Experimental Apparatus for Continuous-Bending-under-Tension and Experiments on A6022-T4

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EXPERIMENTAL APPARATUS FOR CONTINUOUS-BENDING-UNDER-TENSION AND EXPERIMENTS ON AA6022-T4

BY

TIMOTHY JOHN ROEMER

B.S. Mechanical Engineering, University of New Hampshire, 2013

THESIS

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in
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ABSTRACT

EXPERIMENTAL APPARATUS FOR CONTINUOUS-BENDING-UNDER-TENSION AND
EXPERIMENTS ON AA6022-T4

by

Timothy John Roemer

University of New Hampshire, September, 2016

An experimental technique called Continuous-Bending-under-Tension (CBT) can produce
elongations over two times that of a standard tensile test by preventing the necking instability
from occurring. This is achieved by superposing plastic bending on tension along the gauge
length of the material using three rollers. The specimen is kept under tension as the rollers
apply three-point bending while cyclically traversing the gauge length. This subjects the
specimen to plastic deformation only in the region that is visited by the rollers. Details on the
design of various subsystems of this unique CBT machine are presented. The results for a
variety of CBT experiments in the rolling direct (RD) and transverse direction (TD) were
conducted to explore the CBT parameter space. Two additional types of experiments were
conducted using the CBT machine. In one, interrupted CBT experiments were conducted to
study the development of the grain structure within the gauge region during the CBT process. In
the other, friction tests were used to determine the coefficient of friction between AA6022-T4
and the steel rollers during the CBT process. The latter is proposed as a general method to
measure the friction coefficient between a sheet and a die. The manufacturing industry will
benefit from a stronger fundamental understanding of the mechanisms that improve the
potential elongation for the CBT process.
CHAPTER 1
INTRODUCTION

1.1 Motivation

With the rising cost of oil and ever increasing federal environmental standards on fuel consumption, the automotive industry is increasingly of using new high strength, light-weighting materials. The United States Environmental Protection Agency (EPA) has mandated that by the year 2025 [4] the average miles per gallon (mpg) of an automotive company’s fleet of new cars and light-duty trucks must be greater than 54.5 mpg. This trend of increasing fuel efficiency standards is observed across the world (see Figure 1.1). One way that automotive companies could potential reach this mpg standard is by reducing the vehicle’s weight. Companies are continuously exploring different materials to replace the traditional mild steel used for components and frame structures to achieve this.

The automotive industry currently utilizes a wide variety of different light weight or high strength metals ranging from aluminum to magnesium to advanced high strength steels (AHSS). Basically, the stronger the metal, the less bulk material is needed to meet seemingly competing safety standards thus reducing the vehicles weight. The limitation of completely replacing mild steel in vehicles with these alternatives is due to their often poor formability with higher strength (see Figure 1.2). The limited elongation-to-fracture for these higher strength materials forces manufacturers to utilize mild steel in order to achieve the specific dimensions for the vehicle’s frame and body. The materials used in a typical four-door sedan can be seen in Figure 1.3. One can see that very little AHSS is used throughout the frame, with a majority being mild or high strength steels.
Figure 1.1: Rising miles per gallon standards across the world. [5]

Figure 1.2: Diagram of total elongation vs. tensile strength for different steels. [3]
By gaining a fundamental understanding of the material behavior for these higher strength metals, manufacturers can find innovative processes to include more of these metals in automotive frames. The most common and standard material testing technique is the uniaxial tension test. This test is simple to perform and provides sufficient information about the plastic flow of a material for many applications. However, the tension test is limited by the appearance of necking, i.e., non-uniform deformation of the gage area, which causes failure of the material in a localized region. By reflecting upon the tension test, it can be realized that the material is actually capable of much larger strains, e.g., the strains in the neighborhood of the neck throughout the gage length. However, since necking implies a localization of deformation, the remaining material in the test section remains “under-stretched”, i.e. it is stretched significantly less than the material around the neck. Therefore, if a deformation procedure delays necking and prevents localized failure; much larger strains could be achieved. The information gathered from this type of experiment would better represent material behavior in many manufacturing
processes. This can be achieved by a process known as Continuous-Bending-under-Tension (CBT).

1.2 Continuous-Bending-under-Tension Theory

An experimental technique called CBT can generate elongations-to-fracture over six times that of a standard tensile test [1, 2]. This is achieved by locally applying a bending moment using three rollers that travel along the gage length of the specimen during uniaxial tension. The specimen is kept under tension as the rollers apply three-point bending and cyclically transverse along the gage length. A schematic of this process is shown in Figure 1.4.

The three rollers cause the material to plastically deform only at their location and lower the tension load to induce deformation by subjecting the specimen to bending-under-tension. This allows the moving rollers to incrementally deform the specimen over the entire gage length, thus stabilizing the deformation and preventing a diffuse neck from forming. The deformation that occurs in the bending zone is heavily dependent on the location of the neutral axis. If the neutral axis is shifted by the presence of tension, to cause less material to be in compression,
then the strain of the specimen on the opposite surface will increase [6]. At the same time, the net force on the cross-section remains below the critical condition for necking, so that the deformation remains stable.

![Figure 1.5: Through-thickness stress and strain distribution of specimen under ordinary tension (a), ordinary plastic bending (b), and plastic bending under tension (c). [2]](image-url)

Substantial investigation into the fundamental mechanisms behind CBT has yet to be conducted. Currently, there is a proposed theory predicting the through-thickness stress and strain fields of a specimen experiencing plastic bending under tension (see Figure 1.5). Plastic bending under tension is predicted to produce an asymmetric stress-strain field through the thickness, which is believed to produce larger strains while delaying necking. There is no experimental data to back up these theories due to equipment setup limitations, thus further investigation is required.

1.3 Past CBT Research

Several approaches to achieving large amounts of strain using modified tension tests have been reported in the literature. Taraldsen first proposed the idea of using sets of rollers that continuously moved up and down a specimen [6]. The rollers applied a limited amount of contact stress, achieving elongations of up to 600% for copper, (see Figure 1.6).
Rijken showed the same principle by only implementing one set of rollers [6]. Rijken’s tests achieved approximately 100% elongation. Benedyk was the first to propose the experiment known as CBT using three point bending [1]. Benedyk’s test differed from his predecessors by producing high levels of uniform strain along a strip of material as a formability test. Emmens and Van den Boogaard conducted further CBT research exploring different aspects of CBT: stability, formability, material characterization, experiments, and numerical investigations [1, 6]. A diagram of the modified uniaxial tension machine used by Emmens is shown in Figure 1.7.
All prior work on CBT experimental setups utilized existing equipment which was modified to perform the desired experiment. Because of this factor, the experimental setups had limitations that prevented techniques such as Digital Image Correlation (DIC) from being utilized, as well as limiting different specimen geometries, and additional experimental measurements such as roller position from being obtained. This required certain assumptions and predictions regarding the CBT phenomenon to be made that were not validated.

The work presented in this thesis addresses the limitations of past CBT machines with the construction of a dedicated CBT machine (Chapter 2) at the University of New Hampshire. The design and construction of this dedicated CBT machine as well as the experimental investigations into an automotive aluminum AA6022-T4, is discussed (Chapter 3). In addition, a microstructural analysis of the interrupted CBT test was conducted to construct a fundamental understanding of the development of grain structures during the CBT process (Chapter 4).
Furthermore, a modified setup of the CBT machine to perform friction experiments is presented (Chapter 5). Finally, conclusions and the outlook for future work are discussed (Chapter 6).
CHAPTER 2

CBT MACHINE DESIGN AND MATERIAL CHARACTERIZATION

2.1 CBT Device at the University of New Hampshire

At the University of New Hampshire (UNH) a unique and dedicated CBT machine has been constructed. The CBT machine is comprised of three key components: (1) the sub-system for the tension test consisting of the hydraulic cylinder, the moving carriage, the grips, the load cells, and the Micropulse position sensor; (2) the sub-system for the continuous-bending effect consisting of the ball-screw and the roller apparatus; (3) the controls system. The core of the control system is the custom LabVIEW application, which was designed for data-acquisition and control of the hydraulic and ball-screw systems. The experimental setup can be seen in Figure 2.2 and Figure 2.3.

![Figure 2.1: UNH CBT machine cross-section view.](image-url)
Figure 2.2: UNH CBT machine test section view

Figure 2.3: UNH CBT machine experimental setup
There are several specific differences between the UNH CBT machine and its predecessors, some of which can be seen in Chapter 1. The UNH CBT machine is a dedicated system and was designed specifically for this experiment, rather than modifying existing tension machines. The primary motivation behind doing this was to improve upon prior experimental setups by continuously increasing the roller stroke as the specimen elongates. This allows for the CBT region length to increase more readily as deformation occurs, which was not implemented in the experiments reported earlier. Furthermore, both strip and sheet specimens can be accommodated due to the size of the carriage. The rollers and grips can be replaced or adapted to accommodate varying size specimens.

The setup also implements a stationary roller apparatus which allows for observation of through-thickness and in-plane strains using Digital Image Correlation (DIC). A data acquisition system collects the axial loads from two separate load cells attached at each grip. In addition, velocity of the carriage relative to the stationary rollers and hydraulic cylinder crosshead displacement are collected giving the operator the ability to observe loading on the specimen during different stages of the CBT cycle.

In the next two sections we will be looking at the physical setup of the CBT machine’s two primary sub-systems. The first is the carriage, which holds the components used for a uniaxial tension test. This includes the hydraulic cylinder, grips, load cell, and Micropulse position sensor, in addition to the box-shaped carriage itself. The second system contains the components for continuous-bending. This consists of the stationary roller assembly, linear ball screw, limit switches, and the AC brushless servomotor. The cross-section of the CBT machine in Figure 2.1 above shows the various systems and their connections.
2.1.a Tension Sub-System

The tension sub-system is responsible for the tension component of CBT test. This sub-system includes all sensors, components, and structures related to performing and collecting data from the axial loading applied to the specimen. The hydraulic cylinder is a major component of this sub-system. It is a Heavy-Duty hydraulic cylinder (HH Series) manufactured by Sheffer. This HH Series cylinder is rated for 206.8 bar and has a stroke length of 300 mm. The maximum velocity the cylinder can achieve while retracting the crosshead is 33.5 mm/s, with a maximum load capacity of 310 kN. The cylinder bore diameter is 152.4 mm and the crosshead rod has a diameter of 63.5 mm.

The Sheffer HH Series hydraulic cylinder is fitted with a Balluff BTL7 MicroPulse+ displacement and velocity sensor. This sensor uses a magnetostrictive principle, in which the mechanical motion of a magnet produces a potential. This voltage is proportional to the cylinder rod’s position and velocity when time is taken into account. The BLT7 MicroPulse+ uses a 24 V supply, and provides ±10 V analog output signal. The signal resolution is less than 0.33 mV, with 5 µm of hysteresis, and a max sampling rate of 4 kHz.

