Position and Energy Controlled Impact Treatment for Increasing Strength and Ductility in Stainless Steel

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Goal: Strengthening of metal components by patterned grain refinement

- A CNC impactor machine is used to selectively pattern and strengthen metal components
- Process optimizes strength-ductility properties for specific applications
- Designed for both lab-scale experimentation and simple industrial implementation

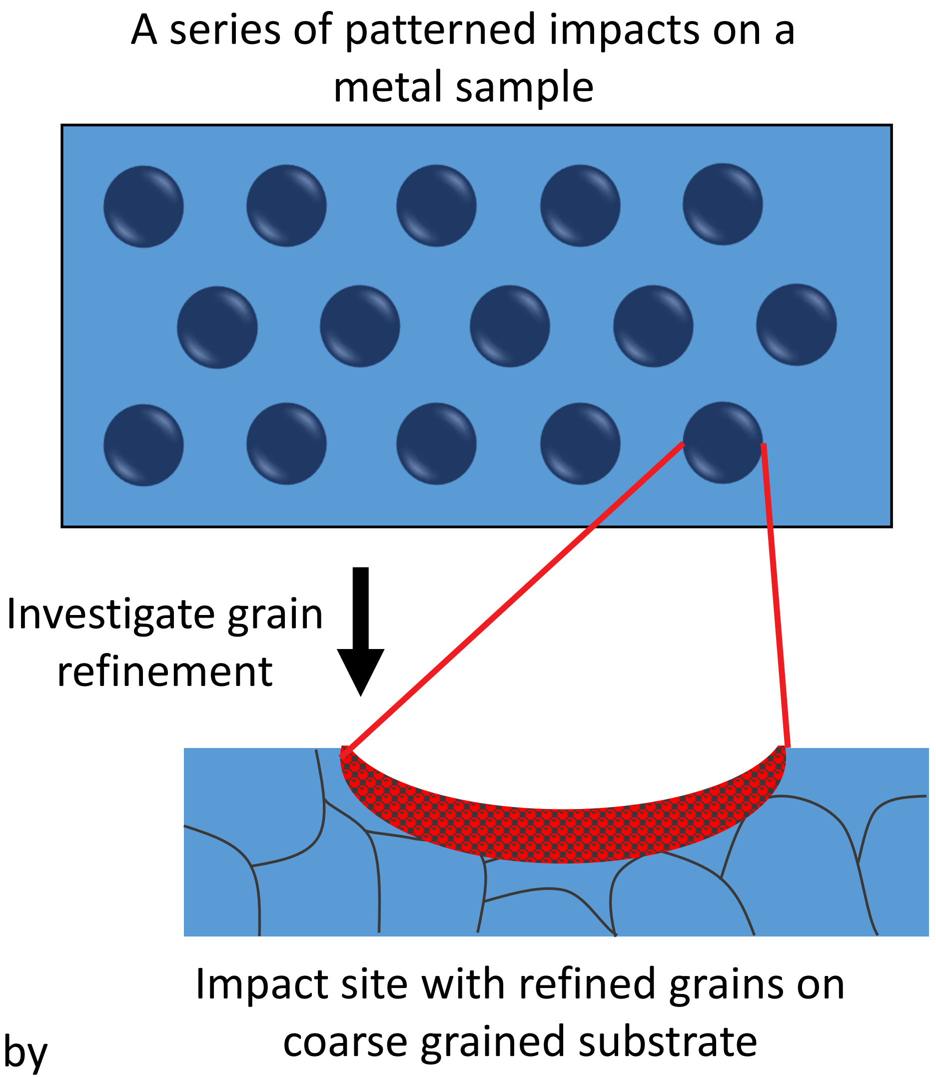


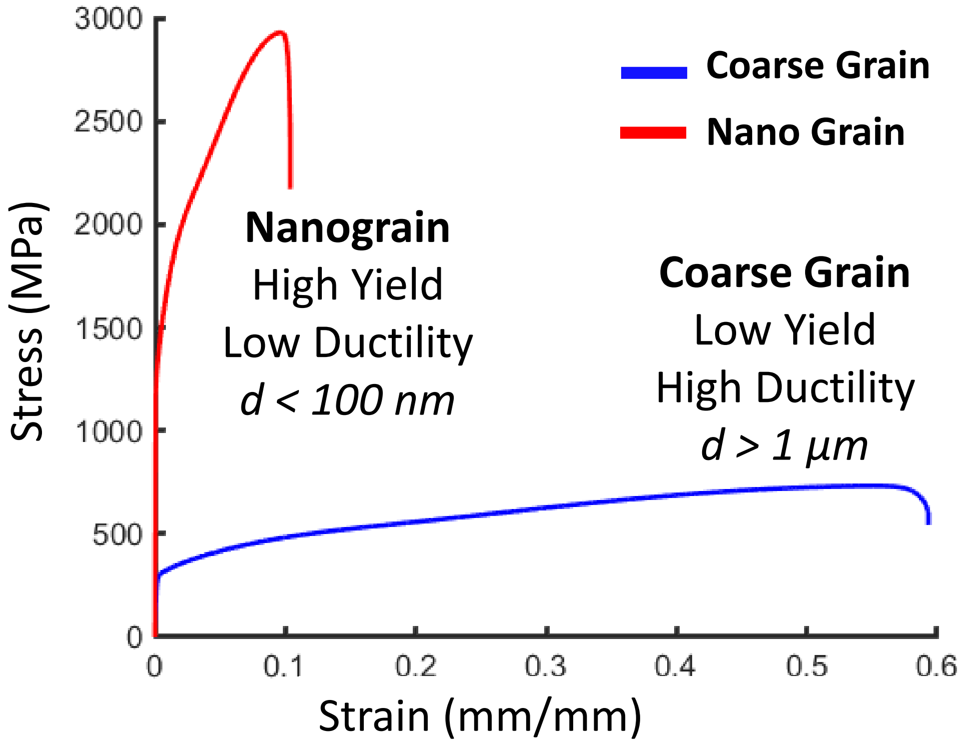
Figure by Samuel Scott

Presentation overview

- Research background:
  - Heterogeneous nanograin structures
  - Partial surface coverage with nanograined impact sites
  - Control and optimization of surface strength
- Position and energy-controlled impactor
  - Impactor design
  - Energy measurement and Validation
- Testing in 304 stainless steel samples
  - Preparing test specimens
  - Observed strengthening behavior
  - Future testing

