diameter tensile specimen was selected to demonstrate the machining process. The configuration of the specimen is shown in Figure 1, along with specimen dimensions and tolerances.

Evaluation of the waterjet-machined tensile specimens was performed in the following sequence: dimensional inspection (including surface profile measurements), mechanical testing, and destructive analysis of the surface and microstructure.

- 1 Reduced section to have gradual 1.0% taper toward center. Not to exceed 1.2%.
- 2 Centers required both ends.

	Specimen Dimensions	
	in.	mm
Nominal diameter	0.250	6.35
G - Gage length	1.000 ± 0.005	25.4 ± 0.13
D - Diameter (Note 1)	0.250 ± 0.005	6.35 ± 0.13
R - Radius of fillet, min	3/16	5
A - Length of reduced section, min	1-1/4	32
L - Length of specimen	4.10	104
B - Grip diameter	0.375 ± 0.001	9.52 ± 0.025
E - Grip length	1.10 ± 0.05	27.9 ± 1.3
d - Button head diameter	0.250 ± 0.005	6.35 ± 0.13

FIGURE 1. Tensile Specimen Configuration

RESULTS AND DISCUSSION

Each of the four waterjet-machined tensile specimens was visually inspected to characterize surface finish and dimensional features. The most noticeable feature of the specimens, as-received, was the pronounced "orange peel" surface texture produced by the waterjet machining process. Another feature noted during initial specimen inspection was the lack of sharp radii (specified 0.010 in. R) on the collet grip-to-button head diameter transitions. Because surface roughness is known to degrade the tensile properties of brittle materials, the specimen evaluation work emphasized dimensional accuracy and uniformity and surface characterization rather than mechanical properties.

DIMENSIONAL INSPECTION

Each of the four waterjet-machined tensile specimens was inspected for dimensional conformity with the specimen drawing according to the inspection layout shown in Figure 2. Designated inspection points included fifteen diameter measurements, a measurement of the length of the collet grip areas (dimensions 16 and 17), and four radius measurements (A,B,C,D) using an optical comparator. The results of these measurements have been tabulated and are listed by specimen numbers (FL-1, FL-2, FL-3, and FL-4) in Appendix A of this report.

These results indicate that the specimens do not meet a number of the nominal and/or tolerance dimensions specified in the design drawing. In particular, the gage sections of the specimens do not show the required 1.0% to 1.2% taper to the center and are instead generally larger in diameter at the center of the gage section than at one or both of the ends. All specimens inspected showed some degree of radius undercut at the gage section ends; the specimen button ends, which should have a maximum 0.010 in. radius, were measured at between 0.040 and 0.050 in. It should also be noted that the specimens received for evaluation did not have specimen centers as required on the design drawing.

The surface finish of two waterjet-machined specimens (FL-1 and FL-4) was inspected using a Talysurf-4 measuring system, and the results were compared

FIGURE 2. Inspection Points for Waterjet-Machined Specimens

with surface profiles for diamond-machined tensile specimens. Even though the conventionally machined specimens were fabricated from Mg/SiC material, optical comparison of diamond-machined Mg/B₄C and Mg/SiC surfaces has shown them to have equivalent surface finishes. Profile traces for the waterjet-machined (FL-4), diamond-machined, and diamond-polished specimens appear in Figure 3. Although the results of the inspections should be used only comparatively, they show that the average peak-to-peak dimensional variation for the waterjet-machined specimens is an order of magnitude greater than for the diamond-machined specimen. Specifically, for the diamond-machined and -polished specimens, the difference between the maximum and minimum surface dimensions was calculated at 0.010-in. longitudinal increments and averaged over a representative 0.100-in. specimen length. The surface deviation for the waterjet-machined specimen was calculated for the same 0.010-in. intervals, but was averaged instead over a 0.200-in. specimen length. The diamond-polished specimen was found to have an average surface deviation of 24.1 μ in.; the diamond-machined specimen had an average value of 65.2 μ in. In contrast, the waterjet-machined specimen had an average deviation of 455 μ in.

