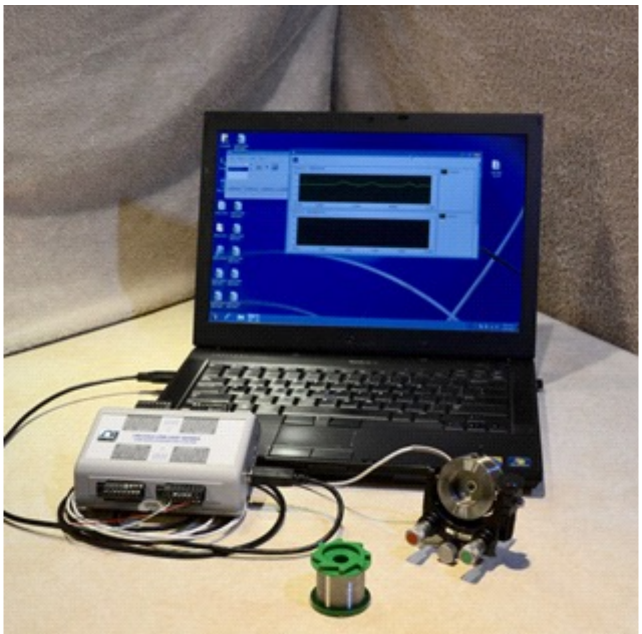

CORRELATION BETWEEN WIRE DIE DRAW FORCE AND WIRE QUALITY

The 3 Marathon Run

ABSTRACT

This is a senior design project in partnership with Fort Wayne Metals. The purpose of the project is to research the possible correlation between wire drawing force and finished wire quality. Establishing this correlation will help to control the drawing process and improve the quality of the finished product. In order to determine if this correlation exists, an accurate device to measure wire drawing force was designed and constructed. The device includes a commercial load cell connected to a data logging interface. Using this new tool, die force data was collected for comparison to the quality of the wire after the production run was completed. Initial testing included production of 80 miles of wire using our apparatus. Fort Wayne Metals now has a method and tooling to research correlations between die force, surface finish, diameter consistency and tooling life

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MET494 – Senior Design Spring 2016

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Introduction

The purpose of this project is to develop a method and tooling to draw correlations between die force, surface finish, diameter consistency and tooling life. Using this new method, die force data can be collected for comparison to the quality of the wire after the production run is complete.

Background

Fort Wayne Metals is a local company specializing in the production of high performance wire for medical and aerospace applications. Their industry leading expertise in the field of wire drawing is due to their continuous investment in research and development. One of their product lines is nonferrous wire with diameters between .002" and .010". Fort Wayne Metals refers to this size range as "fine wire". This wire is stainless steel or other specialty alloys that are later formed into medical grade implants or instruments for surgical use.

Wire is produced in a process called drawing, which elongates the material thus reducing its diameter using a replaceable die. Pulling the wire through the die exerts a linear force on the die referred to in the industry as draw force. The die is fixed in the machine by a die holder that allows for very precise adjustment in all axes of rotation. The current die holder is an off the shelf purchased part shown in Figure 1.

Figure 1 current die holder

When drawing wire of this fine size, identifying defects requires special inspection equipment that isn't practical to use during the drawing process. Surface finish is normally inspected post process in the inspection department using a microscope.

Surface finish is a significant quality concern for all producers of medical grade wire and is a regular source of customer rejections. FWM's customers include Indiana based medical device manufacturers who use the wire as a raw material to make their products. These products are both familiar and lifesaving, impacting people's daily lives. Needles, pacemaker components and cardiovascular stents are all produced from FWM wire. A smooth finish is essential to a needle piercing the skin without pain. Perfect wire is needed to keep a pacemaker reliable. Consistent wire is needed to produce strong effective stents. Anyone on the receiving end of these lifesaving products has a vested interest in the highest quality wire available.

The engineers at Fort Wayne Metals have theorized the die drawing force increases as surface defects appear and throughout the production run. Fort Wayne Metals did not previously have tooling to measure die force during the drawing process. They requested that our group design a method and tooling to measure die force and collect the data during a production run.

Design specifications

Fort Wayne Metals outlined the following criteria for the device.