The cylinder rod is actuated by a Rexroth pressure-compensated axial-piston hydraulic pump. The hydraulic pump can be seen in Figure 2.3 of the experimental setup and has an 11.19 kW motor capable of producing a maximum pressure of 206.8 bar with a flow rate of 540.7 mL/s. The hydraulic system has a DBET-5X relief valve which uses a proportional solenoid to regulate the pressure in the system. The relief valve requires a 24V supply, and can handle pressures up to 350 bar at a maximum flow rate of 33.33 mL/s. The hydraulic cylinder velocity and position is controlled by adjusting the voltage supplied to a Rexroth 4WRE proportional valve. The proportional valves require a 24V supply, and can maintain pressures up to 315 bar at a maximum flow rate of 1333 cm³/s. Currently, the CBT machine Labview code
requires the operator to select a voltage which is correlated with a crosshead velocity. All components of the hydraulic system can be operated independently of the bending operation or in tandem to perform the CBT experiment.

The CBT carriage supports and contains all the components for the tension component of the CBT experiment. The carriage is constructed from three 3/4" thick plates of 1018 steel that are welded together. The carriage was designed to hold a load of 234 kN applied to the structure at the location where the grips mount on the CBT machine (see Figure 2.4).

![Free body diagram of CBT machine demonstrating loading in tension.](image)

Figure 2.4: Free body diagram of CBT machine demonstrating loading in tension.

This maximum force was chosen based on the loads produced when deforming a 1 mm thick sheet of DP 780 with a width of 250 mm. Both finite element analysis and simplified hand calculations were performed to determine if the carriage was able to support the applied load for the DP 780 sheet specimen. The bending stress was calculated using a simply supported beam model. A ¼ model was used in SolidWorks simulations with a Solid Mesh including four Jacobian points and a total of 17,913 nodes and 10,834 elements (see Figure 2.5). A final bending stress of 1,422 MPa was determined for the simplified beam deflection and 1,460 MPa for the SolidWorks FEA simulation with a maximum deflection of 36 mm (see Figure 2.6).
Figure 2.5: SolidWorks FEA simulation of ¼ cross-section of carriage and loading in tension.

Figure 2.6: SolidWorks FEA results showing maximum a) bending stress and b) deflection of 1460 MPa and a max deflection of 36 mm respectively.

2.1.b Continuous-Bending Sub-System

The continuous-bending subsystem consisting of the lathe bed, the ball-screw, the limit switches, and the roller assembly are discussed in this section. The first of these systems is the refurbished cast-iron lathe bed which the carriage travels along by means of the linear ball-screw produced by Nook Industries. The cast-iron lathe bed houses the ball-screw and supports the mounting of the AC brushless servomotor (see Figure 2.7). The ball-nut of the linear ball-
screw is mounted to a block attached to the bottom of the carriage. By rotating the ball-screw, the ball-nut and the attached carriage are traversed along a linear axis parallel to the cast-iron lathe bed. The linear ball-screw is rated for a 30 kN axial load, which is sufficient to translate the CBT machine carriage at a maximum velocity of 66 mm/s.

![Figure 2.7: Linear ball screw mounted to cast-iron lathe bed with AC brushless servomotor.](image)

To produce the continuous-bending, the carriage transverses back and forth on a linear ball screw actuated by a 1 kW AC brushless servomotor. This BSM90 servomotor is produced by Baldor and is operated by a FlexDrive II controller. The FlexDrive II interfaces with a Labview program which has been designed to control all of the functions of the CBT machine sub-systems and is described at a later section.

Limit switches control the range of the roller stroke along the CBT specimen’s gage length. A static limit switch is fixed to the cast-iron lathe bed and defines the “home” position of
the carriage. Prior to a CBT experiment, the carriage will return to the home position; this is the starting point of all CBT experiments for consistency. The dynamic limit switch is fixed to the cylinder crosshead grip. Both of these locations can be seen in Figure 2.8. This is a key feature that makes this particular CBT machine unique in its construction. By having the dynamic limit switch attached to the crosshead grip, the stroke length will adjust to match the elongation of the CBT specimen gage length. With this adjusting stroke, the entire gauge length of the specimen can undergo the CBT process.

Figure 2.8: Locations of the (a) static and (b) dynamic limit switches.

The roller assembly is used to adjust the normalized bending depth and is comprised of several different components as seen in Figure 2.9. The roller support attaches to the cast-iron lathe bed and houses the bottom two rollers which can only rotate. The roller adapter houses the third roller, and is used to adjust the normalized bending depth by a set of “bending depth” bolts, as show in Figure 2.9. By adjusting the position of these depth bolts, the operator can change the normalized bending depth of the experimental setup. Once the depth bolts have been adjusted to give the appropriate normalized bending depth, lock bolts are tightened to fix the roller adapters position for the experiment. The rollers are made out of stainless steel. They
have a diameter of 25 mm and are fitted with 12 mm ID/22 mm OD spherical bearings to reduce friction.

Figure 2.9: Roller assembly: rollers, roller support, depth bolts, and lock bolts.

The roller assembly was designed with the intent to measure through-thickness strains using a Digital Image Correlation (DIC) system. In contrast to the design of prior CBT machines, the roller assembly is fixed and the specimen transverse through the rollers. Prior designs had a roller carriage traverse the specimen’s gage length, which limited the possibility to mount a camera to record images of through-thickness strains. With a stationary roller assembly, there are no limitations to the size or type of equipment needed to collect images for the through-thickness strains as it requires no interaction with the CBT machine. A large viewing window
due to the design of the roller assembly allows for a full view of the specimen as it passes through all three rollers.

2.1.c Control System

The CBT machine is operated from one central LabVIEW program. This program accesses a DAQ board for collection of all sensor data and the hydraulic systems controls. There is also a separate serial line that communicates with the FlexDrive II to control the Nook ball screw’s velocity and number of cycles. All test functions related to operating the ball screw were programmed by Nook Industries. A majority of these functions are password protected and cannot be edited or viewed. The code to operate the hydraulic cylinder and collect data from the various sensors was added to the existing ball screw code developed by Nook. From the main panel, both systems can be accessed giving the operator the full functionality of both sub-systems. A breakdown of these systems and their interactions can be seen in Figure 2.10.
Prior to running a CBT experiment, pre-test functions are available to load a specimen into the grips as well as adjust and validate the roller stroke location. This can be completed using the “EXT” (extend) and “RET” (retract) jog functions. Once the specimen is loaded, selecting the “home” function will move the carriage to the home position, as defined by the limit switch, and allow the test functions to be operated. Upon starting the CBT experiment, two stokes or one cycle was completed before the hydraulic cylinder is started. This initial cycle was done per experiments conducted by Emmens and Van den Boogaard experiments. [6]

At the end of a CBT experiment, a data file is created and sent to the CBT test folder. The data that is collected from each experiment is comprised of the two load cells’ values, roller velocity relative to the carriage, cylinder crosshead displacement, motor current consumption,
and the time stamp. This experimental data is in a text file and can be transferred to an excel document or other data processing software.

2.2 Test Specimen Geometry

The CBT machine required the design of a custom dogbone specimen to meet CBT testing parameters. This was motivated by limitations when using the standard ASTM uniaxial tension specimen in the CBT experimental setup. In essence, the CBT specimen differs from the ASTM dogbone specimen by having an increased gage length. A visual comparison between the two specimens can be seen in Figure 2.11.

![Figure 2.11: CBT dogbone specimen and ASTM standard E8 dogbone specimen.](image)

This increased length was determined based on the desire to achieve a uniform region where all three rollers would make a full pass for each stroke. The term “stroke” is used in the conventional sense, i.e., motion towards a specific direction. The specimen consists of a uniform region which will receive a complete pass from each of the three rollers per stroke (Uniform 3x), the second region on either side of the uniform region which will receive two passes per stroke (2x), and the third region which will only receive one roller pass per stroke (1x) (see Figure 2.12).
The uniform region was selected to be a length of 100 mm. This length was chosen based on the desire to have a matching uniform region with that of the ASTM E-8 uniaxial dogbone specimen. The remaining length of 50 mm on each side of the uniform region was designed such that all three rollers traverse off of this region but without exiting the gage length. This was done as in earlier experiments, where the rollers would finally come to a stop in the shoulder or fillet region, failure occurred at the fillet, ending the CBT experiments prematurely. Shoulder curvature and specimen thickness and width dimensions were kept the same as that of the ASTM E-8 specimen.

During a CBT test, failure occurs at the location between the 3x and 2x regions on the CBT specimen due to the rollers' constraint on the material when the carriage is reversing direction. This temporary pause while an axial load is still applied causes the deformation in between these two regions to concentrate which results in material failure.

### 2.3 Load Data Collection

The CBT machine is equipped with two different types of Futek load cells that are each rated to a maximum load of 22.24 kN. The first type is a LCF450 universal pancake load cell, which is capable of measuring both tensile and compressive loads. This load cell is mounted
between the cylinder rod and grip to measure tensile loads. The second type is a LTH500 donut load cell, which is designed to measure compressive loads only. This load cell is mounted to the opposite side of the cylinder (see Figure 2.1), and is compressed between the carriage frame and a load cell adapter. As the specimen is pulled in tension, the grip pulls the load cell adapter against the carriage frame compressing the LTH500. Two load cells were used to validate that the CBT experiment was indeed symmetric about the rollers. This was assumed to be the case, but never validate in prior CBT experiments.

The two load cells produce a maximum signal output voltage of about 2 mV and thus required amplification. This was achieved with an INA129 precision low power instrumentation amplifier manufactured by Texas Instruments. A 100 Ω resistor was used in the INA129 to create a gain of 500 V/V. It is important to note that the use of a precision resistor and stable supply source are necessary to avoid having a dynamic gain, which will create errors in the output voltage. The constructed amplifier circuit can be seen in Figure 2.13.

It was discovered that the ball screw motor produces a significant amount of back electromagnetic interference which affects any electronic deceives in contact with the CBT machine or on the same electrical circuit. A series of attempts to correct this issue lead to two solutions to correcting this EMI noise from affecting sensor data. The first was to completely
isolate the circuit supplying power to all sensors. This solved the issue with all sensors except
the load cells because they were in contact with the CBT machine’s metal frame. If the load
cells could be isolated from the metal frame, then the EMI noise would not affect their output
signals. This was accomplished for the LTH500 compression load cell by using Teflon to
physically isolate the load cell from the metal components of the machine. The effects of the
EMI noise and physically isolating the LTH500 load cell from the CBT machine’s metal frame
can be seen in Figure 2.15. As shown in the figure, the EMI noise produced about 100 N to 150
N of artificial force in the load cell reading. When isolated, the observed noise was less than 10
N of force. The LCF450 was a different case due to a number of threaded connections on the
load cell. Because this load cell could not be physically isolated, the use of a RC low pass filter
was implemented. This RC filter removed all frequencies above 7.23 Hz by using a 220 kΩ
resistor and a 0.1μF capacitor. A bleed resistor of 115 kΩ is placed across the capacitor to
reduce signal drift.