MECHANICAL TESTING

Following dimensional inspection, the four specimens were tested to failure using standard tensile test procedures. Because of the rough surface finish of the specimens, the results of the tensile tests cannot be considered fully valid (see ASTM E 8^(a)); in addition, two of the four specimens fractured at the gage section radius, which also constitutes an invalid test. Table 1 lists the tensile test results for the waterjet-machined specimens. Specimens FL-2 and FL-3 failed at or near the center of the gage section and displayed tensile fracture surfaces consistent with conventionally machined Mg/B₄C specimens. Microscopic examination of the fracture surfaces of specimens FL-2 and FL-3 showed internal fracture initiation sites associated with either a large B₄C reinforcement particle or a particle agglomeration. It would appear,

(a) American Society for Testing and Materials. 1984. Annual Book of ASTM Standards, Vol. 03.01. Philadelphia, Pennsylvania, pp. 130-150.

FIGURE 3. Surface Profiles for (a) Diamond-Polished, (b) Diamond-Machined, and (c) Waterjet-Machined Magnesium MMC Tensile Specimens

TABLE 1. Tensile Properties for Waterjet-Machined Magnesium/B₄C Material. Specimens in the -F condition.

<u>Specimen ID</u>	<u>0.2% Yield, ksi</u>	<u>UTS, ksi</u>	<u>Elastic Modulus, msi</u>	<u>Failure Strain, %</u>
FL-1(a)	52.5	57.7	10.9	0.9
FL-2	51.1	55.9	11.0	0.8
FL-3	50.5	58.3	11.0	1.1
FL-4(a)	<u>51.3</u>	<u>58.9</u>	<u>11.1</u>	<u>1.1</u>
Average(b)	50.8	57.1	11.0	0.9

(a) Specimen fractured in outer radius, test not valid.

(b) Average of two tests only (FL-2 and FL-3).

therefore, that internal defects of this type have a stronger influence on fracture initiation than does the relatively rough surface condition created by the waterjet cutting process.

A direct comparison with conventionally machined specimens was not possible due to differences in heat treatment (-F for the waterjet-machined specimens, compared with -T5 for conventionally machined specimens); however, the results for the waterjet-machined specimens fall within the range of data obtained for diamond-machined specimens. This indicates that, on a qualitative basis, the waterjet machining process does not appear to have a detrimental effect on basic mechanical properties of the composite.

MACHINED SURFACE CHARACTERIZATION

The surfaces machined using the waterjet lathe were characterized using several techniques. The surface was examined by using a scanning electron microscope (SEM), metallographical cross-sections (for profiles), and optical microscopes (to examine surface roughness).

The micrograph in Figure 4 shows the typical surface morphology achieved with waterjet machining. This surface is typical of the entire specimen. The true direction of machining (rotation) is not known; in this micrograph it is

FIGURE 4. Typical Surface Morphology of the Waterjet-Machined MMC, 40X

either right to left or left to right. The structure is a series of small, raised areas. A single raised area is typically 100 μm wide and 375 μm long. These sizes are greater than those of the individual ceramic particles and would most likely be related to the waterjet cutting and not to the material. The depth of a typical "valley" is approximately 100 μm , which is unacceptable for a final surface finish in a notch-sensitive material. This is illustrated in Figures 5 and 6.

Figure 5 is a low-magnification micrograph of the gage section of the specimen. The top of the figure is the fracture surface; the specimen was pulled to failure before examination. Even at low magnification, the rippled surface can be seen. Figure 6 is a 100X micrograph of the left side of the gage section shown in Figure 5. The rippled appearance of the surface is the cross-section of the raised areas as stated in the discussion of Figure 4. This photo more clearly shows that the raised areas cannot be attributed to individual particles; however, it does illustrate that particles appear to be protruding from the surface.

