Strengthening Copper using Position and Energy Controlled Surface Mechanical Attrition Treatment (PECSMAT)

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Abstract

Surface Mechanical Attrition Treatment (SMAT) has shown positive benefits in the strengthening of nano crystalline materials. SMAT, like shot peening, uses hard materials like steel balls to impact the surface of an object. These impacts increase the yield strength of the material by refining the grain structure. However, this increase in yield strength is at the cost of a lower ductility. Historical SMAT and shot peening techniques lack precision and repeatability. With the use of a custom machine called the Position and Energy Controlled SMAT (PECSMAT), impact location and energy can be accurately controlled. This allows for unique SMAT applications that have not be previously explored. The use of PECSMAT on Oxygen-Free High Conductivity (OFHC) Copper increases yield strength while maintaining ductility. In this study, OFHC copper was annealed to create a homogeneous grain structure. The copper was then impacted with various patterns on the PECSMAT. Each of these conditions were then tested via tensile tests. It was observed that specimens with impacts showed a greater yield strength than the control annealed samples. Greater impact density increased the yield strength at the cost of a lower ductility. The use of this information can help in the creation of strong and ductile material. The use of annealing and impacting via PECSMAT can be used to tailor a material's properties for a specific use case.

Introduction

Shot peening is a surface strengthening technique in which spheres of hard materials like steel are bombarded onto a surface using a stream of pressurized air. This technique has been used to increase yield strength by refining grain structure. Recent studies have been conducted on a similar technique called Surface Mechanical Attrition Technique (SMAT) which is different only in that the spheres (also called shot) are larger. For shot peening the diameter of shot is usually 0.25 – 1 mm (0.0098 - 0.039 in), while SMAT is 2 – 10 mm (0.079 – 0.394 in) [3]. Due to the nature of the shot delivery the main limitation to shot peening and SMAT is that the location and velocity of shot can only be loosely controlled. A novel technique was created to address these issues, and it is called Position and Energy Controlled SMAT (PECSMAT). This technique is different in that a pneumatic impactor is connected to a Computer Numerically Controlled (CNC) mill. Figure 1 shows a picture of the PECSMAT machine created for this purpose. It consists of a Tormach 440 CNC mill and Festo pneumatic impactor controlled by custom software on a Raspberry Pi. The Tormach is responsible solely for precisely positioning the impactor. The Raspberry Pi is responsible for controlling the impactor with settings made by the user. The impactor is outfitted with a 6.35 mm (0.25 in) tungsten carbide hemisphere to represent the shot used in SMAT. This study seeks first to validate the PECSMAT's abilities by comparing stress-strain data of PECSMATed Oxygen-Free High Conductivity (OFHC) Copper (99.99% pure) with literature values for SMATed 99.99% pure copper. All pneumatic impactor settings were kept constant for this study. Next, patterned impacts were PECSMATed on the same OFHC copper to compare how an intentional impact shape would affect the yield strength. For this study American Society of Testing and Materials (ASTM) standard E8 was followed to ensure repeatability of experiments. Finally, all results were graphed and compared for further analysis.

Methods

Annealed OFHC Copper sheets of thickness .04 in (1.02 mm) were purchased from McMaster Carr and cut to E8 specimen dimensions of 10 x 100 mm (0.394 x 3.94 in) in the rolling direction. These specimens were annealed at 500 °C (932 °F) for 1 hr in an argon environment to match the control specimens of Yang *et al.* Then to replicate a SMAT procedure a custom GCode program was created to produce random impact locations based on impact density (impacts per surface area). The impact density of Yang *et al.*'s samples were found using ImageJ. The pressure setting for the pneumatic impactor was set to 0.3 bar, and the standoff distance was set to 6.35 mm (0.25 in) and those settings were used for all tests in this study. After impacting the specimens were cut with an OMAX water jet into dog bone shapes as determined by the ASTM E8 standard. The second specimen from the right on Figure 2 depicts this dog bone shape. Then the specimens were pulled in tension on an Instron test frame at a rate of 1*10^-3 1/s. The stress strain data was captured and used later for further analysis. Three specimens of each set of parameters were created and the stress-strain values were averaged to produce a result for that parameter set. Next, similar impact densities were used for patterned impacts of hexagonal and diamond shapes. The same process for the randomly impacted specimens was used for the patterned shapes. These patterned impacts were then compared with the randomly impacted specimens.