Figure 2.14: Isolated load cell comparison to EMI exposed load cell.
2.4 Material Characterization and CBT Machine Validation

The material used exclusively throughout this CBT investigation was AA6022-T4, which is an advanced automotive aluminum with a thickness of 1 mm. AA6022 is a heat treated, low copper, Al-Si-Mg alloy. It was developed for use by the automotive industry for closure panels on vehicles. It meets both the strength and forming requirements for structural and body panel applications. Prior to investigating the CBT process, a variety of experiments were conducted to characterize this material’s mechanical properties. Uniaxial tension experiments were performed on a MTS Landmark 370 Load Frame universal tension machine for the material cut in the rolling direction, $45^\circ$ from the rolling direction (RD), and $90^\circ$ from the RD (transverse direction (TD)). The material is anisotropic, thus the flow curves do not match as seen in Figure 2.15.

![Figure 2.15: Uniaxial tension tests of AA6022-T4 in the rolling directions and $90^\circ$ to the rolling direction.](image)

To validate that the CBT machine could perform a uniaxial tension test without introducing any out-of-axis loading or any other undesirable effects on the response, a
comparison between tension tests conducted in a standard loading frame and the CBT machine was performed. The uniaxial tension test specimens were made using the ASTM standard E-8. The specimen was prepared from an AA6022-T4 sheet in the TD. The roller assembly was removed from the CBT machine and the ball screw was kept stationary. The specimen was pulled in tension until failure while DIC acquired the strain field. The stress-strain curve was compared to a uniaxial tension test performed on the MTS Landmark 370 with DIC using the same ASTM specimen geometry. A comparison of the two loading curves is shown in Figure 2.16, indicating nearly identical results. The discrepancy may be due to specimen-to-specimen variation.

![Stress-Strain Curve](image)

Figure 2.16: Comparison of MTS and CBT machine uniaxial tensions test performed in the TD.

Another series of experiments characterized the material using ASTM subsize E8 specimens. The two experiments performed were a jump test to assess the strain rate dependence of the material, and a cyclic plastic loading and elastic unloading to determine the springback and strain recovery of the material. To validate that this different geometry will not
have an effect on the flow curve, a uniaxial tension test was performed on both an ASTM subsize E8 specimen and standard E8 specimen using the MTS Landmark 370. This validation was performed in the rolling direction of the material and can be seen in Figure 2.17. Due to the alignment of the flow curves, it's safe to assume that all experimental data collection using the ASTM subsize E8 specimens is reflective of the material properties.

![Flow Curve Comparison](image)

Figure 2.17: Comparison of ASTM standard and subsize uniaxial tension tests.

The determination of the strain-rate dependence for AA6022-T4 was critical to assess prior to initial CBT testing. Having the material’s flow curve vary with different crosshead velocities would require a complexly different approach to the CBT investigation, as crosshead velocity was one of the parameters for our investigation. Our intention was to see how the variation of crosshead velocity would affect the material response due to the CBT process, not the material’s dependence on strain-rate. Testing was performed on the MTS Landmark 370 at three different crosshead velocities of 0.254 mm/s, 0.0127 mm/s, and 0.00254 mm/s. These correspond to strain rates of 0.01 s\(^{-1}\), 0.0005 s\(^{-1}\), and 0.0001 s\(^{-1}\) respectively. The true stress-
strain curve of the jump test can be seen in Figure 2.18. Three experiments were run to validate the results. The strain sensitivity for the three experiments produced m-values of 0.00125, 0.0019, and 0.00101 respectively. These m-values were calculated using Equation 2.1.

\[ m = \frac{\ln \frac{\Delta \sigma_2}{\Delta \sigma_1}}{\ln \frac{\Delta \varepsilon_2}{\Delta \varepsilon_1}} \]  

(2.1)

The strain rate dependence of the material was so insignificant that it can be considered negligible for AA6022-T4.

![Figure 2.18](image)

Figure 2.18: Three jump tests performed at strain rates of 0.01 s\(^{-1}\), 0.0005 s\(^{-1}\), and 0.0001 s\(^{-1}\).

The non-linear unloading of AA6022-T4 was assessed though cyclic loading and unloading experiments performed on the E8 subsize specimens using the MTS universal testing machine. These experiments were conducted to determine the nonlinear recovery strain (NLSR) and the linearly elastic strain (LES) for AA6022-T4. For the experiment, a total of 8 elastic
unloading cycles were performed and the test was ended by pulling the specimen plastically until failure (see Figure 2.19).

For each of the cycles, the NLSR and LSR were measured to get a better understanding of how these parameters develop over the course of plastic deformation until failure. The second cycle of the experiment can be seen in Figure 2.20. The nonlinear strain recovery was significantly smaller than the linearly elastic strain; by about 17 times in the case of cycle two. As a result, the NLSR saturates over the course of the experiment.

![Figure 2.19: Loading and elastic-unloading curve for 8 cycles using subsize RD specimen.](image)
Figure 2.20: Second unloading curve showing the first and third experiment for repeatability.

Figure 2.21: Plot of the NLSR vs. the prestrain.
Thus far, the CBT machine has been validated against the calibrated MTS Universal Testing machine at the University of New Hampshire’s Mechanics, Materials, and Manufacturing lab. A study on the mechanical properties of AA6022-T4 has also been conducted determining the anisotropy, strain rate dependence, and springback of this advanced automotive aluminum alloy.
3.1 CBT Experimental Setup and Specimen Failure

The standard procedure for a CBT test requires the user to first move the carriage to the home position, which is at the far left of the machine, and to raise the rollers. Next the position of the crosshead grip must be adjusted using the hydraulic cylinder to be close enough to the carriage mounted grip to place a specimen between them. The grips are then tightened and the top roller lowered to the appropriate depth. This procedure induces some axial compressive prestrain to the specimen, and ensures that there is no slack at the beginning of the test, which would cause problems. The final configuration of a setup prior to initiating the controller software is shown in Figure 3.1. Once the specimen is secure, the CBT LabVIEW program will first perform one full roller cycle before the hydraulic cylinder begins to apply uniaxial tension. [6] The program and machine are stopped after a desired amount of cycles or when failure occurs.

Figure 3.1: CBT test section with specimen gripped between two rollers.
CBT experiments have three parameters which can be varied to produce a variety of strain and axial loading combinations. The three parameters are the roller depth, roller velocity, and cylinder crosshead velocity. Preliminary testing found that the faster the rollers traversed along the specimen, the more elongation was achieved. Therefore, all CBT experiments are conducted at the machine's maximum velocity of 66 mm/s. The experiments found in Sections 3.3 and 3.4 describe an investigation into the CBT parameter space for AA6022-T4 to discover the optimal machine settings to achieve the most deformation and consequently, ETF.

All CBT tests followed a similar series of stages during the experiment, starting with an initial linear region, saw-tooth plastic deformation region, and ending with specimen failure. Failure was consistent and occurred at one of the edges of the 3x uniform region (see Figure 2.12). Specimen failure occurred depending on the bending depth when the roller direction was changing and only axial loading was applied (i.e., no continuous bending at this instant in the test). This failure location can be seen in Figure 3.2 at the edge of the leading roller. This is similar to the failure location in the corner area of a pan forming operation, where the punch (or in this case the roller) acts as a constraint and causes failure to occur in the adjacent material.

![Figure 3.2: CBT specimen failure at the edge of 3x deformation region.](image)

A comparison between a failed E8 dogbone specimen and the CBT specimen is shown in Figure 3.3. The E8 dogbone specimen fails in the center of the gauge region while the CBT specimen failure occurs at the edge of the 3x region of the specimen as mentioned previously.
The uniaxial tensions failure occurs at a 54° angle which can be seen in the figure below, where the CBT failure is perpendicular to the specimen. This phenomenon is seen in CBT experiments that achieve higher elongation and is believed to occur due to uniform deformation of the material, as necking is delayed.

![Figure 3.3: Failed (a) uniaxial E8 dogbone and (b) CBT specimen.](image)

### 3.2 CBT Curve Analysis

The results produced from a CBT experiment are presented in force-displacement as opposed to the traditional stress-strain due to limitations of measuring strain during an experiment. The rollers passing over the gauge region prevents traditional means of measuring strain from being implemented. The ability to use DIC in the future will enable this capability.

It should be noted that the gauge lengths for a CBT experiment (100 mm) are not directly comparable to that of a uniaxial tension experiment (200 mm). This is due to the 1x, 2x, and 3x regions, which experience different amounts of strain across the entire gauge length based on the number of times that the material is visited by a roller. In comparison, the uniaxial tension tests produce stains that are uniform throughout the gauge length (except at the necked region). Although there are differences between these experiments, they are still plotted together to demonstrate the increased elongation and different net axial loads achieved during testing. Based on the current machine setup, it is not currently possible to measure the increased elongation of the 3x region post experiment. The 3x region could be physically
marked and measured to give approximate elongation of this region, but this technique cannot be performed for the experiments conducted in this study. Again, the uniaxial test using a CBT specimen cannot be directly compared to the CBT experiment, but is provided for a comparison of net axial loads and increased ETF.

![Graph](image.png)

**Figure 3.4**: Comparison of uniaxial tension and CBT experiments performed on the CBT machine.

In **Figure 3.4**, data for a CBT experiment is presented along with a uniaxial tension experiment performed in the rolling direction (RD) for comparison. There are several characteristics of a CBT experiment that distinguish it from the traditional uniaxial tension experiment. The most prominent of these characteristics is the saw-tooth pattern observed in the plastic region of the CBT experiment. This pattern is related to the relative position of the rollers with respect to the load cells. In the initial “saw tooth” pattern in **Figure 3.5a**, a positive slope corresponds to the rollers moving away from the compressive load cell while a negative slope is caused by the rollers moving towards this load cell which is reporting the data. The
maximum and minimum values occur when the roller carriage stops to change directions. As the test progresses, this “saw tooth” shape evolves into a “curved m shape” (see Figure 3.5b). Negative and positive slopes still correspond to the rollers moving with respect to the load cell though there is some loss of linearity. During a change in direction of the rollers, the load decreases as the rollers begin to slow down, a minimum load is reached when the rollers come to a stop, and then an increase in load occurs once the rollers begin to move again. In essence, an axial tension increase occurs on the specimen as the rollers move towards the load cell that is reporting the data, and decreases as it moves away. Within the “saw tooth” region of the CBT curve (see Figure 3.5a), a spike represents the rollers changing directions. After the test has progressed into the “m shaped” region (see Figure 3.5b), the sudden drop in load occurs when the rollers change directions.

Figure 3.5: Plastic region of a CBT experiment containing two patterns.

The next distinguishing characteristic of a CBT experiment is the reduced axial force from that of a uniaxial tension experiment. As shown in Figure 3.4, the axial force remains below
the yield strength of the material during a CBT test. As mentioned in Chapter 1.2, the deformation of the material occurs in the bending zone, thus keeping the net force on the cross-section below the critical value for yielding. In essence, the bending of the material reduces the required axial load to plastically deform the material.