FIGURE 5. Cross-Sectional View of the Gage Section of the Waterjet-Machined Tensile Specimen, 6.5X

Figure 7 is a 250X magnification of the area shown in Figure 6. The higher magnification of Figure 7 displays the protrusion of the particles from the surface in great detail. This protrusion is a result of preferential erosion of the magnesium with no deformation of the ceramic particle.

Figure 8 is a 500X magnification of the center of Figure 7. At this magnification the erosion of the magnesium can be seen in greater detail.

The cutting performance of diamond-tool machining and waterjet machining can be compared by examining Figure 7 and Figure 9. The surface of the latter is typical of that achieved with diamond tools. The waterjet-machined surface

FIGURE 6. Left Edge of Figure 5, Illustrating the Surface Morphology Achieved with Waterjet Machining, 100X

FIGURE 7. Increased Magnification of the Area in Figure 6, Illustrating the Particle Protrusion Observed with Waterjet Machining, 250X

FIGURE 8. Waterjet-Machined Surface Profile, 500X

FIGURE 9. Typical Diamond-Machined Surface Profile, 250X

contains protruding ceramic particles; the diamond-tool surface does not. It appears that the diamond tool may actually be cutting the particles, whereas the waterjet is eroding the magnesium. The tendency for particles to be knocked out of the surface can be more clearly seen in Figures 10 through 12.

Figure 10 is a SEM image of the machined surface at the sharp corner of the specimen. This micrograph again shows the wavy, raised-ridge appearance of the surface as well as the bluntness of the corner. There also appear to be dimples scattered on the surface, which are more clearly distinguished in the following micrograph, Figure 11, a SEM image of the surface near a radius.

The dimple size is approximately 10 μm , slightly smaller than the ceramic particle size; however, this would be expected if the dimples were actually the result of particles being pulled from the surface. Figure 12 is a 1000X magnification of the surface shown in Figure 11. The left hand side of the figure shows the dimpled surfaces to be angular--the same morphology as the particles. This confirms that particles are being torn from the surface rather than cut.

FIGURE 10. SEM Image of the Waterjet-Machined Surface, 100X

FIGURE 11. SEM Image of the Waterjet-Machined Surface Near the Radius, 100X. Dimpling of the surface is readily apparent.

FIGURE 12. SEM Image of the Waterjet-Machined Surface, 1000X

The right hand side of Figure 12 also shows angular particles protruding from the surface, similar to the particles that can be seen in Figures 5 through 7.

The surface and metallographic analyses revealed two important features of the waterjet machining: 1) the waterjet is not performing a smooth, uninterrupted cut and 2) the waterjet is not cutting the ceramic particles but is eroding the magnesium matrix. Thus, the waterjet is preferentially cutting some areas while other areas are not being cut. Closer examination of profiles (Figure 8) shows that the particles are not always at the peak of a "ridge" on the cut surface, leading to the conclusion that the ridges cannot be completely attributed to the protrusion of particles. This observation helps to identify the mechanism of waterjet cutting: magnesium erosion and particle "blow-out."

MICROSTRUCTURAL MACHINING DAMAGE

Due to the nature of the MMC, it is impossible to show an etched microstructure; therefore, the microstructural damage is difficult to characterize. Microhardness measurements were made from the outside surface to near the center of the specimen. The results are given here as Figure 13. The hardness does not significantly vary from the outside surface to the inside surface; it can therefore be assumed that no microstructural damage resulted from the waterjet machining. Surface redistribution of particles due to machining has been seen when carbide cutters were used on the Mg/B₄C. This was not evident with the waterjet machining and it can thus be concluded that waterjet machining is not detrimental to the microstructure of this MMC.

FIGURE 13. Microhardness Results Through the Thickness for Waterjet-Machined and Diamond-Tool-Machined Tensile Specimens

Figure 1: Effect of temperature on the rate of reaction for two different concentrations of a reactant.

CONCLUSIONS

The following conclusions were derived from the results of this waterjet machining study.

