Extrusion Auger Improvement Project

Aaron Wagner
Dept. of Mechanical Engineering
Santa Clara University
Santa Clara, USA
awagner@scu.edu

Maureen O'Neill
Dept. of Mechanical Engineering
Santa Clara University
Santa Clara, USA
moneill@scu.edu

Dr. Panthea Sepehrband
Dept. of Mechanical Engineering
Santa Clara University
Santa Clara, USA
psepehrband@scu.edu

***Abstract*—This project has designed a material treatment process to extend the lifespan of extrusion augers used by the social enterprise Appropriate Energy Saving Technologies (AEST) in Uganda. AEST uses an extruder machine to recycle agricultural waste into charcoal briquettes that they sell to low-income families. The auger components wore down quickly and needed a hardening process to remain useful for longer. The team built a custom pin-on-disk testing apparatus and used it along with optical microscopy to simulate and analyze the wear mechanism. The team then heat-treated and tested additional samples to find the best treatment. The team suggested improving AEST's current case hardening process by increasing the case depth to 0.04 in (0.1016 cm) and using oil quenching.**

Keywords—extruder, extrusion, auger, materials, charcoal, agricultural waste, heat treatment, tribology, wear, social enterprise

I. INTRODUCTION

The social enterprise Appropriate Energy Saving Technologies Limited (AEST) uses recycled agricultural waste to make charcoal briquettes to sell. They are a woman-registered organization that operates in the Teso Region of Uganda. They aim to provide energy solutions for low-income households in the area, and in addition to producing charcoal briquettes, they also make and sell cook stoves [1].

AEST makes their charcoal briquettes through a process called extrusion. Extrusion is the process of pushing a moldable material through a hole at the end of a large drum to create a long, even bar of the material. The auger is the large screw that rotates in the middle of the drum to move the material through. As the part that does the most work and experiences the most force, the auger is the component most vulnerable to wear.

AEST's main problem was that the auger shaft of their charcoal extruder wore out quickly. Fig. 1 shows the severe wear that was rendering augers unusable in a few work days [2]. A new material or hardening method needed to be found to increase the life of the extrusion auger. Short-lived augers have cost AEST time and money to repair or replace constantly, while their briquette production suffered from having too few augers available at once. Improving auger lifetime means distributing more recycled charcoal, which produces much less harmful smoke than wood charcoal [3] and lets families have fuel without losing hours every day to chop wood [1]. To try to achieve this, AEST has worked with a previous team from the MIT D-Labs to slightly improve auger lifetime.

AEST has been case hardening their augers using pack carburization. Carburizing is a kind of surface hardening that increases the carbon content of steels at the surface. Increasing the carbon content of steel will increase hardness but also brittleness. Case hardening thus preserves flexibility in the interior of the part while increasing outer hardness. Pack carburizing involves submerging a steel sample in a high-carbon medium such as graphite or charcoal, and heating the specimen in a furnace. AEST has been carburizing their auger to a case depth of 0.02 in (0.0508 cm) and quenching with water after case hardening, based on the recommendation of the previous MIT researchers that worked with AEST.

MIT D-Labs worked with AEST on case hardening the auger screws. They designed a brick furnace and case hardened the augers to a case depth of 0.0508 cm. They also tested the surface hardness of different quenchants, and they chose water quenching for the highest surface hardness. AEST estimated that these improvements led to a 50% increase in lifespan, but they desired more improvement [2]. To further improve the wear resistance of the auger and increase its lifetime, it is important to properly investigate the wear mechanism and not blindly rely on the hardness increase.

Fig. 1. Comparison of new and worn auger screws.

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Wear is mechanically induced surface damage that involves the removal of material from a surface over time. Usually there is more than one wear mechanism acting on a machine part, and corrosion or other effects can also exacerbate mechanical wear [4]. Depending on the wear mechanism, an increase in hardness can improve or worsen the wear resistance. This project aimed to determine the primary wear mechanism acting on the metal auger and quantify the effects of case hardening on wear resistance. This information would let the team propose a heat treatment process that would lead to an increase in wear resistance and in turn lifetime of the auger.

II. METHOD

The wear mechanism of the auger was investigated using a custom pin-on-disk machine that the team built, which is detailed in Section IV. To simulate the wear condition during service of the auger, Ground Royal Oak 100% All Natural Hardwood Lump Charcoal was added to the cup as the main source of friction against the pin. Since the ground cassava charcoal used by AEST could not be mailed to America, natural wood charcoal was chosen as a substitute, as this type is the main charcoal produced in Uganda. After a few initial trials to find the best testing procedure, the apparatus was run at 300 RPM for 5 hours for all pins whose data were recorded.