Background: Hall-Petch behavior in metals

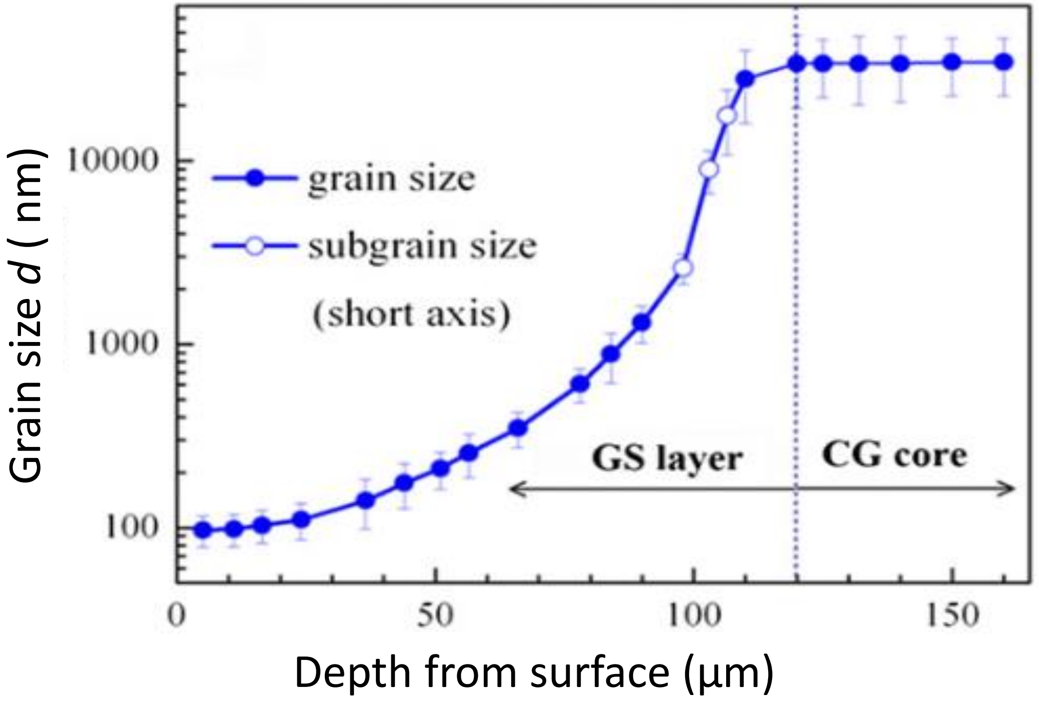
- Hall-Petch behavior in metals: Strength increases as grain size (*d*) decreases.
  - Grains are the crystals that make up a metal
- Small nano grains (NG), *d* < 100 nm, tend to be very strong, but brittle.
- Large coarse grains (CG), *d* > 1 µm, have much more ductility, but low yield strength.



Typical tensile behavior of coarse grain and nano grain metal samples. Figure by Samuel Scott.

Compromise: Gradient grain size for strength and ductility

- Both strength and ductility are highly sought after
- Gradient nano grain (GNG) structures combine the best properties of both NG and CG
  - High strength
  - High ductility and strain hardening
- In GNG, grain size increases from NG at the metal surface to CG in the center



Typical grain size – depth relation for gradient nanograin structures in interstitial-free steel. [Wu *et al.*, 2014]

Creating Gradient Nano Grain (GNG) structures with SMAT

- Surface Mechanical Attrition Treatment (SMAT) impacts the surface of a material with heavy spheres
- Severe plastic deformation (SPD) forms nano grains at impact sites
- Randomly oriented impacts help form a uniform GNG layer

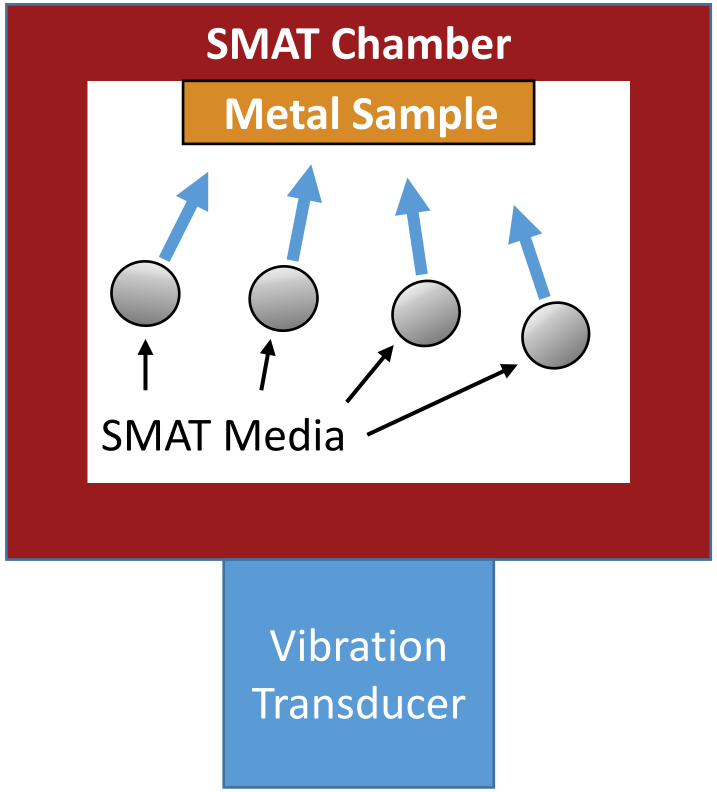
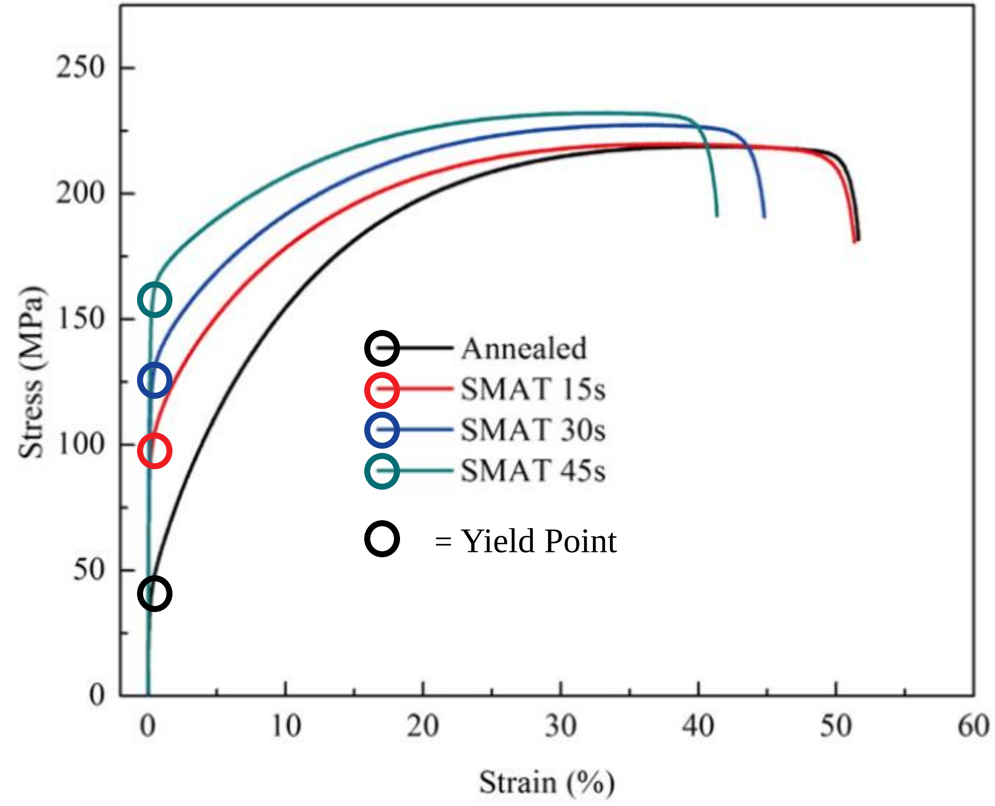