The final characteristic and primary purpose of the CBT experiment is the increased elongation-to-fracture (ETF) of the specimen’s gauge region. All CBT experiments experience more ETF than the specimen loaded in uniaxial tension. This is due to the fact that necking is delayed and larger strains are achieved throughout the specimen gauge length. This chapter will discuss at length the impact of variations in machine parameters on increasing the ETF of the CBT specimen’s gauge region. The repeatability of a CBT experiment should be noted, as the net axial load is consistent between experiments but the ETF is less consistent (see Figure 3.6).
Figure 3.6: Repeatability of the CBT at a fixed parameter.
CBT experiments performed in RD comparing the raw data (Raw) to the Savitzky Golay (SG) and moving average (MA) filters.

The CBT experiments presented in this thesis were conducted with a moving average filter applied to the load cell data within the LabVIEW code. This filter was originally implemented to reduce the EMF noise generated by the ball-screw motor. The moving average filter causes the data to not accurately represent the actual forces measured by the load cells. More recent, CBT experiments are being conducted with a Savitzky Golay filter, which uses a low-degree polynomial by the method of linear least squares to filter the data. There is a notable change in the CBT curves with this new filter applied (see Figure 3.7). The current load cells with the Savitzky Golay filter demonstrate a similar pattern to the CBT experiments conducted by Emmens and Van den Boogaard (see Figure 3.8). All future experiments will be conducted using this new filter, but the CBT results presented in this thesis use the moving average filter. As our study primarily looks at the maximum elongation until failure for a CBT experiment, our results are unaffected by this change. Note that no filtering was applied to the position sensor.
3.3 CBT Parameter Testing in the Transverse Direction

As mentioned previously, there are two parameters that were varied during CBT tests, i.e. the roller normalized bending depth which determines the amount of bending strain experienced and the crosshead velocity which determines the axial strain rate of the deformation. To investigate these parameters and their relation to one another, a series of experiments were conducted on AA6022-T4 in the transverse direction (TD). Experiments were performed where the crosshead speed was varied to 0.6 mm/s, 0.86 mm/s, and 1.2 mm/s and the roller normalized bending depth was varied to 1.0, 1.5, 1.75, 2.0, 2.4, 2.8, and 3.0, which are normalized by the initial specimen thickness $\delta/t_0$. Again, by referencing Figure 2.15, the material is anisotropic, thus it is expected that there are differences between the RD and TD. Further investigations in the development of the grain shapes are needed to understand the causes of the difference in achieved elongations.
The TD experienced the most elongation at a lower crosshead velocity and shallower normalized bending depth. The greatest elongation was achieved at a crosshead velocity of 0.6 mm/s and a normalized bending depth of 1.75 (see Figure 3.9a). The elongation at these parameters had a 91% increase compared to the uniaxial tension specimen in the TD. The second greatest elongation achieved was at 0.86 mm/s and a normalized bending depth of 1.75 (see Figure 3.9b). This test had a 76% increase in elongation from the uniaxial tension test.
Figure 3.9: CBT tests performed at a crosshead velocities of (a) 0.6, (b) 0.86, and (c) 1.2 mm/s in the TD.
If the most elongation achieved in the RD is compared to the same experiment conducted in the TD, a notable increase occurs. At a crosshead velocity of 1.2 mm/s and a normalized bending depth of 2, the RD case experienced a 43% increase in elongation while the TD achieved a 67% increase (see Figure 3.9a). The experiment in the RD is shown in Figure 3.11 and the experiment in the TD (see Figure 3.9). When comparing the percent increases of the two greatest elongations, a 71% difference between the RD and the TD is presented.

![Graph showing elongation comparison between RD and TD](image)

Figure 3.10: CBT tests performed at a normalized bending depth of (a) 1.75 and (b) 2.8 in the TD.
A second set of experiments to investigate the effects of varying crosshead velocity at a fixed normalized bending depth produced similar results to that of the RD tests. Increasing the crosshead velocity resulted in an increase of the net axial load. In Figure 3.10a and Figure 3.10b are the results from these two experiments in the TD.

3.4 CBT Parameter Testing in the Rolling Direction

The same series of parameter experiments were conducted on AA6022-T4 in the RD as well. The TD raised several interesting results, e.g., greater elongations were achieved in TD tests than in the RD of the material. Figure 3.11 shows the results obtained from these three experiments.
Figure 3.11: CBT tests performed at a crosshead velocity of (a) 0.6 mm/s, (b) 0.86 mm/s, and (c) 1.2 mm/s in the rolling direction.
From Figure 3.11, at a crosshead velocity of 1.2 mm/s and a normalized bending depth of 2, the most elongation is achieved, i.e., a 43% increase in elongation in comparison to the uniaxial tension specimen. Furthermore, the same crosshead velocity but at a normalized bending depth of 2.4 achieved the second largest elongation with a 40% increase from the uniaxial. Initially, CBT tests performed at higher normalized bending depths, i.e., 1.75, produced more elongation. This is because at lower normalized bending depths, the experimental setup acts solely like a uniaxial tension test. As higher normalized bending depths were used, it was found that there was a peak value before the elongation began to drop again. The greater normalized bending depth may cause the specimen to fail sooner due to the additional constraint on the edge of the roller. This information was used when performing the next series of experiments to take a deeper look at the effects of varying the crosshead velocity.

A second set of experiments was conducted to further investigate the effects of varying crosshead velocity (i.e., 0.37, 0.6, 0.86, 1, and 1.2 mm/s) at a given normalized bending depth. The normalized bending depths of 1.75 and 2.8 were chosen based off of results from the transverse direction study in Section 3.4, thus they were not performed at was determined to be the optimal normalized bending depth of 2.0 for the RD tests. Figure 3.12a and Figure 3.12b show the results from these experiments.
When the crosshead velocity increases and the normalized bending depth are kept constant, the net axial load also increases. The consequence of this caused the CBT test to become more like a uniaxial tension experiment, e.g., the net axial load may become higher than the yield force. These experiments showed that higher crosshead velocities produce greater amounts of elongation (see Figure 3.11a). The crosshead velocities of 1.2 mm/s and 2.0 mm/s produced the most elongation in the experiments at normalized bending depths of 1.75 and 2.8 respectively. Preliminary experiments, which are not included, showed significant decreases in elongation.
From the current investigation of the CBT parameter space, the optimal parameters were determined when using AA6022-T4 in the RD. A crosshead velocity of 1.2 mm/s at a roller depth of 2.0 achieved the most elongation. Future studies could fine tune these parameters, but are outside the scope of this thesis. If the CBT machine’s roller velocity could be increased from its maximum 66 mm/s value, greater elongations have been achievable using the higher crosshead velocities. However, this would produce a test that was potentially dangerous due to the fast moving components and exceeded the motor’s maximum velocity.

3.5 CBT Parameter Space Study Summary

The results from the CBT parameter space study demonstrate the effect of the machine parameters with regards to the material elongation. Both the RD and the TD tests achieved different amounts of ETF using different processing parameters. Table 3.1 shows the maximum increase of ETF achieved in the RD and TD tests compared to uniaxial tests as well as the machine parameters.

<table>
<thead>
<tr>
<th>Rolling Direction</th>
<th>Normalized Bending Depth ((\delta/t))</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crosshead Velocity (mm/s)</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>Elongation Increase (%)</td>
<td>43</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Transverse Direction</th>
<th>Normalized Bending Depth ((\delta/t))</th>
<th>1.75</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crosshead Velocity (mm/s)</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>Elongation Increase (%)</td>
<td>91</td>
</tr>
</tbody>
</table>

Table 3.1: CBT parameter space study maximum ETF

Both RD and TD experiments show that greater normalized bending depths generally produced more elongation up until a saturation point is reached. There is also a notable difference between the RD and TD tests in the material during the CBT process. Table 3.2 shows the optimal results for the RD and compares this to the same process parameters for the
TD. The TD achieved a percent increase of elongation of 67% where the RD achieved a 43% increase in elongation compared to the uniaxial tests.

Table 3.2: Comparison of RD to TD ETF

<table>
<thead>
<tr>
<th>Rolling Direction</th>
<th>Normalized Bending Depth ($\delta/t$)</th>
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<tr>
<td>Crosshead Velocity (mm/s)</td>
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<td></td>
</tr>
<tr>
<td>Elongation Increase (%)</td>
<td>43</td>
<td></td>
</tr>
<tr>
<td>Transverse Direction</td>
<td>Normalized Bending Depth ($\delta/t$)</td>
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</tr>
<tr>
<td>Crosshead Velocity (mm/s)</td>
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</tr>
<tr>
<td>Elongation Increase (%)</td>
<td>67</td>
<td></td>
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</table>

3.6 **Strain Measurements with Circle Grid Analysis**

The cyclic nature of the CBT machine with the material traversing through the rollers complicates strain measurements. One strain measurement technique which is not affected by the rollers is Circle Grid Analysis (CGA), which was implemented to measure net strains across the specimen’s surface after CBT processing. This method first requires an electro-etched pattern of uniform circles to be created along the gauge region of the CBT specimen. After CBT testing, the etched specimens are removed from the machine. By a comparison of the original circle diameter to the now ellipsoidal major and minor axes, the local strain in the plane of the specimen can be quantified.
These specimens are then photographed and the images are loaded into a custom Matlab code which identifies the ellipsoids. This code was developed in the summer of 2015 with the help of the UNH undergraduate Aleksandra Wojtowicz. Figure 3.13 shows the three stages of this measurement process. By analyzing each ellipsoid along the specimen, and the major and minor strains are calculated.

Figure 3.14: Comparison of uniaxial tension and CBT specimens strain along the specimen’s axis using CGA.
The major strains for a uniaxial tension and CBT tests in the RD are plotted along the axial normalized distance of the specimen in Figure 3.14. The three distinct regions of the CBT test can be seen, as well as the failure location. A less pronounced necking region was observed in the CBT specimen. The 3x region achieved strains larger than the uniaxial tension test necking region, but the 1x roller pass region experiences strains less than that of the uniaxial tension test. This is due to the fact that deformation primarily occurs in CBT due to bending, i.e., when the material passes through the rollers. The CBT test achieved strain values over two times that of the conventional uniaxial tension test. Note that there is a significant error with respect to CGA measurements (~+/- 2%).

The in-plane deformation path for the uniaxial and CBT specimens is the same, as shown in Figure 3.15. This demonstrates that there is a large amount of formability left in the specimen that is unexploited during the traditional uniaxial tension test and which can be captured with CBT processing of the material.

![Figure 3.15: In-plane strain values for uniaxial tension and CBT tests.](image)
CHAPTER 4

INTERRUPTED CBT EXPERIMENTS

4.1 Experimental Procedure

Motivated by the earlier work of Emmens and van den Boogaard [6], CBT experiments were used to assess the residual ductility of the material in uniaxial tension after CBT processing. In addition, a detailed study of the microstructural evolution after CBT processing was performed.

Figure 4.1: Schematic of the interrupted CBT experiments.
For these “interrupted CBT” experiments, the procedure depicted in Figure 4.1 was used. First, a batch of specimens was subjected with varying numbers of CBT cycles, as described in Table 4.1. A CBT cycle is defined as the rollers traversing the entire gauge length and then back again, i.e., the sum of 2 CBT strokes.

