# Chapter 2
# Femtosecond Laser Machining of Micro-tensile Specimens for High Throughput Mechanical Testing

**Daniel J. Magagnosc, Jonathan P. Ligda, Tomoko Sano, and Brian E. Schuster**

**Abstract** Recently, a variety of techniques for fabricating microscale specimens for mechanical testing have been developed. However, many of these techniques are limited by material compatibility, specimen sizes, low throughput, or microstructural damage. In contrast, the advent of femtosecond laser systems offer opportunities to circumvent many of these challenges. Here we demonstrate the use of a femtosecond laser milling system to rapidly fabricate micro-tensile specimens across a range of critical dimensions, from 10's to 100's of microns. By incorporating the laser milling system into a custom micromechanical testing apparatus, we are able to achieve high throughput investigations of mechanical properties at the microscale. These capabilities are demonstrated on metal and ceramic materials.

**Keywords** Micro-machining • Micro-tension • Femtosecond laser • In situ • High throughput

Recent interest in fabricating parts with microscale features has resulted in the development of a variety of sample fabrication routes [1, 2] and spurred interest in studying mechanical properties at small length scales [3, 4]. Common fabrication routes include micro electrodischarge-machining (EDM) [5, 6], micro-milling [7], wafer-scale lithography processes [8, 9], and focused ion beam (FIB) milling [10–12]. However, these fabrication routes all suffer from a combination of either low throughput, specimen size restrictions, limited material compatibility, or produce significant microstructural damage. For instance, micro-EDM and micro-milling are restricted by material compatibility and minimum feature sizes larger than 10's of microns. Similarly, lithographic processes enable high throughput but are often restricted to thin or thick film materials. Finally, the FIB, which is compatible with a broad range of materials and offers sub-micron spatial resolution, is restricted by poor throughput, even with modern high current ion sources, and potentially significant microstructural modification.

In contrast, the development of femtosecond (fs) pulsed laser generators enables rapid fabrication of microscale specimens. Shortening the pulse width results in high power densities, which surpasses the ablation threshold of most materials [13, 14]. In addition, the ultrashort interaction times are much less than typical electron-ion and ion-ion interaction times, thereby minimizing thermal effects during machining [13–15]. As a result, fs-laser machining can achieve high material removal rates without inducing significant microstructural damage, such as a heat affected zone, melting, or significant dislocation generation, during machining [16–18]. As a result, we employ a custom fs-laser milling system to produce microscale tensile specimens from metal, ceramic, and polymer materials. The fs-laser milling system is further integrated with a custom micromechanical testing apparatus to enable high throughput investigations of mechanical properties at the microscale.

The fs-laser milling apparatus consists of a Ti:sapphire based chirped pulse amplifier (Clark MXR) laser, focusing optics, and motorized translation stages with three degrees of freedom (Newport Corp.). The amplified laser has a wavelength of 775 nm, a pulse width of 150–200 fs, and a repetition rate of 1–2 kHz resulting in single pulse energies up to 1 mJ. Using the translation stages, the specimen is translated through the beam to trace the desired geometry. An example machining process is illustrated in Fig. 2.1a. The outline is produced by a first rough cut followed by successive fine cuts to thin the gage section. Finally, the ultimate gage shape is repeatedly traced to produce a clean, vertical edge. Here, typical average laser powers are 10–15 mW and translation rates are 0.2–0.6 mm/s. Using this procedure, tensile bars were successfully machined in rolled aluminum (99.999%), impact modified PMMA, and SiC. The rolled aluminum had a thickness of 25 $\mu$m; the PMMA and sintered SiC (primarily $\alpha$-SiC) were 50 $\mu$m thick. A laser scanning microscope micrograph of a representative tensile bar cut from PMMA is shown in Fig. 2.1b.

D.J. Magagnosc (✉) • J.P. Ligda • T. Sano • B.E. Schuster
US Army Research Laboratory, Aberdeen Proving Ground, Adelphi, MD 21005, USA
e-mail: daniel.j.magagnosc.ctr@mail.mil



L. Starman, J. Hay (eds.), *Micro and Nanomechanics, Volume 5*, Conference Proceedings of the Society for Experimental Mechanics Series, DOI 10.1007/978-3-319-63405-0_2