Diagram of vibratory SMAT application device

Strengthening coarse grained metals with SMAT

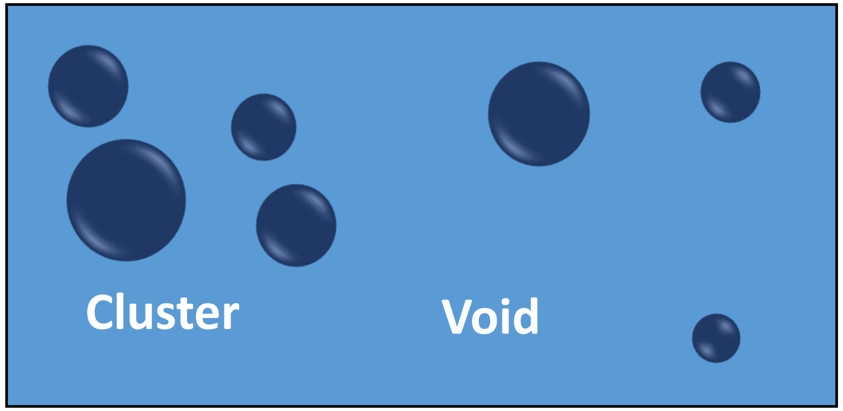
- SMAT processing with longer durations results in greater strength until a saturation point is reached.
- Liu *et al*. (2016) achieved a ~200% increase in the yield strength of copper by SMAT processing
- Only a maximum of ~10% reduction in failure elongation



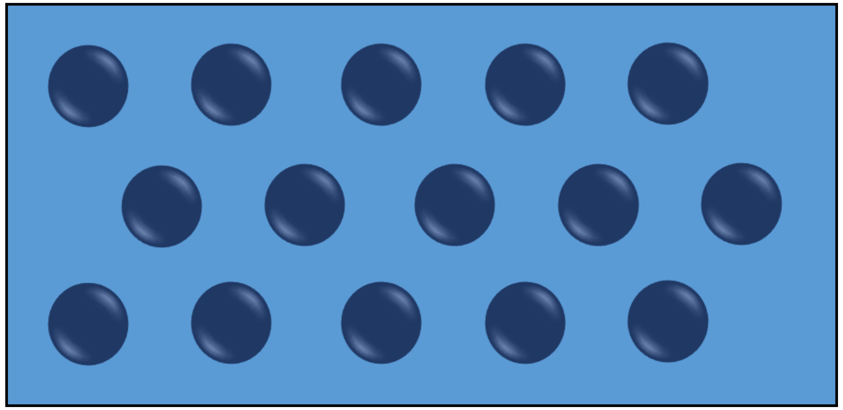
Engineering stress-strain tensile curves demonstrating strengthening of copper with SMAT for different durations. [Liu *et al.*, 2016]

Patterned impacts are desirable

- Short-duration SMAT results in incomplete, random surface coverage
- Clusters and voids of impacts are detrimental to ductility (Sharp *et al.*, 1994)
- Regularly patterned impacts can provide uniform ductility and strengthening



Random impacts (above) can lead to poor performance in the plastic regime, unlike patterned planar heterogeneous structures (below). Figure by Samuel Scott



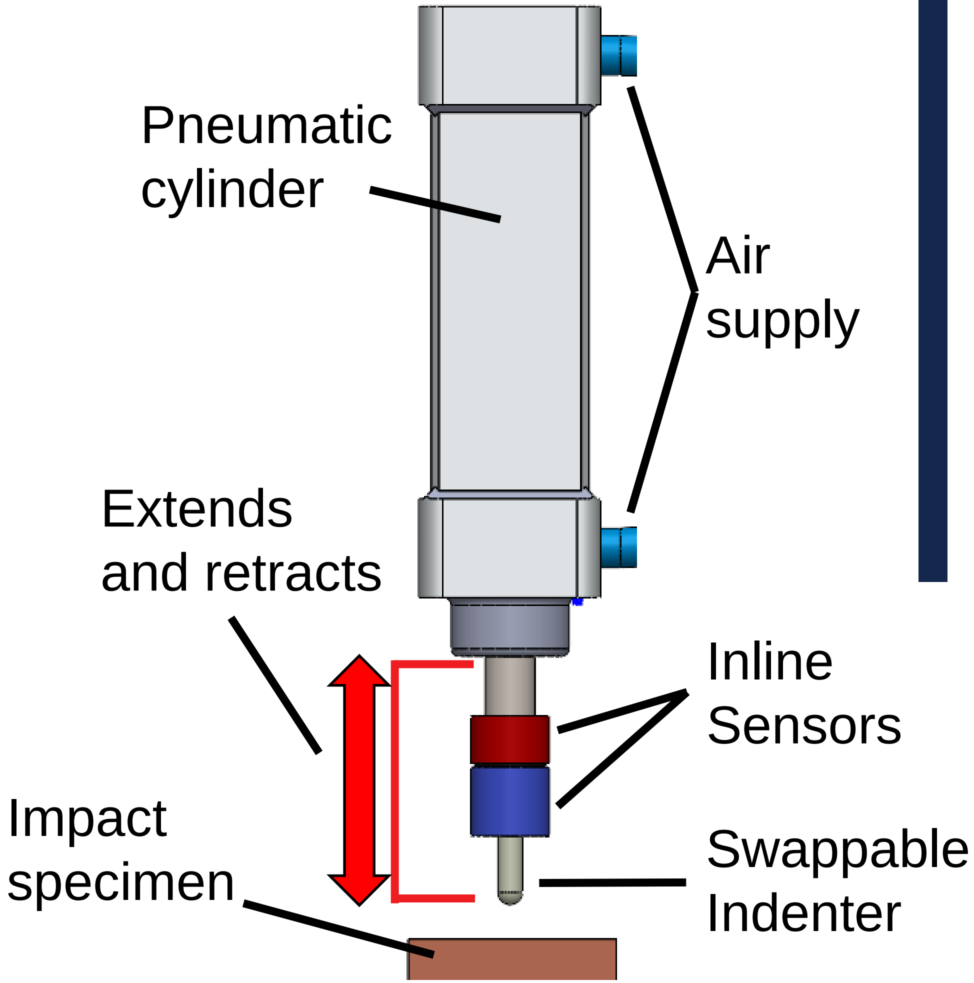
Requirements for patterning-capable SMAT