PECSMAT Machine

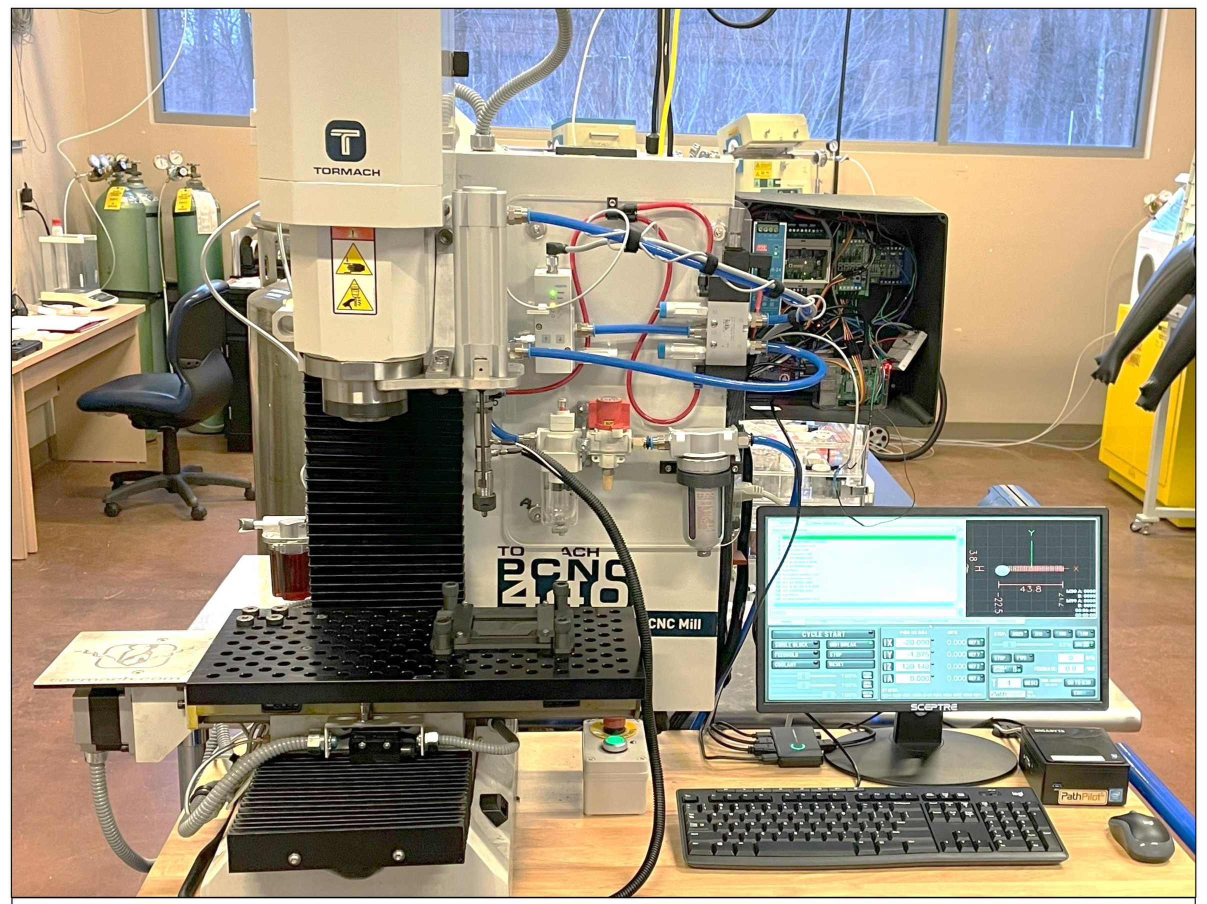


Figure 1: Picture of the PECSMAT machine.