- The waterjet-machined tensile specimens do not meet design drawing specifications for dimensional tolerances and surface finish.
- Surface profile measurements of the waterjet-machined specimens indicate that surface roughness is approximately an order of magnitude greater than for diamond-machined surfaces.
- The waterjet does not perform a smooth, uninterrupted cut, but instead creates a "raised-ridge" surface texture.
- The waterjet does not cut the ceramic particle but erodes the magnesium matrix.
- The waterjet does not appear to cause any microstructural damage to the material near the surface.
- The waterjet does not work harden the surface, as evidenced by the microhardness values.
- Despite the dimensional and surface finish limitations displayed by the tensile specimens, the waterjet machining process would appear to be suitable for sectioning and rough machining of metal matrix composite materials.

APPENDIX A

SPECIMEN DIMENSIONAL CONFORMITY RESULTS

TABLE A.1. Waterjet Machining Specimen Inspection, FL-1

Date: 5 Mar 86

Measurement

Equipment: Knife Edge Micrometer

Material: Phase II Mg/B₄C (15 vol.%)

<u>Measurement Number</u>	<u>Dimension and Tolerance</u>	<u>Measured</u>	<u>Within Specification (Yes/No)</u>
1	d 0.250 ±0.005	0.232	N
2	d 0.250 ±0.005	0.232	N
3	d 0.250 ±0.005	0.250	Y
4	d 0.250 ±0.005	0.248	Y
5	B 0.375 ±0.001	0.363	N
6	B 0.375 ±0.001	0.372	N
7	B 0.375 ±0.001	0.373	N
8	B 0.375 ±0.001	0.371	N
9	B 0.375 ±0.001	0.372	N
10	B 0.375 ±0.001	0.368	N
11	D 0.250 ±0.005	0.254	Y
12	D 0.250 ±0.005	0.255	Y
13	D 0.250 ±0.005	0.255	Y
14	D 0.250 ±0.005	0.252	Y
15	D 0.250 ±0.005	0.252	Y
16	E 1.10 ±0.050	1.12	Y
17	E 1.10 ±0.050	1.13	Y

TABLE A.2. Waterjet Machining Radius Inspection, FL-1

Date: 16 Mar 86

Equipment: Optical Comparator

Material: Phase II Mg/B₄C (15 vol.%)

<u>Measurement Number</u>	<u>Dimension and Tolerance</u>	<u>Measured</u>	<u>Within Specification (Yes/No)</u>
A	0.010 max	0.049	N
B	0.010 max	0.050	N
C	0.1875 min	0.205	Y
D	0.1875 min	0.210	Y

TABLE A.3. Waterjet Machining Specimen Inspection, FL-2

Date: 5 Mar 86

Measurement

Equipment: Knife Edge Micrometer

Material: Phase II Mg/B₄C (15 vol.%)

<u>Measurement Number</u>	<u>Dimension and Tolerance</u>	<u>Measured</u>	<u>Within Specification (Yes/No)</u>
1	d 0.250 ±0.005	0.241	N
2	d 0.250 ±0.005	0.240	N
3	d 0.250 ±0.005	0.254	Y
4	d 0.250 ±0.005	0.253	Y
5	B 0.375 ±0.001	0.371	N
6	B 0.375 ±0.001	0.376	Y
7	B 0.375 ±0.001	0.375	Y
8	B 0.375 ±0.001	0.375	Y
9	B 0.375 ±0.001	0.376	Y
10	B 0.375 ±0.001	0.376	Y
11	D 0.250 ±0.005	0.252	Y
12	D 0.250 ±0.005	0.253	Y
13	D 0.250 ±0.005	0.253	Y
14	D 0.250 ±0.005	0.253	Y
15	D 0.250 ±0.005	0.254	Y
16	E 1.10 ±0.050	1.10	Y
17	E 1.10 ±0.050	1.10	Y