Table 4.1: Interrupted CBT experiment machine parameters.

<table>
<thead>
<tr>
<th>Test Conditions</th>
<th>Normalized Bending Depth</th>
<th>Cross-Head Velocity</th>
<th>Carriage Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBT Cycles Performed</td>
<td>RD</td>
<td>1.75 mm</td>
<td>0.86 mm/s</td>
</tr>
<tr>
<td>CBT Cycles Performed</td>
<td>TD</td>
<td></td>
<td>1, 4, 6, 8, 10</td>
</tr>
</tbody>
</table>

Two families of specimens were tested, one in the RD and the other in TD. In every case, the central region was marked before the CBT experiments and was visited by all three rollers during each stroke (i.e., the 3× region). Therefore the material in this region was subjected to the number of CBT cycles denoted in Table 4.1. After the specified number of cycles, the specimen was removed from the CBT machine. Depending on the number of CBT cycles, the specimens were found to have an increasing amount of residual curvature when removed from the CBT machine (see Figure 4.2).
A subsize tensile specimen (ASTM E-8) was then extracted from the marked central region (3×) of the parent CBT specimen using wire-EDM. In every case, the test-section of the subsize tensile specimen was well inside the 3× region of the parent CBT specimen, as shown in the schematic of Figure 4.1. At the same time, the material on the side of the gauge section (approximate 1 × 2 × 50 mm³ in size but different for each specimen due to varying number of CBT cycles), was saved for subsequent microstructural studies. Finally, the subsize tensile specimens were loaded in uniaxial tension using the MTS Landmark 370 testing machine.

4.2 Experimental Results

The engineering stress-strain curves from these subsequent tension tests are plotted in Figure 4.3 along with the uniaxial tension tests of the as-received materials. As show, the load-carrying capacity of the subsize specimens increased over the as-received one, while their residual ETF was reduced. Furthermore, the load-carrying capacity initially increased and then decreased as the number of CBT cycles increased, while the residual elongation-to-fracture
decreased monotonically. At CBT cycles close to the failure of the material (*i.e.* 10 and 12 CBT cycles, for the RD cases), the subsize tensile coupons fail almost as soon as re-yielding occurs.
Figure 4.3: Engineering stress-normalized extension curves from the interrupted CBT experiments in: (a) the RD and (b) the TD.
It should be noted that the results of Figure 4.3 do not contain the bending stress that is induced when the curved subsize tensile specimen is straightened before being loaded in tension (see Figure 4.4). In addition, the subsize specimens shown in Figure 4.4 demonstrate that the residual curvature did increase monotonically. This may be due to some experiments experiencing a brief moment of tension after the desired number of CBT cycles. This was due to the manual deactivation of the hydraulic cylinder.

![Curved subsize specimens](image)

**Figure 4.4: Curved subsize specimens.**

This bending stress is elastic, as could be verified easily by straightening the curved specimens by hand before installation in the tensile testing machine. As a result, the bending stress is linearly distributed in the test section. Because of the existing bending stress, as well as the residual stresses left from the CBT pre-straining, instead of labeling the axes in Figure 4.3 as stress and strain, which would imply only the tensile stress and strain is being applied over the gauge length, Force/Initial Area and Displacement/Gauge Length x 100, were used. Because of these reasons, it was not attempted to plot the interrupted test results as true stress-true strain, using the initial configuration as stress-free.

Two earlier “proof of concept” experiments were preformed in the TD for a total of 6 and 17 CBT cycles. The results from these experiments produced a unique artifact when the subsize specimen was pulled in uniaxial tension. During the uniaxial tension test, bands of strain began
to develop at multiple locations along the gauge region for greater cycles of CBT. This was discovered when using DIC to measure the strains across the specimen.

![Image]

Figure 4.5: Subsize specimen in the TD after (a) 6 CBT cycles and (b) 17 CBT cycles.

Figure 4.5 shows this DIC image and two distinct strain concentrations towards the bottom of the specimen’s gauge length. In past CBT experiments, materials that experience the larger strains resulted in multiple necks throughout the specimen. Although AA6022-T4 never experienced multiple visible necks, this may be a preliminary stage to this development. This phenomenon will require further investigation, as well as an understanding of its dependence on the number of cycles and normalized bending depth.

4.3 Microstructural Analysis

A microstructural analysis of the material was performed by the UNH graduate student Milovan Zecevic [7]. Milovan performed EBSD analyses generating a map of the deformed samples after 12 CBT cycles in the RD direction as well as SEM micrographs of the specimens.
Again, these samples were extracted during the wire-EDM processing of the subsize tensile specimens. Based on the grain structure, the deformation appears uniform throughout the sample (see Figure 4.6). To further evaluate the uniformity of deformation, the through-thickness texture gradient was also examined. Figure 4.6 also shows pole figures from top, middle, and bottom through-thickness locations in the sheet. These pole figures confirm that the texture evolves uniformly through the thickness of the sheet. The grains have significantly elongated in the RD and slightly contracted in the ND all throughout the 3x region.

![Figure 4.6: EBSD orientation map and pole figures after 12 CBT cycles. [7]](image)

The pole figures in Figure 4.7 present the texture evolution of the material subjected to 12 CBT cycles and the material simply deformed in uniaxial tension. The material away from the neck region (Fig. 4.7c) does not show evidence of substantial texture evolution. However, the material in the necked region (Fig. 4.7d) underwent substantial texture evolution and is similar to the texture developed after 12 CBT cycles (Fig. 4.7b). Unlike the sample deformed in simple tension, the CBT sample deformed uniformly throughout the gauge length, allowing increased displacement values and significant texture and microstructural evolution.
Figure 4.7: Pole figures show a comparison of texture in (a) as received material, (b) 12 cycles of CBT in the RD, (c) within in the gauge section of a simple tension in the RD direction, and (d) within the simple tension test’s necked region. [7]

The SEM micrographs seen in Figure 4.8a are of the sample deformed by 12 cycles of CBT along the RD. Evidence of ductile damage formation in terms of particle fragmentation and decohesion from the matrix as well as surface fracture was found, but no necking. Similar evidence is present in the sample deformed to 14 CBT cycles along the TD, Figure 4.8b. In contrast, Figure 4.9b shows that damage in terms of particle fragmenting develops locally under tension and quickly causes necking. No damage is found away from the necked region in tension (Figure 4.9a).
Figure 4.8: SEM images of randomly selected locations of damage formation in terms of voids after (a) 12 cycles of CBT in the RD and (b) 14 cycles of CBT in the TD. [7]

Figure 4.9: SEM image showing damage formation after (a) simple tension to failure within the gauge and (b) within the neck. [7]
The CBT process postpones the onset of necking by uniformly depleting the ductility over the entire gauge length. The microstructure characterization revealed that a material under CBT preserves higher integrity to large plastic strain than under simple tension. In the former case, damage is distributed uniformly through the material while in the latter case damage evolves rapidly in a localized region leading to necking and fracture.
CHAPTER 5
FRICION MEASUREMENT USING THE CBT MACHINE

5.1 Friction Coefficient Theory

Friction between the tool and the workpiece has a significant effect on manufacturing processes. An increase in the friction between the surfaces will increase the shear stresses, which may be desired depending on the particular manufacturing process but should be kept under control. Furthermore, friction controls material flow. Future work on this project will involve Finite Element Analysis (FEA) of the CBT process. One input into these simulations is the coefficient of friction between the rollers and the specimen. Experimental coefficients exist in the literature but do not represent the specific materials used in a CBT process.

H.W. Swift [8] first applied the belt friction equation (Equation 5.1) to determine an estimated coefficient of friction for a bent workpiece pulled over a roller. The diagram of the model which Swift applied to determine Equation 5.1 can be seen in Figure 5.1.

\[
\mu = \frac{1}{\theta} \ln \left[ \frac{F_1}{F_2} \right]
\]  

(5.1)

This model assumes that the roller is fixed and the bending forces due to the deformation of the materials are negligible. The forces \( F_1 \) and \( F_2 \) represent the axial force in front of and behind the roller with respect to the applied force direction. The angle of contact (\( \theta \)) between the work piece and roller can be varied for the surface of friction between the roller and the workpiece.
This model underestimates the force due to bending, especially in terms of the CBT test where the three bends occur along the specimen. R.T. Fox et al. [9] proposed a modified approach, which takes into account the bending force \( F_b \) of the material around the roller. The bending force is determined by finding the difference between \( F_1 \) and \( F_2 \) where the roller is free to move. It assumes that the roller does not experience any friction and that all forces are due to bending. This modification can be seen in Equation 5.2. Fox et al. [9] further modified the equation by including the roller radius \( r \) and sheet thickness \( t \).

\[
\mu = \frac{1}{6} \left[ r + 0.5t \right] \ln \left[ \frac{F_1 - F_b}{F_2} \right] \tag{5.2}
\]

These equations were designed with the intent of using one roller. To adjust for the CBT machine’s three roller system, the angle of contact for all three rollers was considered. A diagram of our modified application of Equation 5.2 to the CBT machine can be seen in Figure 5.2. Axial Forces were measured in front of and behind the rollers similar to experiments conducted by Swift and Fox, but the angle of contact was summed over all three rollers. The
increased bending force involved in CBT is measured by allowing the rollers to rotate freely to determine the bending force \( F_b \).

![Diagram of the front and back forces experienced in a continuous-bending-under-tension test.](image)

**Figure 5.2:** Diagram of the front and back forces experienced in a continuous-bending-under-tension test.

### 5.2 Friction Test Experimental Setup

Friction tests are conducted on a single strip of AA6022-T4 with a length of 455 mm (of which 380 mm were between the grips) and a cross-sectional area of 18.1 mm wide x 1 mm thick. The width of the specimen was chosen to be the size of the grip to provide the largest contact surface with the rollers. The length of the specimen was selected to be the maximum distance between the two grips with the crosshead fully retracted. This would allow for the rollers to reach a constant velocity for the majority of the stroke, thus maintaining steady state frictional forces during the test. The roller velocity was set to 8 mm/s to decrease the amount of time spent transitioning between strokes. The edge of the rollers stopped 50 mm from the grips to prevent bending near the grips. The normalized bending depth chosen for these experiments was 2.04, which under the assumption of perfect wrapping of the strip on the rollers results in a total contact angle of 18.06° for all three rollers.

Initially, friction tests were conducted on the CBT machine prior to having dual load cells, which posed a challenge for measuring forces on both sides of the rollers (see Equations 5.2 and 5.3, and Figure 5.2 and Figure 5.3). A solution was devised by mounting strain gages on
both sides of the specimen near the grips. Each side of the specimen has a top and bottom surface mount strain gage (Micro-Measurements, EA-06-125AC-350/W). By averaging these collected strains measured on the top and bottom of the specimen, the beam-bending forces are removed from the axial forces. A diagram of the friction test experimental setup is shown in Figure 5.3.