1. Positional control of impact location
2. Control of impact energy applied by indenter
3. Energy measurement of impact plastic deformation energy

Goal: Control component strength and ductility by varying pattern parameters

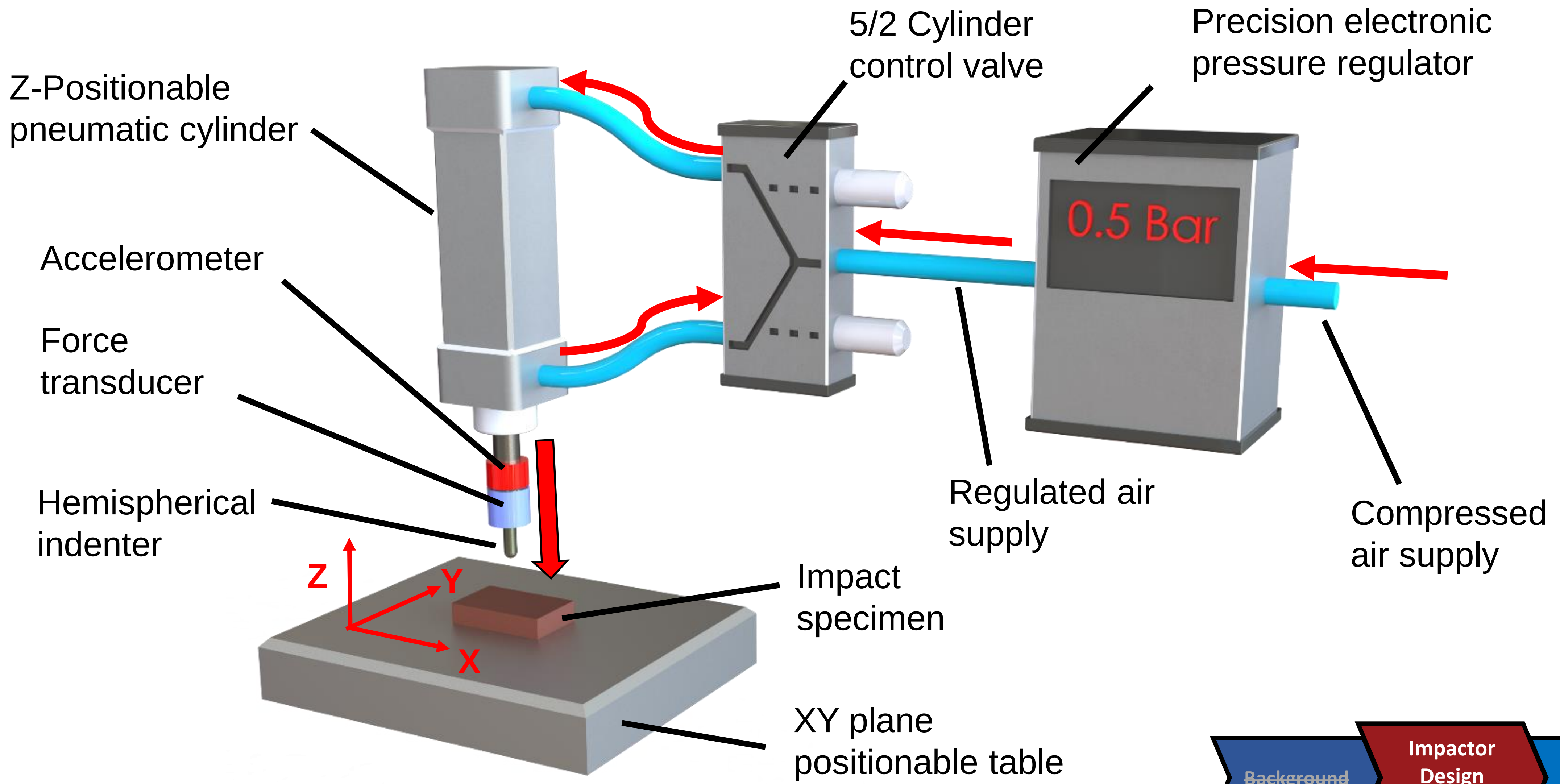
Position and Energy Controlled SMAT (PECSMAT)

- Pneumatic cylinder-based impactor
- Inline energy sensors and indenter mounted on extending piston rod
- Specimen position, standoff height, and impactor pressure controlled by Computer Numerical Control (CNC)
- <u>Direct control of position and energy with energy measurement</u>