Pin-on-disk tests have been performed on as-received round-stock samples of 1018, 1214, 1045, and 8620 steel and carburized 1018 steel samples. Pins were cleaned before and after pin-on-disk testing, as well as after heat treatment, via ultrasonic cleaning in a Branson 2800 Ultrasonic Cleaner. Pins were weighed before and after each trial on a Tree HRB224 analytical scale. The pins were 2 inches long with a rounded tip that was machined using the lathe, with diameters of 0.3125 in (1018, 1214), 0.4375 in (8620), and 0.5 in (1045) based on available round-stock diameters. All pins for the pin-on-disk testing were first mounted in Buehler SamplKwick two-part epoxy using 1 in (2.54 cm) diameter mounting cups.

Carburizing was conducted using graphite powder as the carbon medium. Carburizing samples (pins and the smaller process control samples) were placed inside alumina crucible boats filled with graphite. The crucibles were then placed and heated inside a Barnstead/Thermodyne 21100 tube furnace. A total of 11 pins, 10 of which were used for the final set of results, have been carburized. Other than the first attempt, the pins were all heat treated in pairs via two crucibles in the furnace at once; one was quenched in water and the other in oil. Table 1 shows the time, temperature, quenchant, and expected case depth for each heat treatment performed. Pins have been given a sample code based on their approximate case depth and quenchant. For example, sample 0.05-W was case-hardened to a depth of 0.0508 cm and quenched in water, while 0.05-O was quenched in oil.

TABLE I. HEAT TREATMENT PROCEDURES

Sample Code	Temp. (°C)	Time (hours)	Quenchant	Case Depth (cm)
0.05-W	975	1.8	Water	0.0508
0.05-O	975	1.8	Oil	0.0508
0.07-W	1000	3.1	Water	0.0762
0.07-O	1000	3.1	Oil	0.0762
0.09-W	1025	3.5	Water	0.0914
0.09-O	1025	3.5	Oil	0.0914
0.10-W	1025	4.3	Water	0.1016
0.10-O	1025	4.3	Oil	0.1016
0.11-W	1000	9.2	Water	0.1143
0.11-O	1000	9.2	Oil	0.1143

Process control specimens from heat treatment were mounted in epoxy and then ground and polished starting with 200 grit sandpaper and ending with a 0.1 µm alumina powder.

Microscopy was done using a Leica DM IRM Inverted Materials Microscope, a Leica DFC450 Digital Color Microscope Camera with 5 Megapixel Resolution, and the Leica Application Suite. Due to the unusual shape of the pins, a holder was constructed out of PVC pipe and three screws in order to suspend the ground plane of the pin over the microscope. Images at 5 and 100 times magnification were taken for each sample.

Vickers hardness tests were performed on most of the process control samples to verify that heat treatment had increased the hardness near the surface of the steel. A LECO LM 248AT Microhardness Tester was used to indent each sample repeatedly at a load of 300 gf, starting in the center and proceeding toward the edge in intervals of 0.025 in (0.0635 cm). This was repeated in at least five directions from the center for each sample.

III. PIN-ON-DISK TESTING

Pin-on-disk testing is used to understand the sliding wear between two different materials. One specimen is a pin with a spherical tip and the other specimen is a flat disk. Either the pin or disk rotates creating a circular sliding path. For a pin-on-disk apparatus, the results can be considered more accurate the closer the testing environment mimics the working environment; however, it is often impractical to fully recreate the working environment. For this reason, pin-on-disk testing can only predict the relative ranking of different material combinations, and should be combined with other testing methods to produce a clear picture of the wear mechanism. Tribology alone cannot accurately predict the lifetime of a part, but can predict the relative lifetimes of different part materials [5].

Although there are commercially available pin-on-disk testing machines, most pin-on-disk testing apparatuses have been custom produced for a specific experiment in order to better model the wear environment of a specific system. As such, it is difficult to compare the results from one study to another. While adhering to the established standard, ASTM G99, can help, it is necessary to fully understand the applied conditions of each result set in order to compare them [4].

The pin-on-disk testing apparatus built for this experiment was a single horizontal arm design with a spinning disk. The sample disk locked into a support disk that was surrounded by a cup, as shown in Fig. 2. Ground charcoal was placed into the cup during testing to better mimic the conditions in the auger. The CAD model of the complete Pin-on-Disk Apparatus is shown in Fig. 2.

The main motor need was the ability to run continuously for at least 8 hours and be able to plug into a normal wall outlet. A rated torque of 18 in-lb (2.0337 N-m) and an axial load of at least 9 lb (40.034 N) were desired, along with the ability to vary the speed between 60-600 rpm. The motor system purchased from Oriental Motor Co. consisted of a motor and driver. The model purchased was the BMU5120AP-5A-3 Brushless DC Motor Speed Control System which has a rated torque of 17.17 in-lb (1.9399 N-m) and a max axial load of 33 lb (146.791 N). As the estimates for torque were calculated with a 3x factor of safety, 17.17 in-lb (1.9399 N-m) was considered sufficient. The motor can vary in speed from 16-800 rpm and has a high dust protection rating.