![Diagram of the friction test](image)

**Figure 5.3: Diagram of the friction test.**

Assuming that all of the axial strains are elastic (which was verified as axial loads did not exceed 22 MPa which is below the yield stress of AA6022-T4, i.e., 22 MPa, for data in Chapter 2), the Young's Modulus, seen in Equation 5.3, allows us to determine the axial force can be calculated using the cross-sectional area of the specimen ($A$) and the material's elastic modulus ($E$; 67.3 GPa again form data in Chapter 2) using:

$$F_{axial} = E \times \varepsilon \times A$$

(5.3)

The friction experiments were later revisited after the installation of the second load cell. To validate that the load cells were able to measure the axial loads on a magnitude of $10^2$ N, an experiment comparing the strain gage measurement to the dual load cells was conducted. The results of this experiment can be seen in Figure 5.4, which shows that the two sensors provide identical readings. The percent difference between the average of the load cell and strain gage
forces was found to be 0.76%, which is within an acceptable range. The only notable difference is that the load cells had more noise in their signals, which is due to their range of load measurement. (Note that the capacities and accuracies of both load cells are 22.24 kN and they operate at 2 mV/V nom. of full scale. Based on these findings and accounting for cost, ease of implementation, and time of setup, it was decided to conduct all friction tests using the dual load cells.

Friction tests were broken into two stages, the free roller experiments which account for the forces due to bending, and the fixed roller experiments which account for the friction between the roller and the specimen. The free roller tests were conducted first. The load cells were zeroed, the specimen was clamped in the grips and the center roller positioned to the desired normalized bending depth. Once in place, lubricant was added to the surface of the specimen and the roller cycles began. An image of this experimental setup is shown in Figure 5.5. Note the darkened strip found in Figure 5.5, this strip appears after several round of fixed
roller experiments. Currently, the cause of these dark regions found on both top and bottom of the specimen is unknown. It is believed to be related to the inconsistent stroke forces experienced during testing.

![Free Rollers](image1.png)

**Figure 5.5:** Friction test with free rollers using dual load cells for force measurements.

The fix roller tests occur immediately after the free roller experiments. The rollers are not re-adjusted, thus keeping the same normalized bending depth and ensuring that there are consistent test parameters for one specimen. To create the fixed conditions, several loops of electrical tape are applied around the rollers, as shown in **Figure 5.6.** This prevents the rollers from rotating and forces the material to pass over them.

![Fixed Rollers](image2.png)

**Figure 5.6:** Friction test with fixed rollers using dual load cells for force measurements.

Continuous lubrication is required to prevent gouging of the specimen during testing. When gouging occurs on the specimen’s surface, the force significantly increases as the rollers displace the material. This would lead to frictional conditions that will not be encountered during
CBT, and hence were avoided. Prior experiments showed that the addition of the mineral oil lubricant did not significantly decrease the forces measured by the strain gages [10], but prevented gouging.

### 5.3 Friction Test Results

The CBT machine was used to perform the experiments and collect the load cell data for the friction tests. The data acquisition equipment collects the time increment, velocity of the rollers, and the two forces measured in kN. From this data, the bending and frictional forces, as well as the relative position of the roller stroke were determined. The position of the rollers is important to assure that the data is from the center of the specimen where the roller velocity is constant. A sample of the forces collected during a standard fixed roller friction test is shown in Figure 5.7.

![Figure 5.7: Sample of friction test data for fixed rollers for right and left load cells (LC). Data from experiment 4.](image-url)
The fixed roller data shown in Figure 5.7 demonstrates the potential reputability and consistency of a stroke over the course of one experiment. Both the right and left load cells achieved similar force values. The fixed roller experiments produced slightly greater force averages than the free roller experiments (see Figure 5.8).

![Figure 5.8: Sample of friction test data for free rollers for right and left load cells (LC). Data from experiment 4.](image)

The plot in Figure 5.8 shows the potential for inconsistencies over a friction test. Initially, there are larger forces measured on the load cells and as the test progresses, these forces become more consistent. Currently, the sources of these inconsistencies have yet to be identified. Again, free roller experiments were conducted to determine the bending forces of the experiment. The averages of the forces before and after rollers are subtracted to calculate the bending force. This proved to be an issue for the data set found in Figure 5.8, as alternating strokes produced different bending forces.
An average over the entire experiment, determined as described below, was used to determine the bending force and $F_1 / F_2$ ratios (see Equation 5.2) when calculating the coefficient of friction. This was achieved by taking the average force of each individual stroke (i.e., direction of roller motion). The force values obtained from the ten same-direction strokes (for each of the four specimens) were then averaged together to create a single value for an experiment. Outliers (i.e., inconsistent strokes) were removed from the averaged data set (e.g., the first stroke in Figure 5.8). The experiments were conducted at a shallow normalized bending depth of 2.04, which was originally required to prevent the strain gage measurement system from experiencing plastic deformation.

The contact angle between the rollers and the specimen is critical, as minor fluctuations can drastically change the coefficient of friction. Figure 5.9 demonstrates the sensitivity of the coefficient of friction to the contact angle. Figure 5.9 was created using Equation 5.2, where the angle of contact was varied from $0^\circ$ to $360^\circ$. Force values were selected from the first friction experiment. With the 2.04 normalized bending depth and assuming perfect wrapping of the specimen around the rollers which is known to be not the case, the friction experiments were performed at an angle of contact of $18.06^\circ$, which is in a region of the curve in Figure 5.9 with a significant gradient. Ideally, future experiments will be conducted an angle of contact greater than $100^\circ$, as the load cell measurement system will be implemented and plastic deformation is no longer a concern.
Despite the concerns with the friction coefficient measurement method, the results from the four different experiments conducted to determine the friction coefficient are shown in Table 5.1.

Table 5.1: Coefficients of Friction (in two directions of roller motions).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Friction Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.499 / 0.187</td>
</tr>
<tr>
<td>2</td>
<td>0.700 / 1.180</td>
</tr>
<tr>
<td>3</td>
<td>0.697 / 0.439</td>
</tr>
<tr>
<td>4</td>
<td>0.0205 / 0.874</td>
</tr>
</tbody>
</table>

It was assumed that the coefficients of 1.18 and 0.0205 were outliers, leaving a range of friction coefficients of 0.187 to 0.874. The consistent data shown in Figure 5.7 was from specimen 4. This seemingly consisted experiment had an inconsistent free roller test (see Figure 5.8), which caused conflicting friction values of 0.0205 and 0.874. Based on the large...
range of potential friction coefficients for a CBT process, the conclusion was that additional testing is required using a greater normalized bending depth.
CHAPTER 6
CONCLUSION

6.1 Summary of CBT Machine

The goal of designing and constructing a dedicated CBT machine was achieved. The CBT machine was validated against a calibrated MTS universal tension machine at the UNH Mechanics, Materials, and Manufacturing lab. The CBT machine was designed to be versatile and accommodate different types of experiments (i.e. sheet specimen experiments) or measurement techniques (i.e. DIC). The machine will clarify the effects of the CBT process on different materials and deepen the understanding of microstructural development at different CBT cycles. It is also capable of running uniaxial tension experiments at higher loads than other machines in the lab, and can be adapted to conduct fictional experiments to determine coefficients between different materials and a die.

6.2 Summary of CBT Parameter Space

The parameter space study showed the dependence of the elongation on the parameters of crosshead velocity and normalized bending depth. It was found that for AA6022-T4 the TD tests achieved more elongation than the RD tests. Also, the maximum elongation-to-fracture was achieved under different parameters for the RD and TD cases. For the TD tests, the maximum elongation percent increase from a uniaxial tension test was 91%. The maximum percent elongation for the RD tests was 43% from the uniaxial test. In both experiments, an increase in normalized bending depth consistently increased the elongation, but only up to a peak where the elongation would then begin to decrease. By understanding optimal machine
parameters for AA6022-T4, future studies into the CBT phenomenon can be investigated using the necessary number of CBT cycles for a desired material response.

6.3 Summary of Interrupted CBT Experiments

The interrupted experiments were conducted to better understand the grain development of AA6022-T4 undergoing CBT. The results from EBSD and SEM micrographs showed that the CBT process produced uniform grains with elongations that matched that of the necking region in a uniaxial tension test. Additionally, the load-carrying capacity of the subsize specimens pulled in tension after a number of CBT cycles increased over the as-received material. The residual elongation-to-fracture was reduced while the load-carrying capacity initially increased and then was reduced as the number of CBT cycles accumulated. If the amount of bending strain can be accurately incorporated into the results, then the stress-strain curves for a material could be extended well beyond strain values which are obtained from uniaxial tension tests.

6.4 Summary of Friction Experiments

An experimental process utilizing the CBT device to determine the coefficient of friction is still under development. Improvements were made to the experimental setup. In place of using strain gages to measure forces, all future experiments will use the CBT device’s load cells. In addition, by increasing the angle of contact, coefficients of friction become more stable. The large range of coefficients over the course of four different experiments lead to the conclusion that additional experiments conducted at a greater contact angle were needed to produce a more reliable coefficients of friction.

6.5 Future Work
The future work planned for the CBT machine can be broken down into two phases, machine upgrades and new materials to be tested. New grips and sheet specimens were recently designed [26]. Accommodating for sheet specimens was one of the original design requirements for the dedicated CBT machine. The sheet specimens will be subjected to a set of CBT cycles to prestrain the material. The prestrained sheet will then be used to assess the residual post-CBT formability using the Greenerd hydraulic press.

The current roller assembly was not designed for strips of high strength materials. As one of the design requirements was to accommodate sheets of DP 780, the roller assembly will need to be redesigned to handle the higher stresses required to CBT process this material. The new roller assembly design has not been started yet, as sheets of a lower strength material were sufficient for initial testing.

A fixture and software are currently under design and development to allow the integration of DIC into the CBT device. The DIC cameras will be mounted to the machine and remain stationary during testing. Two cameras will collect images simultaneously of different locations along the CBT specimen. These images will then be stitched together by applying markers (i.e., black lines) to the specimen so that the DIC analyses can be performed on the area of interest. From this technique, the surface as well as the through-thickness strains can be measured during the CBT process. This has not been achieved previously and will deepen the understating of the mechanism behind the CBT phenomenon.

Additional high strength steels and aluminum alloys are under investigation using the CBT machine. Currently, experiments are being performed on an Extra-Deep-Drawing (EDDS) steel. In the future, DP 780, a dual-phase steel will also be studied using the CBT process. For all of these materials, frictions coefficients will be determined using the friction test procedure
described in Chapter 5. A parameter space study for each of these materials will need to be conducted to determine their maximum elongations.