1. Force is to be measured with a load cell.
2. Device should fit in a fine wire drawing machine without modification to the machine.
3. Apparatus should collect data for an entire 8-hour shift.
4. Should be easy to use so that engineers are not required to operate.
5. Needs to withstand the environment of wire drawing. This includes heat, drawing oils and accidental drops and bumps.

The 3 steps in device development:

I. The load cell

Before we could proceed with the design of the die holder, we first had to decide on a load cell that would satisfy the following criteria:

1. Range of measurement- In order to establish the range of measurement required, we first drew a free body diagram of the proposed system. As you can see in the photograph, shown in Figure 2, the wire pulling to the right is the force the load cell will measure. The free body diagram in Figure 3, details the reactions and forces in the die holder assembly system. We want to ensure that applying too much force doesn't damage the load cell. Since pulling on the wire is the only way to apply force to the load cell in this system, we know that the maximum force applied is limited by the strength of the wire being drawn. Fort Wayne Metals provided us with the wire diameters and strength properties for the wires drawn on the small wire machines [2]. Using the formulas shown in Appendix A2 [5], we calculated the force required to break each of the wires. These breaking force values can be seen in Appendix A3. Applying a safety factor of 2, the maximum load design requirement would be about 70 lbs. According to the load cell manufacturer's specifications [1], all of the cells are capable of enduring 150% of their rated capacity. This would lead to the choice of a 50 lb. load cell.

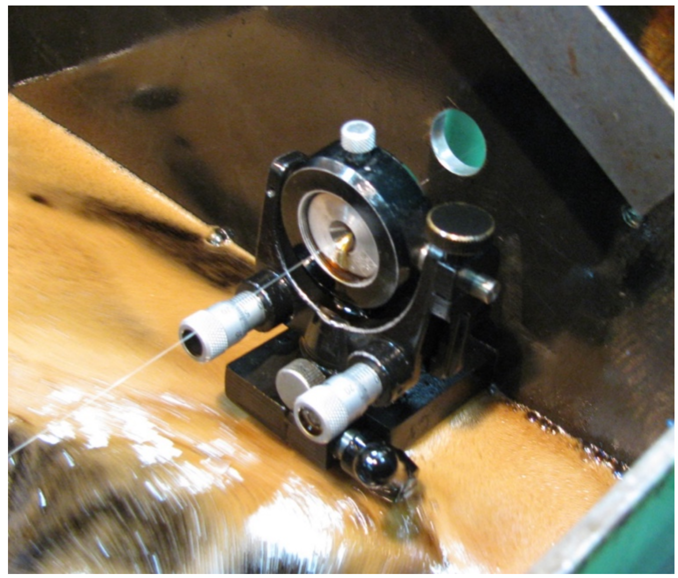


Figure 2 current die holder in use

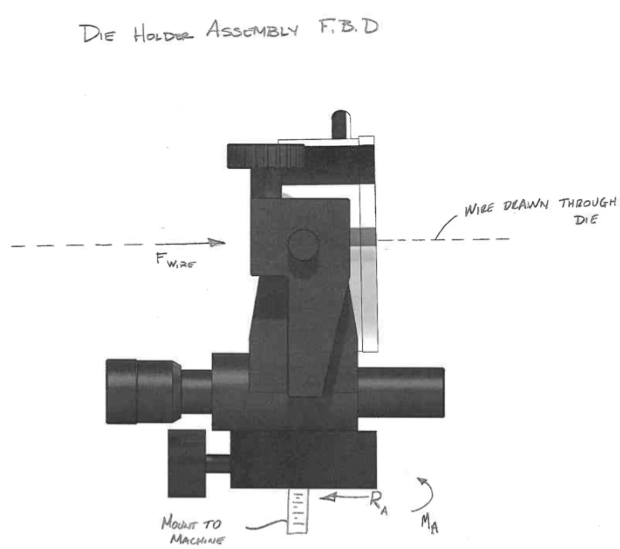


Figure 3 free body diagram

The 50lb. would be capable of withstanding up to 75 lbs. Unfortunately, the 50 lb. load cell at both manufacturers had extremely long lead times. We chose to use a 100 lb. load cell that FWM had in house from another project.