PECSMAT Indenter.
Figure by Samuel Scott

PECSMAT Impactor

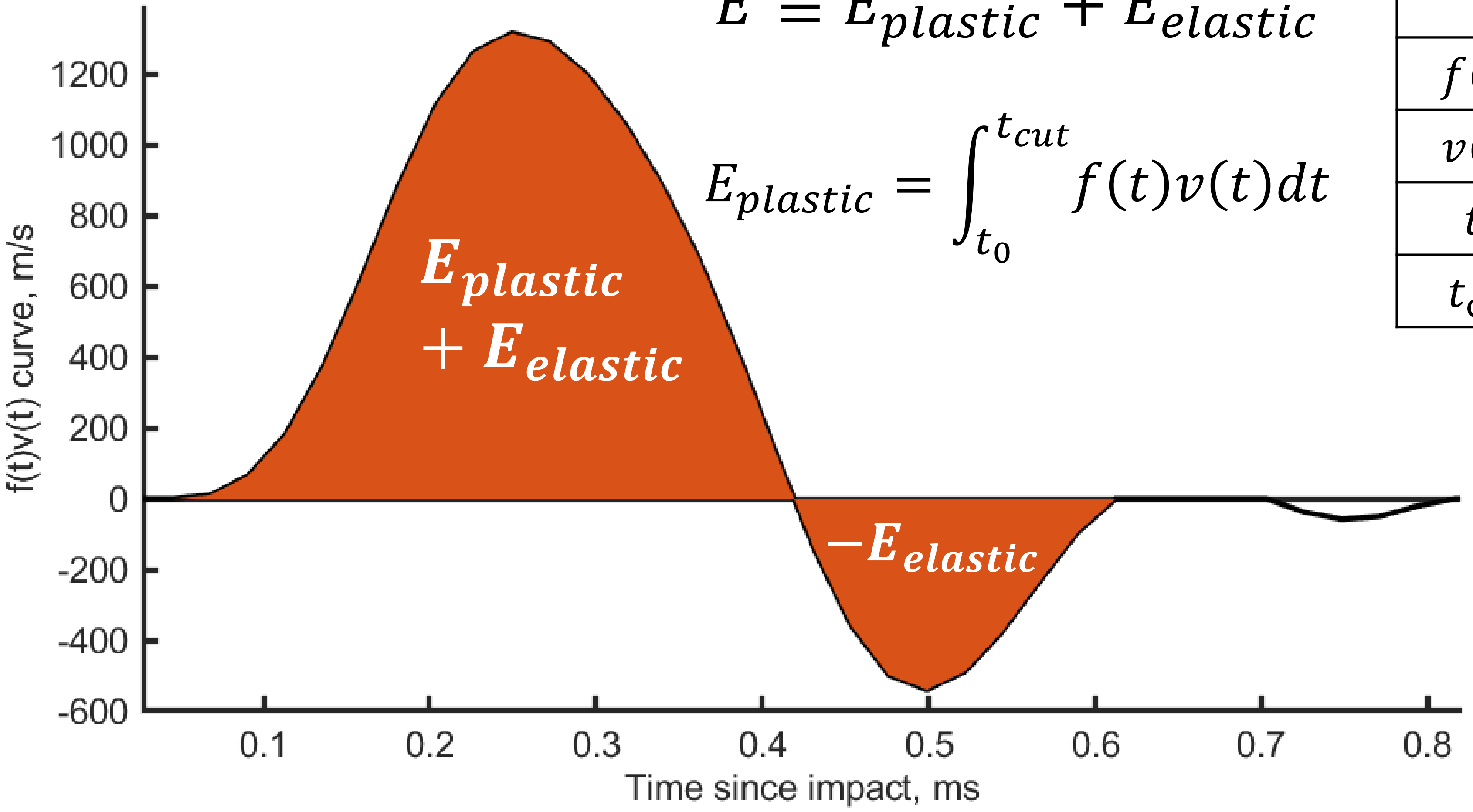


Energy measurement of a PECSMAT impact

$$E \cong E_{plastic} + E_{elastic}$$

$$E_{plastic} = \int_{t_0}^{t_{cut}} f(t)v(t)dt$$

E	Total impact energy
$f(t)$	Force time curve
$v(t)$	Velocity time curve
t_0	Time at impact
t_{cut}	Integration cutoff time



Force-velocity curve for a PECSMAT impact in pure copper demonstrating self-elimination of elastic energy from integration. Figure by Samuel Scott

Impactor performance validations

- A series of experiments were carried out to confirm the precision and accuracy of the PECSMAT impactor.
- Positional accuracy of individual indents was $\pm 17\ \mu m$
- Plastic deformation energy was controllable to within 8.9% of the set point energy value.

Strengthening of 304 Stainless Steel

- Objectives:
  - Prove that PECSMAT indentation can control strength properties in 304 stainless steel (304 SS)
  - Characterize grain size refinement at impact sites
  - Observe strain behavior between uniform impact sites
- Testing:
  - Indent 304 SS sheet metal with a hexagonal impact pattern
  - Vary only the spacing of the indent pattern
  - Manufacture tensile specimens from indented sheet and characterize

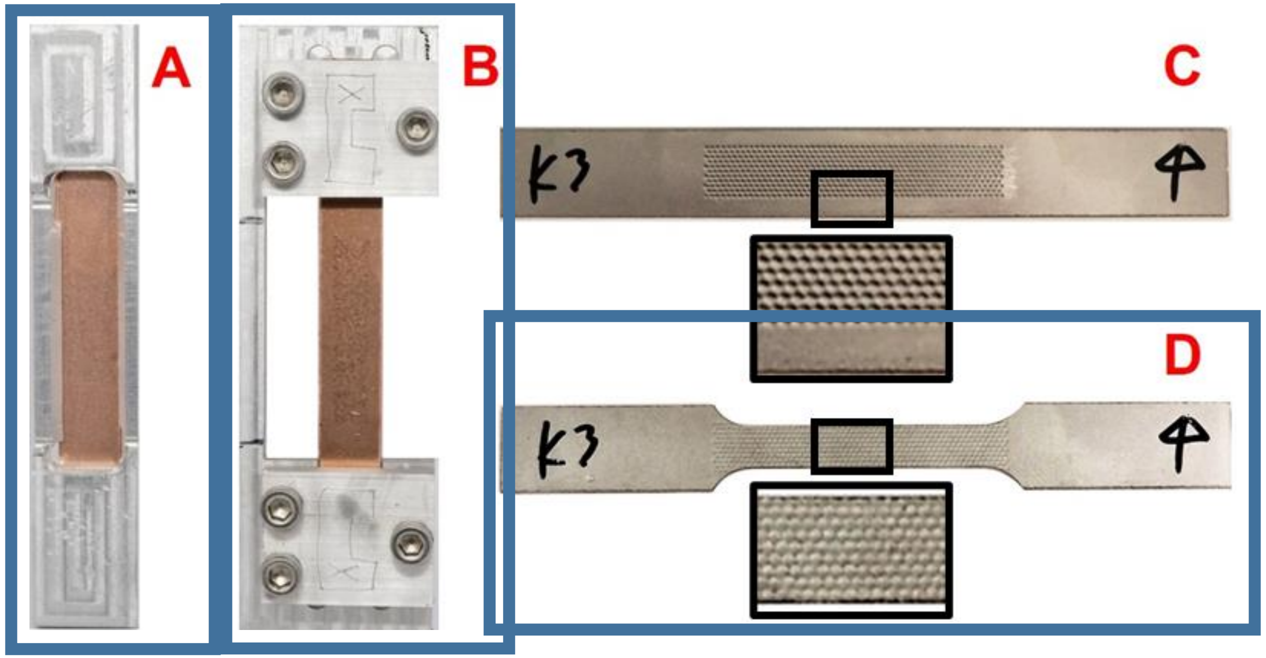
304 SS material data

- Description and typical applications of 304 SS:
  - Austenitic stainless steel with high strain hardening ability
  - Very corrosion resistant
  - Often used in structural components, marine applications, aerospace, and kitchen appliances.

- 304 SS stock used in this testing:
  - Cold-rolled and annealed 0.048” thick sheet stock
  - Measured microhardness: 190.1 $\pm$ 4.6 HV (Vickers microhardness)
  - Fully annealed hardness is 155 HV (Naghizadeh and Mirzadeh, 2019)

304 SS specimen preparation

1. Rectangular blanks are cut from the 304 SS sheet stock
2. Blanks are indented on both sides in the PECSMAT indenter.
3. Patterned blanks are cut to form ASTM E8 subsize standard dog bone specimens in a waterjet cutter



A. Hold-down fixture locates rectangular blank securely for impacting.
B. Waterjet fixture locates impacted blank for waterjet cutting.
C. An example of a patterned 304 SS blank
D. A final-form dog bone tensile specimen after waterjet cutting.