It was very important to have charcoal dust on the surface of the disk to simulate wear. To have an application system with moving parts that was robust enough to run unsupervised, a cup shaped disk was designed. The cup shape disk avoids charcoal to fly away during the test. The bottom of the cup was made out of stainless steel disk that locked into an aluminum base. The sides of the cup were cut from a schedule 40 6 in (15.24 cm) ABS plastic pipe.

The locking mechanism between the stainless steel disk specimen and the aluminum support disk was modeled after the plates used on specimen polishers, as shown in Fig. 3. It consists of three raised cylinders on the aluminum plate, which fit into three cylindrical bore holes on the stainless steel disks to keep them in matching rotation. A more complete description of the apparatus can be found in [6].

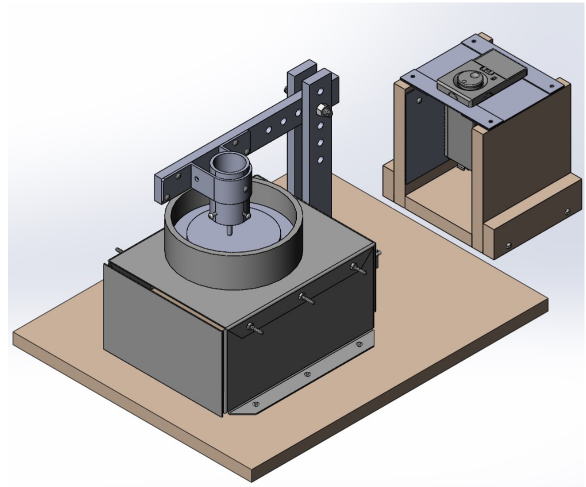

Fig. 2. CAD model of Pin-on-Disk Apparatus.

After several trial tests, a speed of 300 RPM and a test time of 5 hours was chosen as this allowed for a visible wear pattern as well as the ability to run multiple tests in one day. All tests were run with the arm pin joint in the last hole on the horizontal arm as this provided the largest wear track radius.

Fig. 3. Locking mechanism in disk subsystem.

IV. RESULTS AND DISCUSSION

To identify the wear mechanism, the micrographs taken form the surface of the worn samples (after pin-on-disk test) are compared with images of typical wear patterns found in the *Friction, Wear, and Erosion Atlas* [7]. The microscopy images most closely resemble the image of three-body abrasion from the Atlas [7]. This can be seen in Fig. 4, where the untreated steel samples exhibit the long, color-varying streaks typical of three-body abrasion. Although pockmarks have been found on several samples, as in sample 0.05-O shown in Fig. 5, this was likely due to construction of the pins rather than corrosion since they do not appear consistently.

To study the efficiency of the implemented case hardening process, changes in hardness throughout the sample are measured. Fig. 6 shows the Vickers hardness testing results for two of the process control samples, 0.09-W and 0.10-O. The hardness increases near the edge as expected, a good indication of a successful that carburizing heat treatment.

For each heat treatment condition, the expected depth of case hardening was calculated as reported in Table 1. The depth of the case hardened region depends on the diffusivity constant, the temperature, and the process time. Carbon concentration at a certain case depth can be calculated from Equation 1:

$$C = C_s - (C_s - C_0) \cdot erf[x/(2 \cdot [Dt]^{1/2})] \qquad (1)$$

C is the carbon concentration at depth x from the material surface, C_s and C_0 are respectively the concentrations at the surface (usually 100%) and the center (the untreated metal's concentration), D is the diffusion rate calculated by Equation 3, and t is the amount of time spent diffusing at that rate.

A recommended concentration C to examine is halfway between C_s and C_0 such that the *erf* term is 0.5. Conveniently, this occurs when everything inside

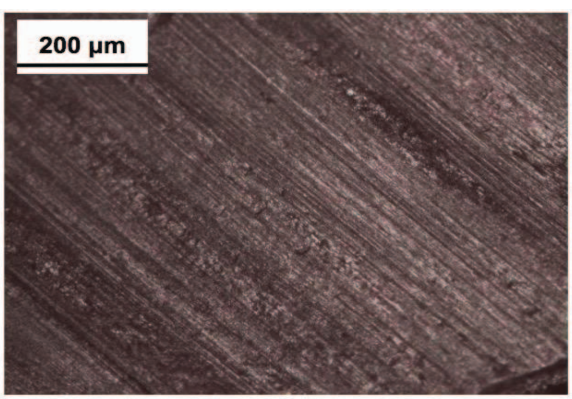

Fig. 4. Untreated 1018 steel and ground charcoal showing three-body abrasion.