OFHC Copper Samples

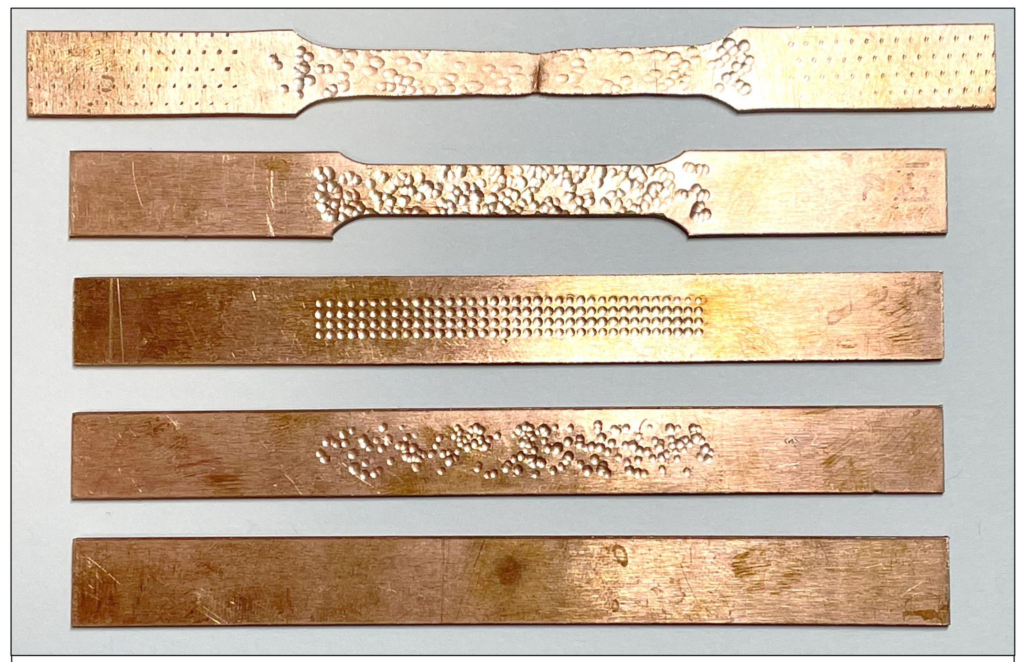


Figure 2: Picture of, from top to bottom, a tested E8 sample, a cut E8 sample, a square PECSMATed sample, a random impact sample, and a blank 8 specimen.