Images by Samuel Scott

~~Background~~ ~~Impactor Design~~ Tests & Future 1 / 8

Sample descriptions

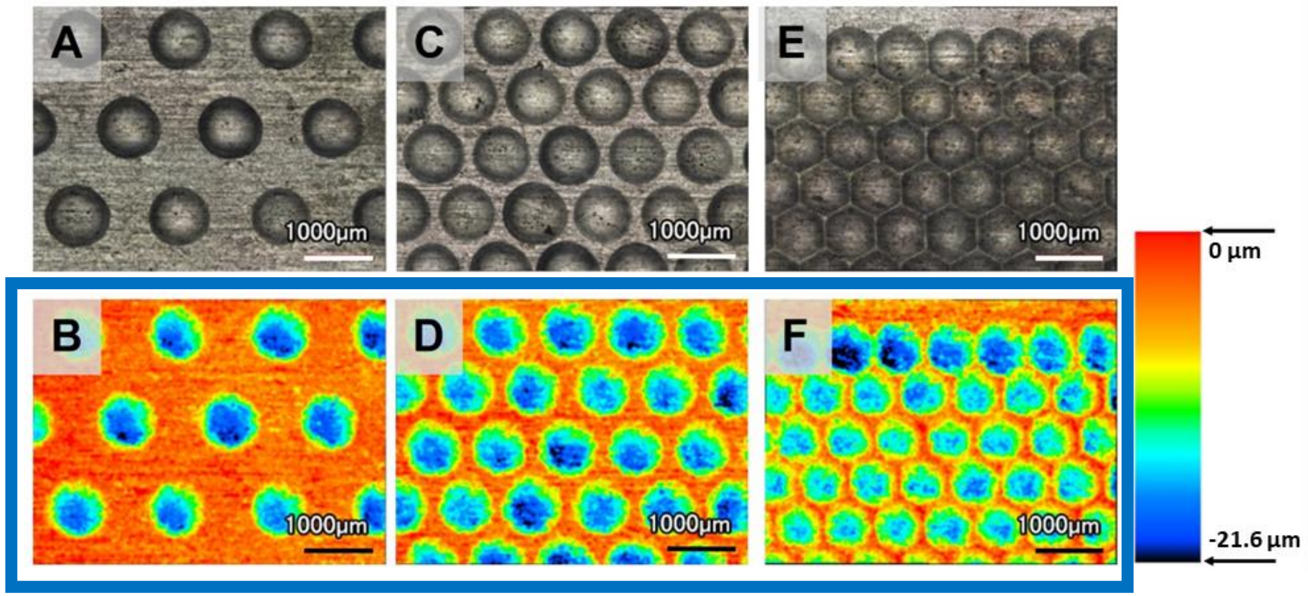
- Hexagonal impact pattern
- Spacings:
  - 1.5 mm
  - 1.0 mm
  - 0.75 mm
- Impactor pressure: 30 kPa
- Target impact energy: 20 mJ
- 3 samples for each spacing, in addition to unindented controls.

Impact spacing (mm)	Indent surface coverage (%)	Average diameter (µm)	Plastic deformation impact energy (mJ)
1.5	40.90%	922 ± 22	19.9 ± 0.6
1	78.00%	899 ± 33	20.3 ± 0.8
0.75	132.00%	868 ± 13	19.8 ± 0.5

Experimental data from preparation of PECSMAT tensile specimens.

Laser confocal analysis of impact specimens

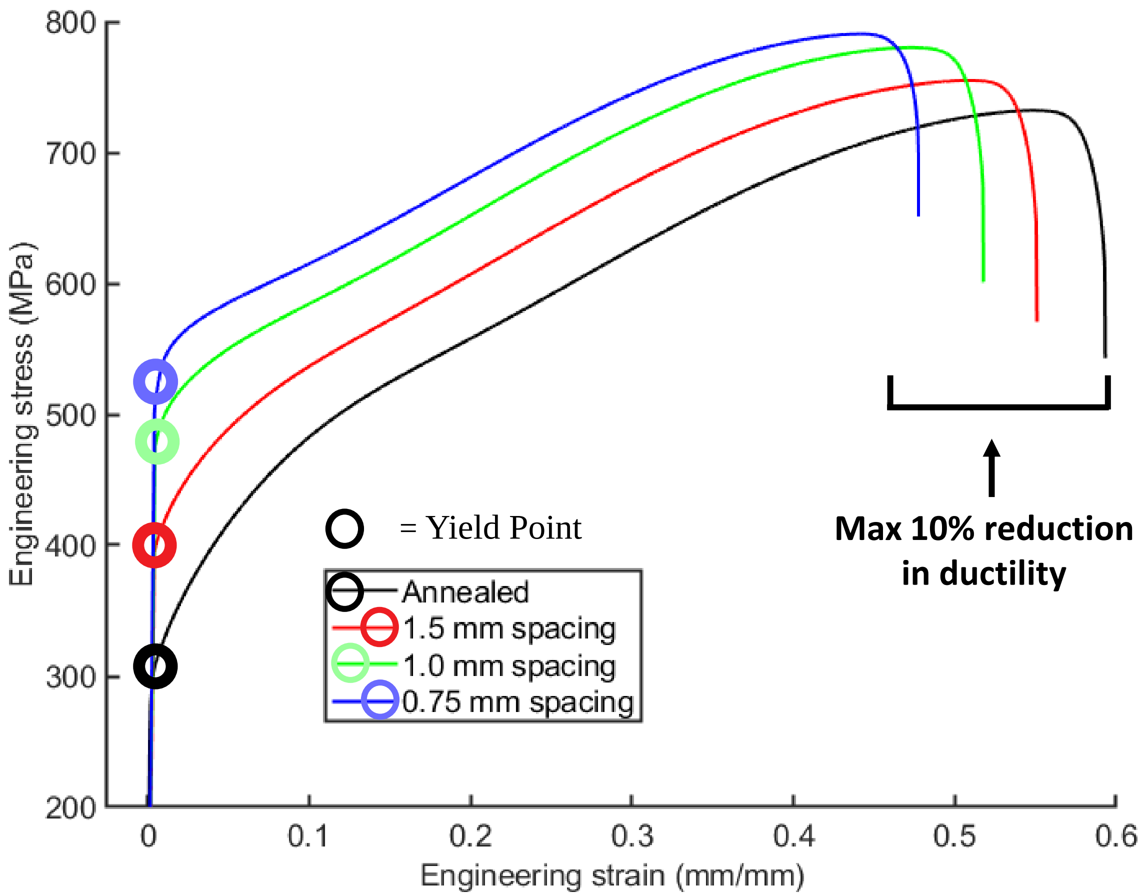
- Laser confocal microscopy was used to observe dog bone samples from all three trials.
- Indent diameter, depth, and spacing were found to be consistent.



Optical microscopy (above) and laser confocal microscopy depth mapping (below) of indented 304 SS specimens.
Figure by Samuel Scott

Tensile testing

- Each sample was pulled on an Instron test frame to obtain strength data. (Strain rate = $1 \cdot 10^{-3}\ \mathrm{s}^{-1}$)
- Significant increases in yield strength and ultimate strength were noted.
- Minimal reduction in ductility was noted.
- Strengths increased as pattern spacing decreased.



Engineering stress vs. strain for indented and control 304 SS tensile specimens.