2. Accuracy of measurement- After researching the various load cells, it was apparent that they are all very accurate instruments. The majority of those available can measure to within 1% linearity [1]. After meeting with FWM engineers, they felt that this level of accuracy would be more than adequate for our purposes.
3. Physical Size - The final die in the drawing process has an outer diameter of 1". The measuring surface of the load cell must sit directly against the die, so choosing a load cell with the same 1" diameter was a logical choice. This made the holding fixture easier to manufacture and assemble with the load cell and die in place. The 100 lb. load cell that we selected meets the dimensional criteria and is shown in Figure 4.

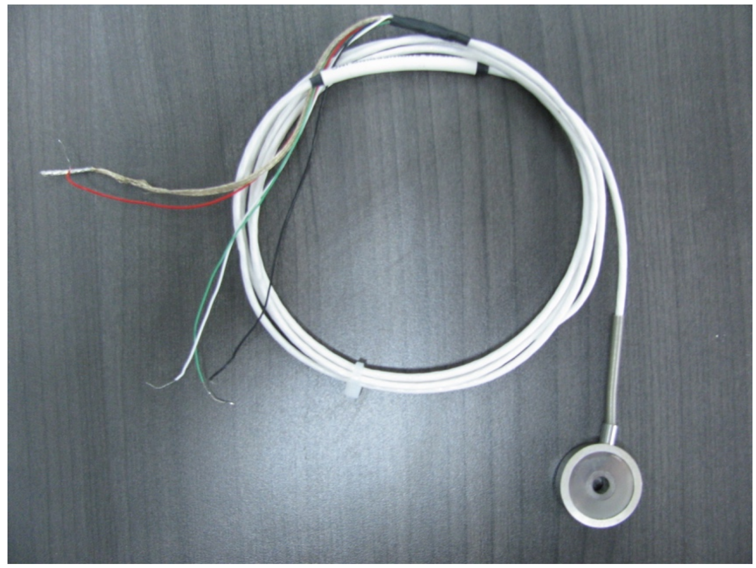


Figure 4 the load cell

II. Initial Evaluation

Before beginning design, a used die holder was acquired from FWM maintenance for analysis. The assembly was originally designed to hold a lens in a telescope, and the team decided to investigate the design in search of enhancements before proceeding. The die holder was carefully disassembled to determine its construction and to understand its function. The pivoting die holder assembly is attached on one side with a threaded insert. Figure 5 – The ring has a shaft pressed into one side and pivots with clearance between the shaft and bushing. The shaft has a taper that locates on the taper inside the insert. The taper arrangement if adjusted properly, will remove play between the shaft diameter and the insert bore. The opposing side has a ball bearing, shown at the end of the Allen wrench in Figure 6, which locates in a seat opposite the shaft on the die holder ring.