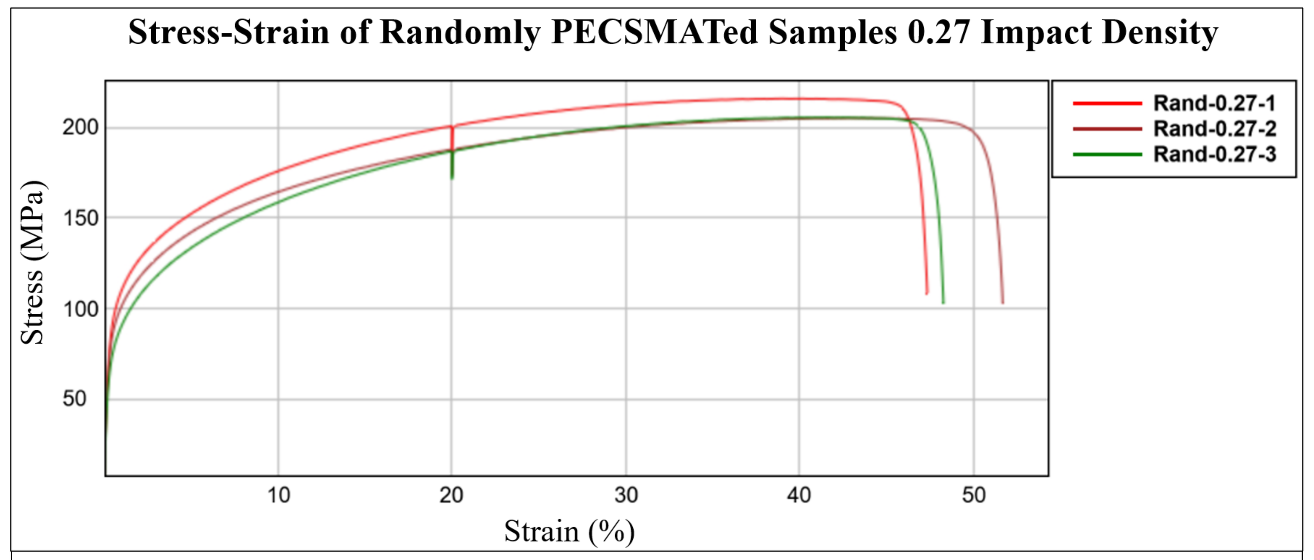
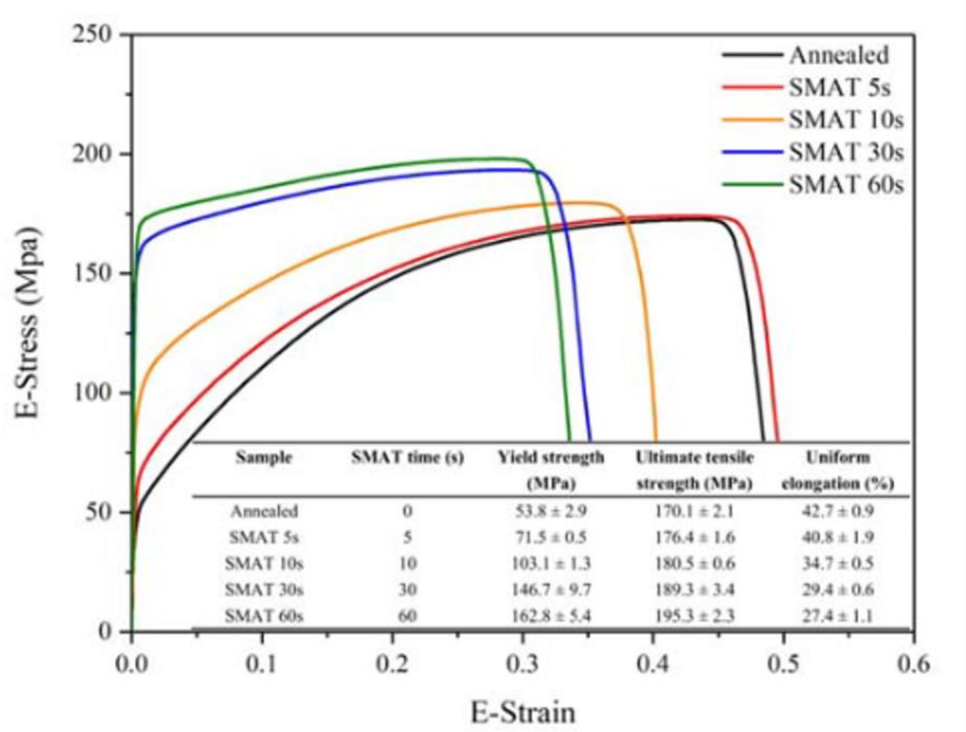


Figure 3: Graph of Stress-Strain data for specimens PECSMATed randomly with 0.69 impact density.



Sample	SMAT time (s)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Uniform elongation (%)
Annealed	0	53.8 ± 2.9	170.1 ± 2.1	42.7 ± 0.9
SMAT 5s	5	71.5 ± 0.5	176.4 ± 1.6	40.8 ± 1.9
SMAT 10s	10	103.1 ± 1.3	180.5 ± 0.6	34.7 ± 0.5
SMAT 30s	30	146.7 ± 9.7	189.3 ± 3.4	29.4 ± 0.6
SMAT 60s	60	162.8 ± 5.4	195.3 ± 2.3	27.4 ± 1.1

Figure 4: Summary of results presented by Yang *et al*. [1].