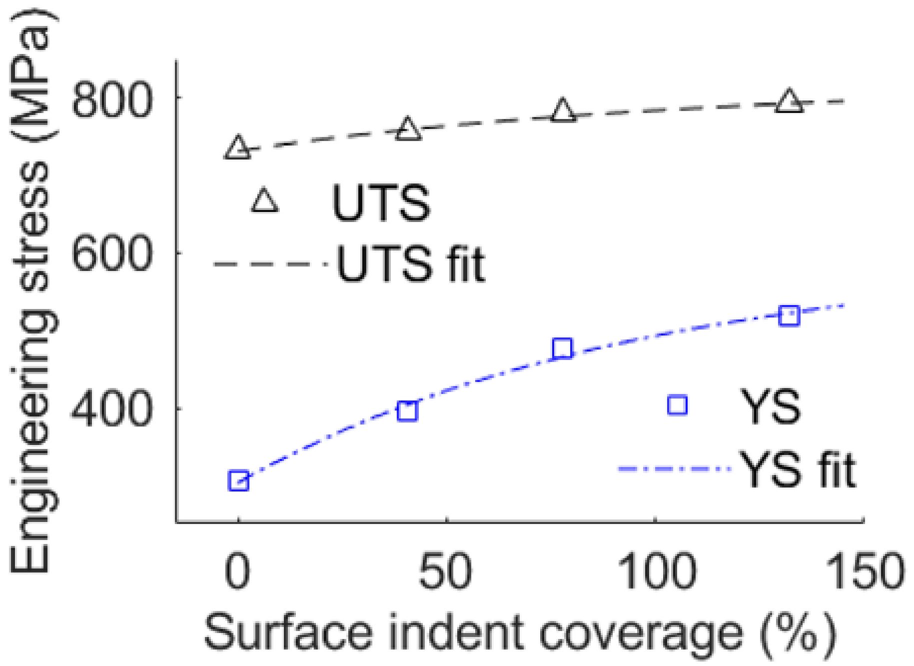
Figure by Samuel Scott

Data comparison

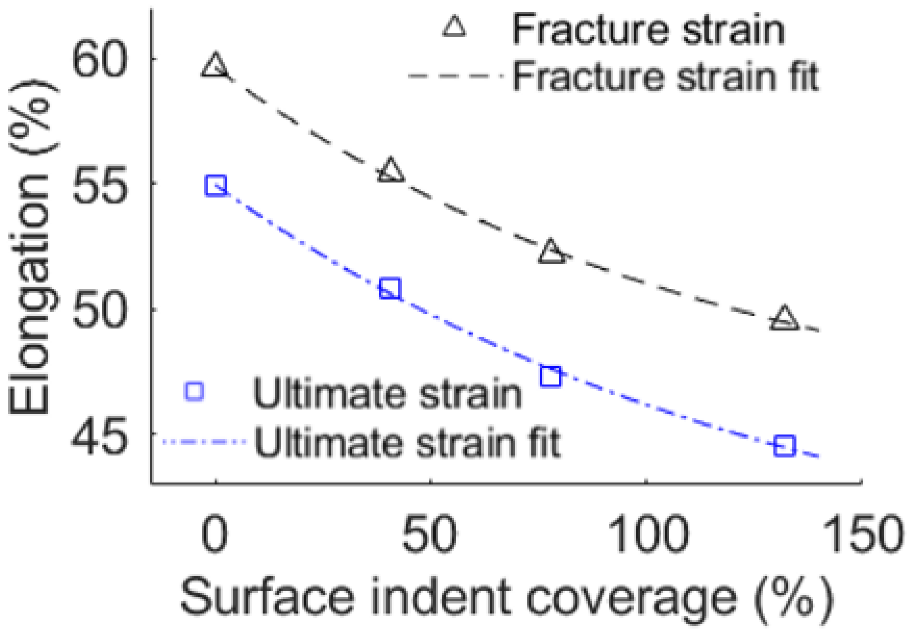
Data series	0.2% Yield strength (MPa)	Ultimate tensile strength (MPa)	Ultimate elongation (%)	Fracture elongation (%)	Source
Control	305 ± 1	732 ± 2	55 ± 0.2	60 ± 0.2	-
1.5 mm spaced	396 ± 6	755 ± 2	51 ± 0.2	55 ± 0.3	-
1.0 mm spaced	476 ± 5	780 ± 1	47 ± 0.2	52 ± 0.3	-
0.75 mm spaced	519 ± 26	792 ± 5	45 ± 1.6	50 ± 1.8	-
SMAT-processed with GNG structure	610 ± 5	858 ± 5	45 ± 2	50 ± 2	Chen et al. (2016)
Hot-rolled 304H at 900 °C	780 ± 30	920 ± 10	-	12	Yanushkevich et al. (2011)
Hot-rolled 304H at 500 °C	1030 ± 75	1130 ± 25	-	25	Yanushkevich et al. (2011)

Strength behavior is controllable and predictable

Ultimate tensile strength and yield strength as a function of surface indent coverage



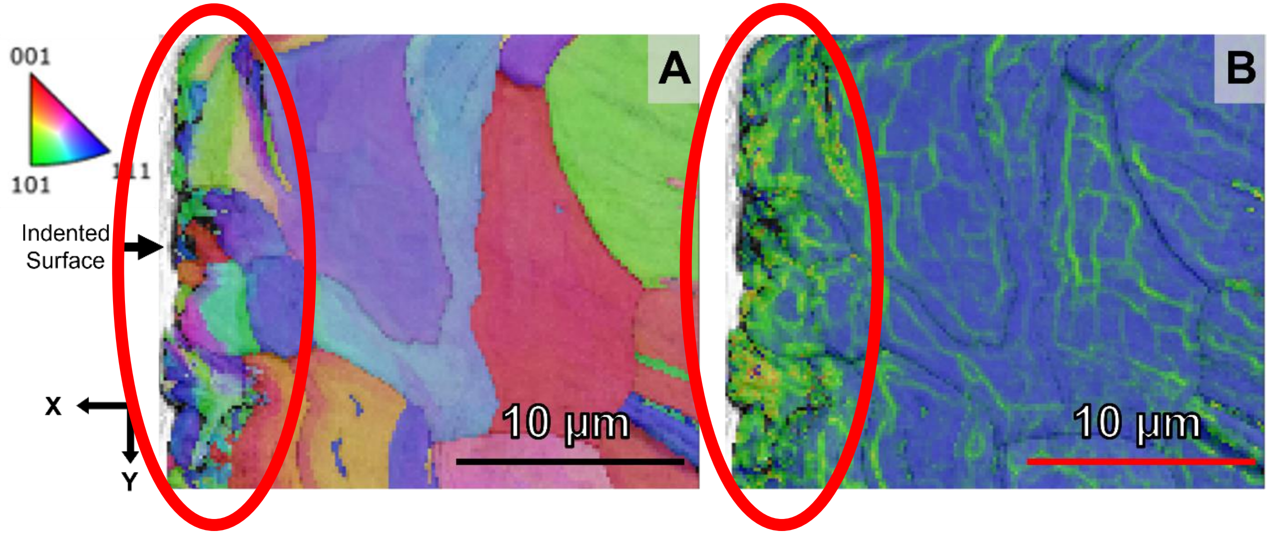
Ultimate strain and fracture strain as a function of surface indent coverage