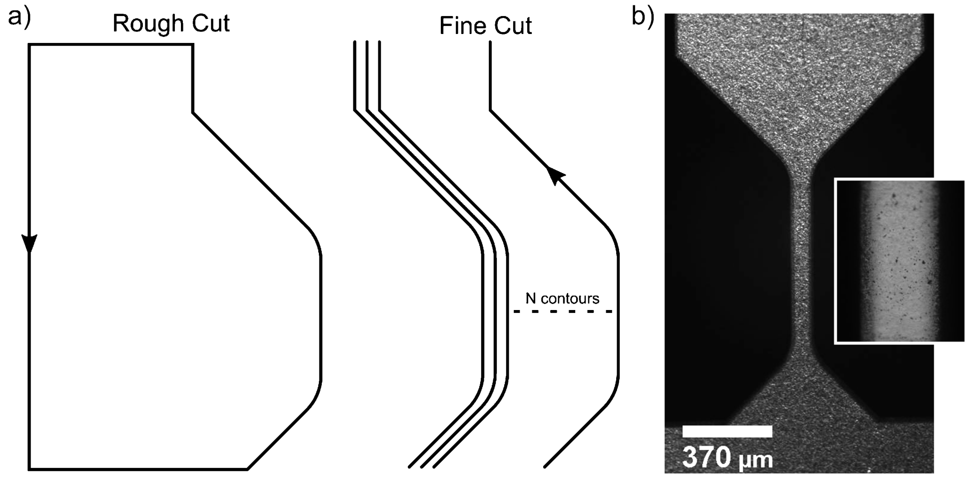


**Fig. 2.1** Samples are fabricated using a multistep machining process as illustrated in (**a**). A rough cut is first used to define the tensile bar shape followed by a series of fine cuts to successively thin the gage section. The final shape is repeatedly traced to create a clean, vertical sidewall. A representative micrograph of a PMMA tensile bar is shown in (**b**). The inset shows a detailed view of the center gage section

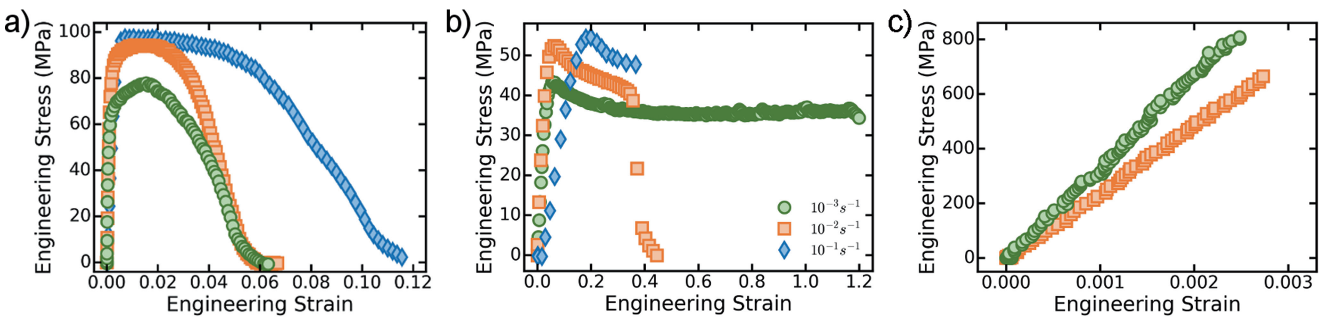


**Fig. 2.2** Representative stress-strain for fs-laser machined (**a**) 25 μm thick rolled aluminum, (**b**) 50 μm thick impact modified at PMMA at three strain rates, and (**c**) 50 μm thick SiC

After machining, the tensile specimens are transferred into a custom micromechanical testing apparatus. The apparatus consists of translation stages for alignment and applying strains, an S-beam load cell (Futek Advanced Sensor Technology, Inc.), and optical microscope. After aligning the tensile bar in the grips, the specimen is strained while simultaneously measuring the force and recording images for determining strain via digital image correlation. Here, the aluminum and SiC are strained at $10^{-3}$ $s^{-1}$ while strain rates from $10^{-3}$ to 1 $s^{-1}$ are applied to the PMMA.

Tensile tests performed on rolled aluminum, PMMA, and SiC demonstrate capabilities of fs-laser machining to fabricate reliable mechanical testing specimens. The rolled aluminum (Fig. 2.2a) exhibited tensile strengths between 75 and 100 MPa as well as 6–12% elongation at failure. This response is indicative of an as-worked, high purity aluminum [19]. Impact modified PMMA (Fig. 2.2b) exhibits strong strain rate sensitivity at strain rates between $10^{-3}$ and $10^{-1}$ $s^{-1}$; as the strain rate is increased, the strain to failure significantly decreases while the tensile strength increases. The observed trends in strength and strain to failure are in good agreement with previously reported strain rate sensitivity in PMMA [20, 21]. Finally, the SiC (Fig. 2.2c) exhibits linear elastic loading behavior before failing abruptly. The observed failure stress is higher than typical tensile stresses in SiC [22]. However, this result is consistent with the trend of smaller is stronger, typical of flaw dominated failure in brittle materials, given the reduced specimen size [23].

As a whole this work demonstrates the potential for sample fabrication via fs-laser ablation. A machining method, which employs multiple cutting steps, for producing high quality test specimens was presented. The machining process was used to fabricate tensile bars from thin sheets of three representative materials, rolled aluminum, impact modified PMMA and SiC. Subsequent tensile tests suggest that the tensile properties of the laser machined specimens are in good agreement with the bulk properties of the parent material. Thus, a reliable and high throughput fabrication and mechanical testing method, which avoids many limitations characteristic of established fabrication methods has been demonstrated.