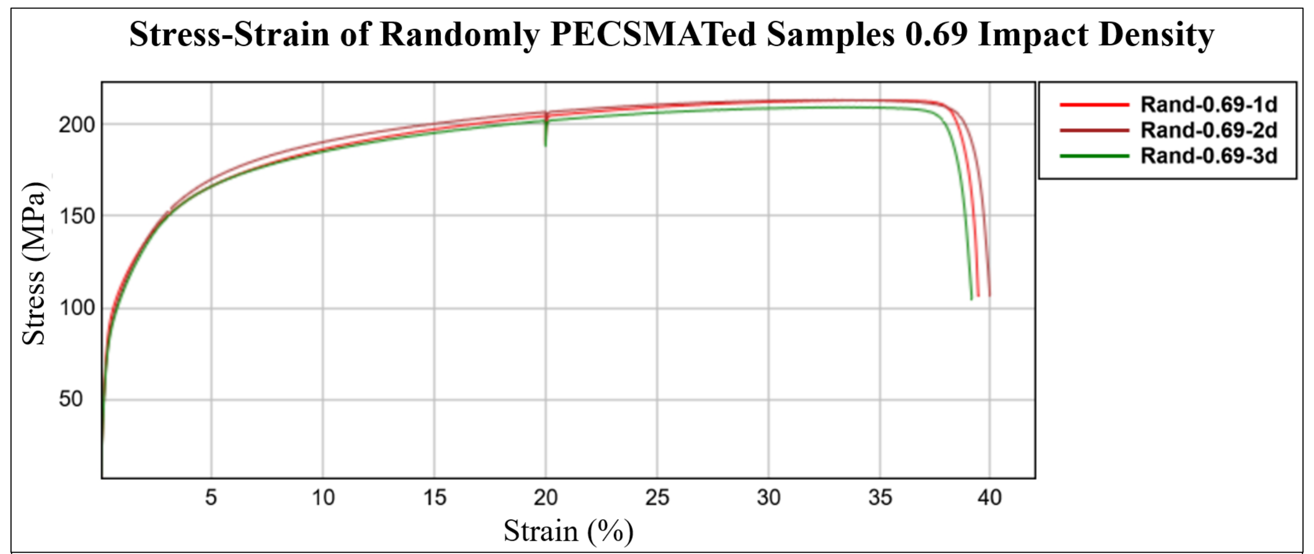


Figure 5: Graph of Stress-Strain data for specimens PECSMATed randomly with 0.69 impact density.

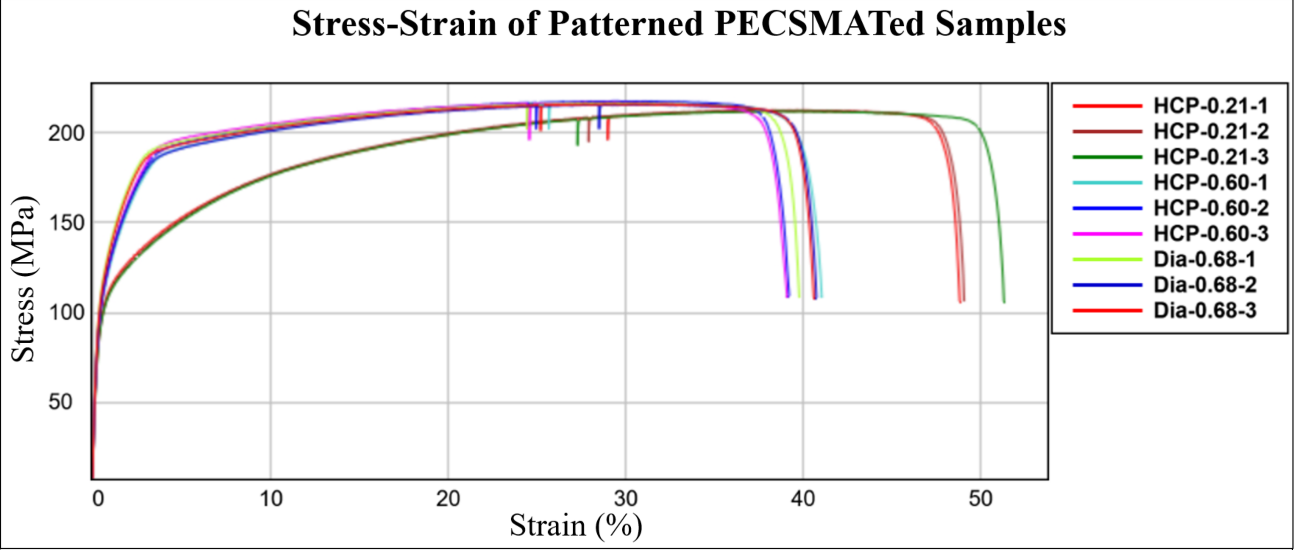


Figure 6: Graph of Stress-Strain data for specimens PECSMATed with patterns and various impact densities.