The CBT project at the University of New Hampshire has a bright future ahead and will provide many opportunities for research and learning. The scope of the project extends beyond the CBT experiments themselves and involves FEA simulations, microstructural characterization, and will provide future manufacturing innovations.
LIST OF REFERENCES


APPENDIX A

CBT Parameter Space Procedure

I. Connect the hydraulic pump to the CBT machine
II. Connect the proportional and relief valves to the CBT machine
III. Turn on the electrical panel. The electrical panel powers the ball screw which drives the carriage.
IV. Open the ‘CBT Main Panel’ LabVIEW program and click ‘Run’
V. Under the pre-test controls, click “Home” to move the carriage to its starting position.
VI. Click “Stop” to stop the “CBT Main” program
VII. Turn on the hydraulic pump
VIII. Open the “CBT Cylinder” program
IX. Click ‘Run’
X. Under the pressure tab, type in ‘400’ for 400 psi
XI. Click ‘Extend’ to draw out the cylinder crosshead to the desired position, based on the length of specimen
XII. Turn off the hydraulic pump
XIII. Click ‘Stop’ to stop the ‘CBT Cylinder’ program
XIV. Insert the specimen into the machine by placing the ends of the specimen into the grips and tighten the grips
XV. Unscrew the bolts holding the top roller and drop the roller onto the specimen
XVI. Use a dial caliper to measure the desired distance between the roller support and top roller.
XVII. Tighten the bolts holding the top roller to secure it at the desired height

XVIII. Click ‘Run’ in the CBT Main LabVIEW program.

XIX. Set the desired carriage velocity, number of cycles, and system pressure (see Chapter 3)

XX. Click ‘Start’ to run the experiment

XXI. After one cycle, click the ‘Cylinder’ button to start retracting the cylinder crosshead

XXII. Once the specimen fractures, immediately click ‘Cylinder’ again to stop the cylinder from retracting and click ‘Stop’ to stop the carriage and end the test.

**CBT Interrupted Test Procedure**

I. Record initial area of gauge region

II. Place CBT Specimen into CBT machine grips

III. Allow 25 mm of space between the edge of the rollers and the edge of the gauge region

IV. Set machine to 66 mm/s crosshead velocity, the crosshead velocity (0.86 used in Chapter 5), and the number of desired cycles to conclude experiment (see Chapter 5)

V. Tighten grips on specimen and bring rollers down to desired normalized bending depth (1.75)

VI. Click “home” and begin test

VII. Turn on the cylinder’s crosshead after one cycle

VIII. Turn off the cylinder’s crosshead after the desired number of cycles

IX. Remove CBT specimen and document area of gage length and measure curvature
X. Create subsize specimen by machining away undesired material
XI. Place subsize tension specimen into CBT machine
XII. Conduct uniaxial tension test on specimen
XIII. Record data and use DIC if so desired
XIV. Repeat for each specimen covering range of desired cycles

Friction Test Procedure

I. Turn on the electrical panel which powers the ball screw and drives the carriage
II. Open the ‘CBT Main Panel’ LabVIEW program and click ‘Run’
III. Under the pre-test controls, click “Home” to move the carriage to its starting position (50 mm from the grip).
IV. Click “Stop” to stop the “CBT Main” program
V. Turn on the hydraulic pump
VI. Open the “CBT Cylinder” program
VII. Click ‘Run’
VIII. Under the pressure tab, type in ‘400’ for 400 psi
IX. Click ‘Retract” to draw back the cylinder crosshead to the desired position, based on the length of specimen
X. Turn off the hydraulic pump
XI. Click ‘Stop’ to stop the ‘CBT Cylinder’ program
XII. Insert the specimen into the machine by placing the ends of the specimen into the grips and tighten the grips
XIII. Unscrew the bolts holding the top roller and drop the roller onto the specimen
XIV. Use a dial caliper to measure the desired distance between the roller support and top roller

XV. Tighten the bolts holding the top roller to secure it at the desired height

XVI. Click ‘Run’ in the CBT Main LabVIEW program

XVII. Set the desired carriage velocity to 8 mm/s and the number of cycles to 5

XVIII. Click ‘Start’ to run the experiment

XIX. For “free roller” tests, add lubricant during testing, rollers are allowed to rotate freely

XX. For “fixed roller” tests, add lubricant during testing, rollers are locked by wrapping them in electrical tape

XXI. Fixed roller tests are conducted after free roller tests, this should be done on the same specimen without changing the bending depth

XXII. After the desired number of free and fixed roller tests, the experiment will stop and the specimen is removed

**Electro-Etch Circle Grid Procedure**

This process was done using a Lectroetch power unit and marking kit.

I. Lay out the base pad on a working surface and plug the power unit into an outlet.

II. Supply power to the grid marker by connecting it to the cord with the red end coming out of the power unit.

III. Connect the cord with the black end to the base pad. This grounds the base.

IV. Lay a felt pad on top of the base

V. Choose the appropriate electrolyte fluid for the material that is being etched and pour the fluid on the felt pad.

VI. Lay the stencil on top of the felt pad and attach it to the base.
VII. Smooth over the stencil with a cloth or paper towel in order to remove air bubbles between the stencil and felt pad.

VIII. Set the power unit to DC to generate black marks on your specimen or AC to generate white marks.

IX. Set the desired power setting by turning the dial on the power unit. The higher the power level, the deeper the resulting etch.

X. Lay down the specimen on top of the stencil and turn on the power unit.

XI. Slowly roll the marker across specimen while applying a constant, even pressure.
APPENDIX B

Circle Grid Matlab Code

%% SECTION 1

load('uniaxial.mat');

Img1=imread('CBT_TD_2.8_0.6_66_2_AW_1','jpg'); % Reads in image jpg or png (First Half)
Img1=rgb2gray(Img1); % Suppress this with % if the image is already grayscaleimbw (First Half)
% Adjusts the contrast (First Half)
newImg1 = imadjust(Img1,[.4,.85],[],1); %.45,.85 % The picture of the Specimen (First Half)
figure;
imshow (Img1);

Img2=imread('CBT_TD_2.8_0.6_66_2_AW_2','jpg'); % (Second Half)
Img2=rgb2gray(Img2); % (Second Half)
% (Second Half)
newImg2 = imadjust(Img2,[.4,.7],[],1); %.45,.85 % (Second Half)
figure;
imshow (Img2);

%% SECTION 2

% Adjusts the contrast (First Half)
imbw1=im2bw(newImg1);
% Plots the contrast image (First Half)
figure
imlabel1=bwlabel(imbw1);
imshow(imbw1);
s1=regionprops(imlabel1,'MajorAxisLength','MinorAxisLength');

% (Second half)
imbw2=im2bw(newImg2);
% (Second half)
figure
imlabel2=bwlabel(imbw2);
imshow(imbw2);
s2=regionprops(imlabel2,'MajorAxisLength','MinorAxisLength');

%% SECTION 3

% All Identified Circles (First Half)
majorAl1=[s1.MajorAxisLength];
minorAl1=[s1.MinorAxisLength];
% Adjusts the acceptable "Circle" Size (First Half)
f1=(ismember(imlabel1, find(majorA1>=46 & majorA1<=90 & minorA1>=22 & minorA1<=50))); % 40-100 && 20-50

% (Second Half)
majorA2=[s2.MajorAxisLength];
minorA2=[s2.MinorAxisLength];

% (Second Half)
f2=(ismember(imlabel2, find(majorA2>=46 & majorA2<=90 & minorA2>=22 & minorA2<=50))); % 40-100 && 20-50

% SECTION 4

% Plots the Red Circles for measurement (First Half)
figure
imshow(f1)

% Extracts information about Circles in image (First Half)
s21=regionprops(f1,'MajorAxisLength','MinorAxisLength','Eccentricity','Centroid','Orientation','BoundingBox');

% Accepted Circle Major/Minor Axis lengths (First Half)
majorA21=[s21.MajorAxisLength];
minorA21=[s21.MinorAxisLength];
centroid1 = [s21.Centroid];
hold on;

phi = linspace(0,2*pi,50);
cosphi = cos(phi);
sinphi = sin(phi);

for k = 1:length(s21);
    xbar1 = s21(k).Centroid(1);
ybar1 = s21(k).Centroid(2);
a1 = s21(k).MajorAxisLength/2;
b1 = s21(k).MinorAxisLength/2;
theta1 = pi*s21(k).Orientation/180;
R1 = [ cos(theta1) sin(theta1) -sin(theta1) cos(theta1) ];
xy1 = [a1*cosphi; b1*sinphi];
x1 = xy1(1,:) + xbar1;
y1 = xy1(2,:) + ybar1;
plot(x1,y1,'r','LineWidth',2)
end
hold off

% (Second Half)
figure;
imshow(f2)

% (Second Half)
s22=regionprops(f2,'MajorAxisLength','MinorAxisLength','Eccentricity','Centroid','Orientation','BoundingBox');

% (Second Half)
majorA22=[s22.MajorAxisLength];
minorA22=[s22.MinorAxisLength];
centroid2 = [s22.Centroid];
hold on;

for k = 1:length(s22);

    xbar2 = s22(k).Centroid(1);
ybar2 = s22(k).Centroid(2);
a2 = s22(k).MajorAxisLength/2;
b2 = s22(k).MinorAxisLength/2;
theta2 = pi*s22(k).Orientation/180;
R2 = [ cos(theta2) sin(theta2); -sin(theta2) cos(theta2)];
xy2 = [a2*cosphi; b2*sinphi];
xy2 = R2*xy2;
x2 = xy2(1,:) + xbar2;
y2 = xy2(2,:) + ybar2;
plot(x2,y2,'r','LineWidth',2)

end

hold off

%% SECTION 5
% Conversion from Pixels to mm

% Rows to columns
majorA21=majorA21';
majorA22=majorA22';
minorA21=minorA21';
minorA22=minorA22';
pixels1 = [majorA21 minorA21];
pixels2 = [majorA22 minorA22];

% Histogram of Axis Pixel Sizes
figure;
hist(pixels1,300)
xlabel('pixel size');
ylabel('number of circles');
legend('Major Axis','Minor Axis')