## References


1. Jain, V., Sidpara, A., Balasubramaniam, R., Lodha, G., Dhamgaye, V., Shukla, R.: Micromanufacturing: a review – part I. Proc. Inst. Mech. Eng. B J. Eng. Manuf. **228**, 973–994 (2014)
2. Jain, V., Dixit, U., Paul, C., Kumar, A.: Micromanufacturing: a review – part II. Proc. Inst. Mech. Eng. B J. Eng. Manuf. **228**, 995–1014 (2014)
3. Sharpe, W.N.: Murray lecture tensile testing at the micrometer scale: opportunities in experimental mechanics. Exp. Mech. **43**, 228–237 (2003)
4. Hemker, K.J., Sharpe, W.N.: Microscale characterization of mechanical properties. Annu. Rev. Mater. Res. **37**, 93–126 (2007)
5. Liu, K., Lauwers, B., Reynaerts, D.: Process capabilities of micro-EDM and its applications. Int. J. Adv. Manuf. Technol. **47**, 11–19 (2009)
6. Mahendran, S., Devarajan, R., Nagarajan, T., Majd, A.: A review of micro-EDM. In: Proceedings of international multi-conference of engineers and computer scientists, International Association of Engineers, Hong Kong, 17–19 March 2010
7. Aramcharoen, A., Mativenga, P.T.: Size effect and tool geometry in micromilling of tool steel. Precis. Eng. **33**, 402–407 (2009)
8. Ziaie, B.: Hard and soft micromachining for BioMEMS: review of techniques and examples of applications in microfluidics and drug delivery. Adv. Drug Deliv. Rev. **56**, 145–172 (2004)
9. Judy, J.W.: Microelectromechanical systems (MEMS): fabrication, design and applications. Smart Mater. Struct. **10**, 1115–1134 (2001)
10. Volkert, C.A., Minor, A.M.: Focused ion beam microscopy and micromachining. MRS Bull. **32**, 389–399 (2011)
11. Reyntjens, S., Puers, R.: A review of focused ion beam applications in microsystem technology. J. Micromech. Microeng. **11**, 287–300 (2001)
12. Burnett, T.L., Kelley, R., Winiarski, B., Contreras, L., Daly, M., Gholinia, A., Burke, M.G., Withers, P.J.: Large volume serial section tomography by Xe plasma FIB dual beam microscopy. Ultramicroscopy. **161**, 119–129 (2016)
13. Gamaly, E.G., Rode, A.V., Luther-Davies, B., Tikhonchuk, V.T.: Ablation of solids by femtosecond lasers: ablation mechanism and ablation thresholds for metals and dielectrics. Phys. Plasmas. **9**, 949 (2002)
14. Liu, X., Du, D., Mourou, G.: Laser ablation and micromachining with ultrashort laser pulses. IEEE J. Quantum Electron. **33**, 1706–1716 (1997)
15. Nolte, S., Momma, C., Jacobs, H., Tünnermann, A., Chichkov, B.N., Wellegehausen, B., Welling, H.: Ablation of metals by ultrashort laser pulses. J. Opt. Soc. Am. B. **14**, 2716 (1997)
16. Feng, Q., Picard, Y.N., Liu, H., Yalisove, S.M., Mourou, G., Pollock, T.M.: Femtosecond laser micromachining of a single-crystal superalloy. Scr. Mater. **53**, 511–516 (2005)
17. Titus, M.S., Echlin, M.P., Gumbsch, P., Pollock, T.M.: Dislocation injection in strontium titanate by femtosecond laser pulses. J. Appl. Phys. **118**, 075901 (2015)
18. Echlin, M.P., Titus, M.S., Straw, M., Gumbsch, P., Pollock, T.M.: Materials response to glancing incidence femtosecond laser ablation. Acta Mater. **124**, 37–46 (2017)
19. A.S.M.I.H. Committee. ASM Handbook, Volume 02 – Properties and Selection: Nonferrous Alloys and Special-Purpose Materials. ASM International, Materials Park (1990)
20. Li, Z., Lambros, J.: Strain rate effects on the thermomechanical behavior of polymers. Int. J. Solids Struct. **38**, 3549–3562 (2001)
21. Wu, H., Ma, G., Xia, Y.: Experimental study of tensile properties of PMMA at intermediate strain rate. Mater. Lett. **58**, 3681–3685 (2004)
22. Munro, R.G.: Material properties of a sintered α-SiC. J. Phys. Chem. Ref. Data. **26**, 1195 (1997)
23. Bažant, Z.P.: Size effect on structural strength: a review. Arch. Appl. Mechan. (Ingenieur Archiv). **69**, 703–725 (1999)


**Daniel J. Magagnosc** received his bachelor's degree in Materials Science from Penn State University in 2010 and his PhD in Materials Science from the University of Pennsylvania in 2016. Daniel's research interests focus on using in situ testing methodologies to understand deformation mechanisms in microscale materials.

Springer

http://www.springer.com/978-3-319-63404-3

Micro and Nanomechanics, Volume 5
Proceedings of the 2017 Annual Conference on
Experimental and Applied Mechanics
Starman, L.; Hay, J. (Eds.)
2018, VII, 81 p. 78 illus., 43 illus. in color., Hardcover
ISBN: 978-3-319-63404-3