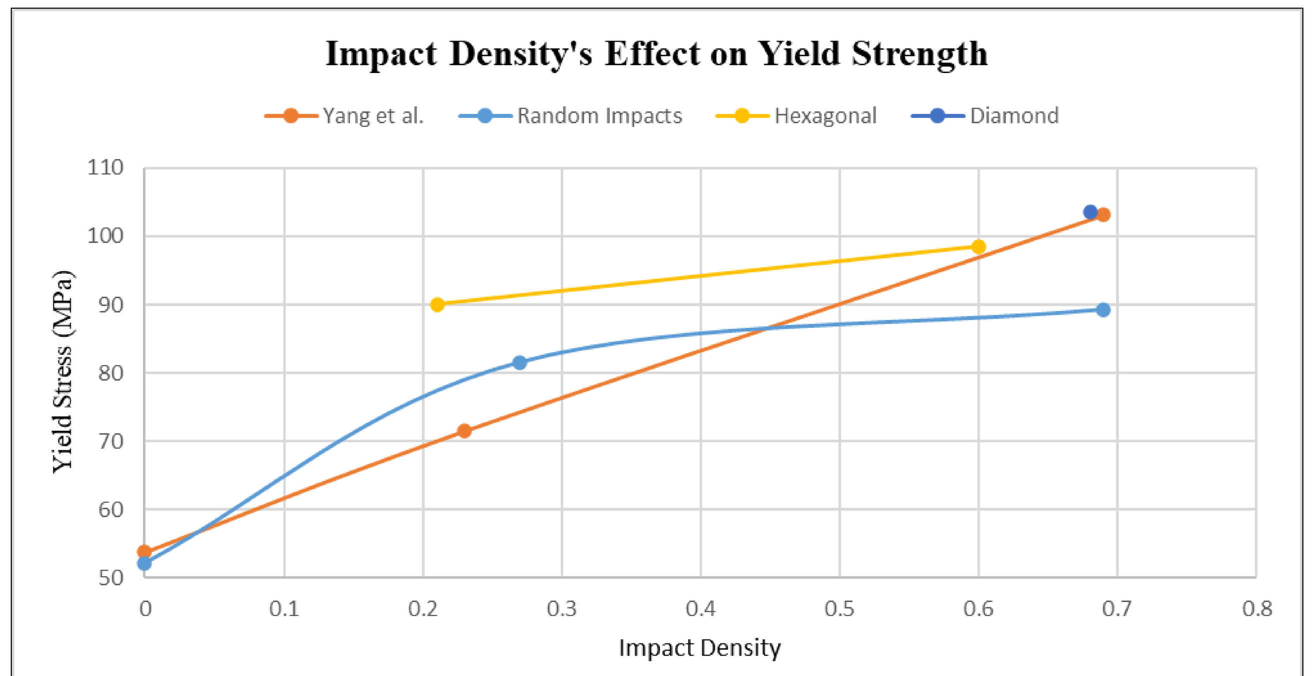


Figure 7: Graph of tested specimen's yield strength as impact density increases.