- Exponential curve fitting to $f(x) = a\left(1 - e^{-bx}\right) + c$
- High correlation coefficients, $R^2 > 0.985$

Grain size observation

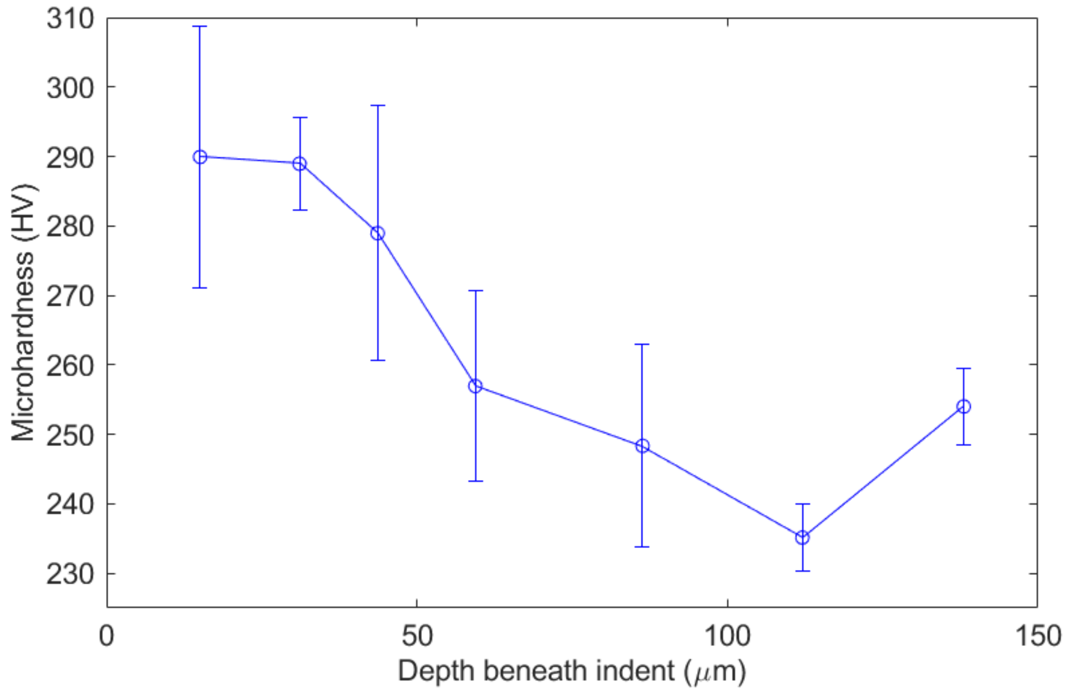
- Electron backscatter diffraction was used to observe impact sites on polished 304 SS specimens.
- A 2 μm deep layer of nanograins with $d = 1.04 \pm 0.65\ \mu m$ was observed.
  - Coarse grain size was $d = 7.59\ \mu m$
- High angular misorientation was observed at the surface, indicating strain and grain refinement



EBSD observation of an impact site with inverted pole figure (A) and kernel average misorientation (B).
Figure by Samuel Scott

Hardness gradient beneath PECSMAT impacts

- Microhardness testing was performed under PECSMAT indents.
- A gradient hardness layer ranging from 290 HV at the surface to 235 HV at a depth of 120 μm.
- Wu *et al.* (2016) report a gradient hardness layer of 200 μm in SMAT-processed 304 SS.



Vickers microhardness testing gradient beneath a PECSMAT indent site.

Figure by Samuel Scott

Conclusion

- Gradient nano grain structures (GNGs) in metal can significantly increase strength without compromising ductility.
- PECSMAT offers a way to prescribe impact location and energy, with per-impact energy measurement.
- Stainless steel was strengthened by up to 70% by PECSMAT treatment with less than 10% reduction in ductility.
- Gradient hardness and nanograin layers were confirmed beneath PECSMAT impact sites.
- PECSMAT can be used to prescribe material strengths.

References

- Mohamed, W.; Miller, B.; Porter, D.; Murty, K. The Role of Grain Size on Neutron Irradiation Response of Nanocrystalline Copper. *Materials* **2016**, *9*, 144. https://doi.org/10.3390/ma9030144
- X. Wu, P. Jiang, L. Chen, F. Yuan, and Y. T. Zhu, “Extraordinary strain hardening by gradient structure,” Proc. Natl. Acad. Sci. U. S. A., vol. 111, no. 20, pp. 7197–7201, May 2014, doi: 10.1073/pnas.1324069111.
- Y. Yang et al., “Effect of bimodal grain size and gradient structure on heterogeneous deformation induced (HDI) stress and mechanical properties of Cu,” Mater. Res. Express, vol. 9, no. 3, p. 035004, Mar. 2022, doi: 10.1088/2053-1591/ac5a37.
- Sharp, P.K., Clayton, J.Q., Clark, G., 1994. The Fatigue Resistance of Peened 7050-T7451 Aluminium Alloy—Repair and Re-Treatment of a Component Surface. Fatigue Fract. Eng. Mater. Struct. 17, 243–252. https://doi.org/10.1111/j.1460-2695.1994.tb00226.x
- Naghizadeh, M., Mirzadeh, H., 2019. Effects of Grain Size on Mechanical Properties and Work-Hardening Behavior of AISI 304 Austenitic Stainless Steel. Steel Res. Int. 90, 1900153. https://doi.org/10.1002/srin.201900153
- X. Liu et al., “High strength and high ductility copper obtained by topologically controlled planar heterogeneous structures,” Scripta Materialia, vol. 124, pp. 103–107, Nov. 2016, doi: 10.1016/j.scriptamat.2016.07.003.
- M. Umemoto, Y. Todaka, and K. Tsuchiya, “Formation of nanocrystalline structure in carbon steels by ball drop and particle impact techniques,” Materials Science and Engineering: A, vol. 375–377, pp. 899–904, Jul. 2004, doi: 10.1016/j.msea.2003.10.198.
- J. Long, Q. Pan, N. Tao, M. Dao, S. Suresh, and L. Lu, “Improved fatigue resistance of gradient nanograined Cu,” Acta Materialia, vol. 166, pp. 56–66, Mar. 2019, doi: 10.1016/j.actamat.2018.12.018.

References

- Chen, A., Liu, J., Wang, H., Lu, J., Wang, Y.M., 2016. Gradient twinned 304 stainless steels for high strength and high ductility. Mater. Sci. Eng. A 667, 179–188. https://doi.org/10.1016/j.msea.2016.04.070
- Yanushkevich, Z., Mogucheva, A., Tikhonova, M., Belyakov, A., Kaibyshev, R., 2011. Structural strengthening of an austenitic stainless steel subjected to warm-to-hot working. Mater. Charact. 62, 432–437. https://doi.org/10.1016/j.matchar.2011.02.005