Fig. 5. Example of pockmarks on sample 0.05-O.

erf is also 0.5, so at this particular concentration the case depth equation becomes:

$$x = (Dt)^{1/2} \qquad (2)$$

where D is evaluated by:

$$D = D_0 \cdot exp[Q/(RT)] \qquad (3)$$

D_0 is a material-dependent diffusivity constant (0.23 cm^2/s for carbon into steel), Q is the activation energy (32,900 cal/mol for diffusion of carbon into iron), R is the ideal gas constant, and T is the temperature in degrees Kelvin.

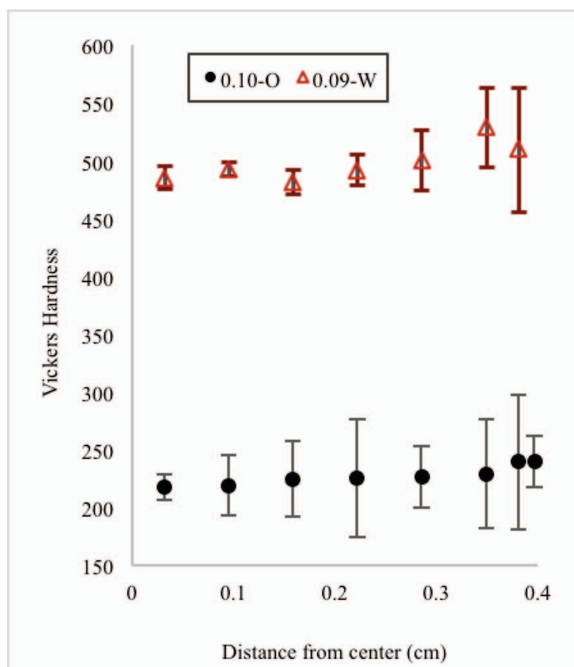

Fig. 6. Vickers hardness testing results for process control specimens 0.09-W and 0.10-O.

After hardening, steel pieces are quenched to promote the development of martensite. Different quenching media offer different rates of heat extraction [8], so different levels of hardness are expected for the samples quenched differently with the same case depth.

The results of mass loss measurement during the pin-on-disk test as a function of the depth of the case hardened region (i.e. case depth) for various heat treatment conditions tested are reported in Fig. 7.

Most notable are the results for the samples with 0.0508 cm case depth [samples 0.05-W and 0.05-O] (where AEST is currently achieving their case hardening) and 0.1016 cm case depth [samples 0.10-W and 0.10-O]. Doubling the case depth reduced wear by about 80%, from a mass loss of 0.55 g to a loss of only 0.0108 g. The time required also fits into an AEST workday of five hours. While case hardening to 0.1143 cm [samples 0.11-W and 0.11-O] reduces the wear even more drastically, the very long heating time required would not be feasible for AEST to perform.

Also notable is the extremely similar performance of oil- and water-quenched samples at these two highest case depths. AEST currently uses water quenching, which likely distorts the auger and reduces its effectiveness. Since the higher case depths offer the same hardness regardless of quenchant, oil becomes more advantageous to reduce distortion.

The increased fuel costs associated with longer case hardening are expected to be offset by the increase in lifespan, and quenching oil can be reused many times.

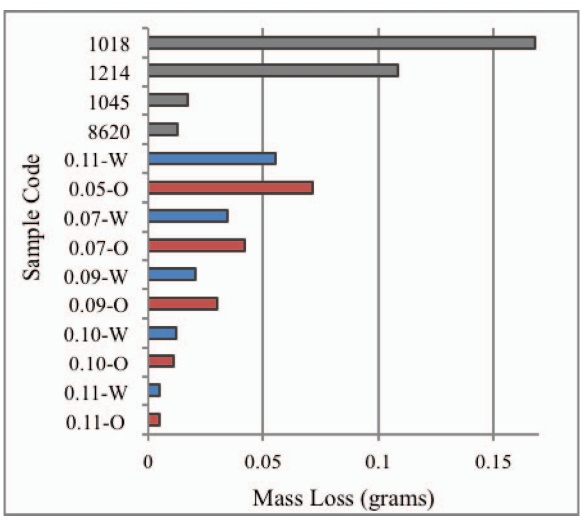

Fig. 7. Bar graph showing the mass loss in grams of different pin specimens after undergoing pin-on-disk testing at 300 RPM for 5 hours.

VI. CONCLUSIONS AND RECOMMENDATIONS

Currently AEST case hardens their augers to a depth of 0.02 in (0.0508 cm) and uses water quenching. The team's final suggestion to AEST was to switch to a case depth of 0.04 in (0.1016 cm) and switch to oil as a quenchant for the best combination of improvement and time investment. The increase in lifespan is expected to offset the increases in cost.

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