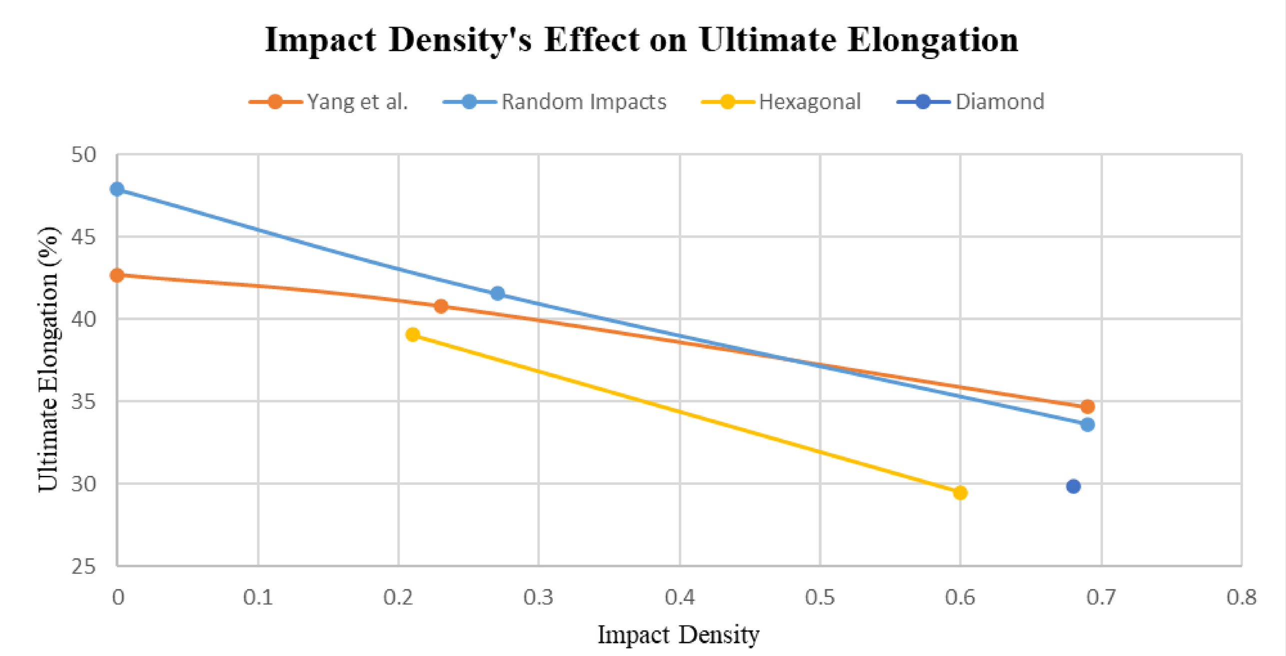


Figure 8: Graph of tested specimen's ultimate elongation with increasing impact density.

Results and Conclusions

Results

The impact densities of Yang *et al.*'s samples were found to be 0.27 and 0.69 for the SMAT 5s and 10s, respectively. SMAT times of 30s and 60s were not studied due to not being able to find their impact densities. It was found that the randomly impacted specimens on the PECSMAT matched closely with the literature data provided by Yang *et al.*. This can be seen in Figure 7 which shows the effect of increasing impact density on yield strength for the copper specimens. All specimens increased in yield strength as impact density increased which is to be expected. It appears that the yield strength gain is almost linear with respect to increasing impact density. But further studies would need to be conducted to show if PECSMATed specimens follow this trend. It should be noted that the randomly impacted specimens always failed in a location with the least number of impacts. This is due to the random nature of the SMAT process and there will usually be a location of least impacts. This causes a huge problem in repeatability of SMAT processes. A process like PECSMAT can deal with this by using a patterned impact in which every area of the treated area has the same number of impacts. The patterned impacted specimens failed much more consistently near the center. The patterned impacts performed equal to or better than all specimens shown by Yang *et al.* The greatest increase for PECSMATed samples versus SMATed samples is at low impact density. It should be noted that the hexagonal patterned performed best at 0.21 impact density as compared to Yang et al.'s 0.23 estimated impact density. It was not clear if the diamond pattern performed better than the hexagonal pattern, but further study could be conducted to find the differences. Most specimens failed with a 45-degree angle, so a new pattern could be optimized to cover as much area at an angle of 45 degrees.

Conclusions

Shot peening and SMAT are useful techniques for creating high strength high ductility metals by refining grain structure. But both techniques lack precision and repeatability. Also, their parameters can only be loosely controlled. The custom made PECSMAT addresses these issues by using a pneumatic impactor connected to a CNC mill. This adds precision and repeatability to the SMAT process. This study observed the use PECSMAT methodology on annealed pure copper. Various parameters were tested, and all were compared to literature values. It was found that the PECSMAT can replicate the SMAT procedure using a random impact generator. Next, it was observed that patterned impacts performed equal to or better than similar impact densities from literature SMAT values. The randomly impacted specimens failed at locations of fewer impacts, but patterned impacts addressed this issue with even surface coverage. Those patterned impacts performed equal to or better than literature SMAT values.

Future Work

1. Find optimal pattern for strength increase while maintaining ductility
2. Impact at stress concentrations for strengthening
3. Improve fatigue life in pre-cracked cylindrical specimens
4. Find effect of PECSMAT on stress corrosion cracking

References and/or Acknowledgments

[1] 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.

[2] S. Scott and M. Atwater, "New method for position and energy controlled surface mechanical attrition treatment and its effects in 304 stainless steel," J Mater Sci, vol. 59, no. 4, pp. 1679–1698, Jan. 2024, doi: 10.1007/s10853-023-09274-w.

[3] K. Dai and L. Shaw, "Comparison between shot peening and surface nanocrystallization and hardening processes," Materials Science and Engineering: A, vol. 463, no. 1–2, pp. 46–53, Aug. 2007, doi: 10.1016/j.msea.2006.07.159.