TABLE A.4. Waterjet Machining Radius Inspection, FL-2

Date: 16 Mar 86

Equipment: Optical Comparator

Material: Phase II Mg/B₄C (15 vol.%)

<u>Measurement Number</u>	<u>Dimension and Tolerance</u>	<u>Measured</u>	<u>Within Specification (Yes/No)</u>
A	0.010 max	0.040	N
B	0.010 max	0.040	N
C	0.1875 min	0.220	Y
D	0.1875 min	0.220	Y

TABLE A.5. Waterjet Machining Specimen Inspection, FL-3

Date: 5 Mar 86

Measurement

Equipment: Knife Edge Micrometer

Material: Phase II Mg/B₄C (15 vol.%)

<u>Measurement Number</u>	<u>Dimension and Tolerance</u>	<u>Measured</u>	<u>Within Specification (Yes/No)</u>
1	d 0.250 ±0.005	0.240	N
2	d 0.250 ±0.005	0.238	N
3	d 0.250 ±0.005	0.249	Y
4	d 0.250 ±0.005	0.245	Y
5	B 0.375 ±0.001	0.365	N
6	B 0.375 ±0.001	0.372	N
7	B 0.375 ±0.001	0.372	N
8	B 0.375 ±0.001	0.370	N
9	B 0.375 ±0.001	0.369	N
10	B 0.375 ±0.001	0.366	N
11	D 0.250 ±0.005	0.252	Y
12	D 0.250 ±0.005	0.252	Y
13	D 0.250 ±0.005	0.251	Y
14	D 0.250 ±0.005	0.251	Y
15	D 0.250 ±0.005	0.252	Y
16	E 1.10 ±0.050	1.05	Y
17	E 1.10 ±0.050	1.10	Y

TABLE A.6. Waterjet Machining Radius Inspection, FL-3

Date: 16 Mar 86

Equipment: Optical Comparator

Material: Phase II Mg/B₄C (15 vol.%)

<u>Measurement Number</u>	<u>Dimension and Tolerance</u>	<u>Measured</u>	<u>Within Specification (Yes/No)</u>
A	0.010 max	0.040	N
B	0.010 max	0.040	N
C	0.1875 min	0.200	Y
D	0.1875 min	0.200	Y

TABLE A.7. Waterjet Machining Specimen Inspection, FL-4

Date: 5 Mar 86

Measurement

Equipment: Knife Edge Micrometer

Material: Phase II Mg/B₄C (15 vol.%)

<u>Measurement Number</u>	<u>Dimension and Tolerance</u>	<u>Measured</u>	<u>Within Specification (Yes/No)</u>
1	d 0.250 ±0.005	0.234	N
2	d 0.250 ±0.005	0.233	N
3	d 0.250 ±0.005	0.251	Y
4	d 0.250 ±0.005	0.249	Y
5	B 0.375 ±0.001	0.365	N
6	B 0.375 ±0.001	0.371	N
7	B 0.375 ±0.001	0.371	N
8	B 0.375 ±0.001	0.374	Y
9	B 0.375 ±0.001	0.375	Y
10	B 0.375 ±0.001	0.372	N
11	D 0.250 ±0.005	0.251	Y
12	D 0.250 ±0.005	0.252	Y
13	D 0.250 ±0.005	0.252	Y
14	D 0.250 ±0.005	0.252	Y
15	D 0.250 ±0.005	0.253	Y
16	E 1.10 ±0.050	1.10	Y
17	E 1.10 ±0.050	1.11	Y

TABLE A.8. Waterjet Machining Radius Inspection, FL-4

Date: 16 Mar 86

Equipment: Optical Comparator

Material: Phase II Mg/B₄C (15 vol.%)

<u>Measurement Number</u>	<u>Dimension and Tolerance</u>	<u>Measured</u>	<u>Within Specification (Yes/No)</u>
A	0.010 max	0.045	N
B	0.010 max	0.045	N
C	0.1875 min	0.200	Y
D	0.1875 min	0.200	Y

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