figure;
hist(pixels2,300)
xlabel('pixel size');
ylabel('number of circles');
legend('Major Axis','Minor Axis')
\% Pixels to \text{mmm}
lo = 2.54; \%mm
\text{Pixels} \_\% \text{mm} = 48/lo; \%pix/mm
\text{Pixels} \_\% \text{mm} = 48/lo;
\text{Strain}1 = [((\text{majorA}21/\text{Pixels} \_\% \text{mm})/lo)-1]*100
((\text{minorA}21/\text{Pixels} \_\% \text{mm})/lo)-1)*100];
\text{Strain}2 = [((\text{majorA}22/\text{Pixels} \_\% \text{mm})/lo)-1]*100
((\text{minorA}22/\text{Pixels} \_\% \text{mm})/lo)-1)*100];
\% X position of pixels (First Half)
\text{for j = 1:} (\text{length(centroid)}1)/2;
 \quad \text{x\_pixel\_position}1(j) = \text{centroid}1(2*j-1);
\text{end}
\% Y position of pixels (First Half)
\text{for j = 1:} (\text{length(centroid)}1)/2;
 \quad \text{y\_pixel\_position}1(j) = \text{centroid}1(2*j);
\text{end}
\% (Second Half)
\text{for j = 1:} (\text{length(centroid)}2)/2;
 \quad \text{x\_pixel\_position}2(j) = \text{centroid}2(2*j-1);
\text{end}
\% (Second Half)
\text{for j = 1:} (\text{length(centroid)}2)/2;
 \quad \text{y\_pixel\_position}2(j) = \text{centroid}2(2*j);
\text{end}
\% Converting from Pixels to \text{mm}
\text{x\_position}1 = (\text{x\_pixel\_position}1/\text{Pixels} \_\% \text{mm}1)';
\text{x\_position}2 = (\text{x\_pixel\_position}2/\text{Pixels} \_\% \text{mm}2)';
\text{y\_position}1 = (\text{y\_pixel\_position}1/\text{Pixels} \_\% \text{mm}1)';
\text{y\_position}2 = (\text{y\_pixel\_position}2/\text{Pixels} \_\% \text{mm}2)';
\text{Strain}1(:,3) = -\text{Strain}1(:,1)-\text{Strain}1(:,2);
\text{Strain}2(:,3) = -\text{Strain}2(:,1)-\text{Strain}2(:,2);
\text{Uniaxial\_Strain}(:,3) = -\text{Uniaxial\_Strain}(:,1)-\text{Uniaxial\_Strain}(:,2);
\% SECTION 6
\% ratio of the major and minor strain (minor/major)
\text{Ratio1} = (\text{Strain}1(1:\text{length(Strain)1},2))./(\text{Strain}1(1:\text{length(Strain)1},1));
\text{Ratio2} = (\text{Strain}2(1:\text{length(Strain)2},2))./(\text{Strain}2(1:\text{length(Strain)2},1));
\% calculates the mean of ratio
\text{mu}1=\text{mean}\_\%\text{Ratio}1;
\text{mu}2=\text{mean}\_\%\text{Ratio}2;
\text{OneSigma}1=\text{mu}1+\text{std}\_\%\text{Ratio}1;
\text{OneSigma}2=\text{mu}2+\text{std}\_\%\text{Ratio}2;
\text{TwoSigma}1=\text{mu}1+(2*\text{std}\_\%\text{Ratio}1);
\text{TwoSigma}2=\text{mu}2+(2*\text{std}\_\%\text{Ratio}2);
\text{ThreeSigma}1=\text{mu}1+(3*\text{std}\_\%\text{Ratio}1);
\text{ThreeSigma}2=\text{mu}2+(3*\text{std}\_\%\text{Ratio}2);
\text{figure}
% calculates the standard deviation
sigma1=std(Ratio1);
sigma2=std(Ratio2);

% Create a matrix of mean values by replicating the mu vector for n rows
[n1,p1]=size(Ratio1);
[n2,p2]=size(Ratio2);
Mean1=repmat(mu1,n1,1);
Mean2=repmat(mu2,n2,1);

% Create a matrix of standard deviation values by replicating the sigma vector for n rows
StandardDeviation1=repmat(sigma1,n1,1);
StandardDeviation2=repmat(sigma2,n2,1);

% Create a matrix of zeros and ones, where ones indicate the location of outliers
% Use 1 sigma for region that includes 68% of data, 2 sigma for 95% and 3 sigma for 99.7%
outliers1=abs(Ratio1-Mean1)>(1.5*sigma1);
outliers2=abs(Ratio2-Mean2)>(1.5*sigma2);

% Calculate the number of outliers in each column

nout1=sum(outliers1);
nout2=sum(outliers2);

% removes the entire row of outliers in the column
Ratio1(any(outliers1,2),:)=[];
Ratio2(any(outliers2,2),:)=[];

figure
hist(Ratio1,200)
hold on
histfit(Ratio1,200,'normal')
hold off
ylabel('Number of Instances')
xlabel('Poisson Ratio')
title('Strain Ratio (After Data Elimination)')

figure
hist(Ratio2,200)
hold on
histfit(Ratio2,200,'normal')
hold off
ylabel('Number of Instances')
xlabel('Poisson Ratio')
title('Strain Ratio (After Data Elimination)')

%% SECTION 7
% Remove outlying Strain values

StrainNew_Major1=zeros(length(Ratio1),1);
StrainNew_Major2=zeros(length(Ratio2),1);
StrainNew_Minor1=zeros(length(Ratio1),1);
StrainNew_Minor2=zeros(length(Ratio2),1);
x_position_New1=zeros(length(Ratio1),1);
x_position_New2=zeros(length(Ratio2),1);

for ii=2:length(Ratio1);
    if outliers1(ii)==0
        StrainNew_Major1(ii)=Strain1(ii,1);
        StrainNew_Minor1(ii)=Strain1(ii,2);
        x_position_New1(ii)=x_position1(ii);
    else
        % StrainNew_Major1(ii)=Strain1(ii-1,1);
        % StrainNew_Minor1(ii)=Strain1(ii-1,2);
        % x_position_New1(ii)=x_position1(ii);
        StrainNew_Major1(ii)=0;
        StrainNew_Minor1(ii)=0;
        x_position_New1(ii)=0;
    end
end

for ii=2:length(Ratio2);
    if outliers2(ii)==0
        StrainNew_Major2(ii)=Strain2(ii,1);
        StrainNew_Minor2(ii)=Strain2(ii,2);
        x_position_New2(ii)=x_position2(ii);
    end
end
else
    StrainNew_Major2(ii)=Strain2(ii-1,1);
    StrainNew_Minor2(ii)=Strain2(ii-1,2);
    x_position_New2(ii)=x_position2(ii);
    StrainNew_Major2(ii)=0;
    StrainNew_Minor2(ii)=0;
    x_position_New2(ii)=0;
end

% Specifying new conditions
TF1=StrainNew_Major1(:,1)==0;
TF2=StrainNew_Minor1(:,1)==0;
TF3=x_position_New1(:,1)==0;
TF4=StrainNew_Major2(:,1)==0;
TF5=StrainNew_Minor2(:,1)==0;
TF6=x_position_New2(:,1)==0;

% Redefine variables
StrainNew_Major1(TF1,:)=[];
StrainNew_Major2(TF4,:)=[];
StrainNew_Minor1(TF2,:)=[];
StrainNew_Minor2(TF5,:)=[];
x_position_New1(TF3,:)=[];
x_position_New2(TF6,:)=[];

figure
% plot(x_position2,Strain2(:,1),'k')
% hold on
plot(x_position1,Strain1(:,1),'k')
hold off

% SECTION 8

[ StrainMajorFinal1, xFinal1 ] = AvgStrainThreeColumns( x_position_New1,
    StrainNew_Major1 );
[ StrainMajorFinal2, xFinal2 ] = AvgStrainThreeColumns( x_position_New2,
    StrainNew_Major2 );
[ StrainMinorFinal1, xFinal1 ] = AvgStrainThreeColumns( x_position_New1,
    StrainNew_Minor1 );
[ StrainMinorFinal2, xFinal2 ] = AvgStrainThreeColumns( x_position_New2,
    StrainNew_Minor2 );

% Specifying new conditions
TF7=StrainMajorFinal1(1,:)==0;
TF8=StrainMajorFinal2(1,:)==0;
TF9=StrainMinorFinal1(1,:)==0;
TF10=StrainMinorFinal2(1,:)==0;
TF11=xFinal1(1,:)==0;
TF12=xFinal2(1,:)==0;

% Redefine variables
StrainMajorFinal1(:,TF7)=[];
StrainMajorFinal1(:,TF8)=[];
StrainMinorFinal1(:,TF9)=[];
StrainMinorFinal2(:,TF10) = []; xFinal1(:,TF11) = []; xFinal2(:,TF12) = [];

% plotting the average major strain (three columns) vs the average x position
shift = xFinal2(end) + 1;
exFinal1 = xFinal1 + shift;
shift2 = x_position2(end) + 1;
x_position1 = x_position1 + shift;
figure
plot(xFinal1, StrainMajorFinal1)
hold on
plot(xFinal2, StrainMajorFinal2)
plot(xFinal1, StrainMajorFinal1, 'x')
plot(xFinal2, StrainMajorFinal2, 'x')
hold off
xlabel('X Position (mm)')
ylabel('Average Major Strain (% Elongation)')
title('Average Major Strain vs. x Position')

figure
plot(x_position1, Strain1(:,1), ':k')
hold on
plot(x_position2, Strain2(:,1), ':k')
plot(xFinal1, StrainMajorFinal1, 'k')
plot(xFinal2, StrainMajorFinal2, 'k')
xlabel('X Position (mm)')
ylabel('Average Major Strain (% Elongation)')
title('Average Major Strain vs. x Position')
legend('Original Data', 'Smoothed')
hold off

%% SECTION 9

StrainThicknessFinal1 = -StrainMajorFinal1 - StrainMinorFinal1;
StrainThicknessFinal2 = -StrainMajorFinal2 - StrainMinorFinal2;

StrainFinal1 = [StrainMajorFinal1
                StrainMinorFinal1
                StrainThicknessFinal1];
StrainFinal2 = [StrainMajorFinal2
                StrainMinorFinal2
                StrainThicknessFinal2];

StrainFinal1 = StrainFinal1';
StrainFinal2 = StrainFinal2';

%% SECTION 10

figure;
hist(StrainFinal1, 400);
ylabel('Number of Instances')
xlabel('Major & Minor Strain Percent (%)')
title('Average Data')
legend('Major Strain','Minor Strain','Thickness Strain')
xlim([-45 87])

figure;
plot(StrainMinorFinal1,StrainMajorFinal1,'o','MarkerEdgeColor','r')
hold on
plot(Uniaxial_Strain(:,2),Uniaxial_Strain(:,1),'o')
xlabel('Minor Strain Percent (%)')
ylabel('Major Strain Percent (%)')
title('Average Data')
legend('CBT','Tension')
axis equal

figure;
hist(StrainFinal2,400);
ylabel('Number of Instances')
xlabel('Major & Minor Strain Percent (%)')
title('Average Data')
legend('Major Strain','Minor Strain','Thickness Strain')
xlim([-45 87])

figure;
plot(StrainMinorFinal2,StrainMajorFinal2,'o','MarkerEdgeColor','r')
hold on
plot(Uniaxial_Strain(:,2),Uniaxial_Strain(:,1),'o')
xlabel('Minor Strain Percent (%)')
ylabel('Major Strain Percent (%)')
title('Average Data')
legend('CBT','Tension')
axis equal

Data_Out_x=[xFinal2 xFinal1];
Data_Out_S=[StrainMajorFinal2 StrainMajorFinal1];

%%
% calculating the area under the curve shown in figure 19

int1=trapz(xFinal1,StrainMajorFinal1);
int2=trapz(xFinal2,StrainMajorFinal2);
INT=int1+int2;

%%
figure
plot(Data_Out_x,Data_Out_S,'k')
xlabel('Position (mm)')
ylabel('Average Major Strain (% Elongation)')
title('Major Strain vs. Position')
%legend('Smoothed Data','Original Data','location','best')
Contact Angle Matlab Code

```matlab
%% Define variables
depth = 2.65; %mm
syms alpha

%%
a=vpa(solve( (13.7*sin(alpha)) + (12.7*sin(alpha)) ...
    + ( (depth-(13.7*( 1-cos(alpha) )))-( 12.7*( 1-cos(alpha) )))) ...
    /sin(alpha))*cos(alpha) ==26.87,alpha);

rad2deg(real(a))
```