Figure 5 current ring assembly

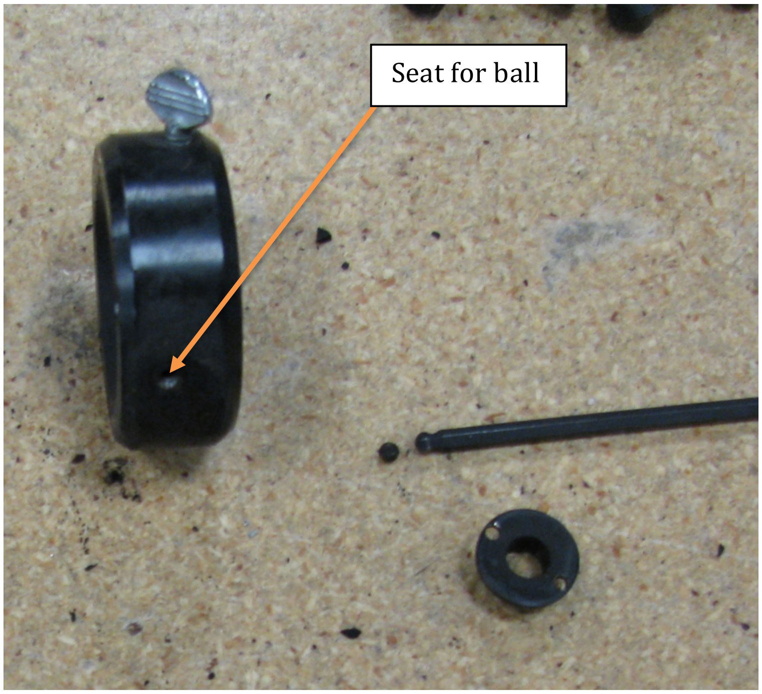


Figure 6 ring showing ball seat

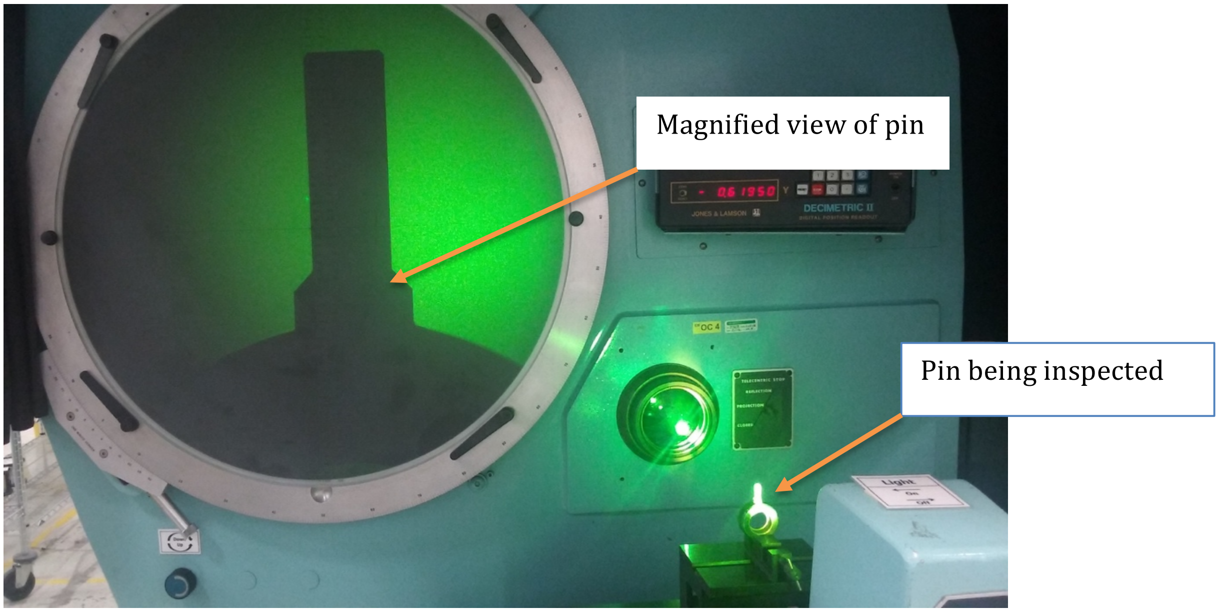
The ball is then compressed to support that side, by tightening a setscrew. This contains the ball axially and is adjusted to remove end play. It is then locked by a second setscrew that is perpendicular to the first. A clamp device locates on the shaft and allows initial adjustment. The knurled screw is then tightened to allow fine micrometer adjustment.

III. Mechanical design

The following steps were taken to complete the new design.

1. Measured the pin on the optical comparator to accurately determine the angle of the engagement surface
2. Verified load cell diameter using micrometer
3. Designed ring to meet criteria:
    - Material hardness & toughness sufficient to withstand use
    - Calculated the necessary depth of the ring (load cell height + die thickness)
    - Load cell cable provision to clear lid
    - Die and load cell easily removable
    - Detent screws to retain die and load cell position
    - Proper fit with current pivot pin bushing
4. Produced detailed blueprints of all machined components using Solidworks 2015
5. Released complete project detail drawings to vendor for quotation
6. Created BOM and assembly drawings
7. Received quote and placed order for machined parts.

Analysis of the assembly revealed several design requirements, and involved several key decisions and calculations. We began by evaluating the pin. The angle on the pin that initially looked like a simple chamfer was determined to be an engagement and location surface. Therefore, this critical angle and its length needed to be accurately measured. The angle of a round pin is difficult to measure, and the only accurate equipment available to us for this purpose is an optical comparator.



The existing pin is shown during the measuring process in Figure 7 (above).

The new pin designed to interact with the die holder ring is shown in Figure 8. The shear strength calculation [5] of this pin is shown in Appendix A4.

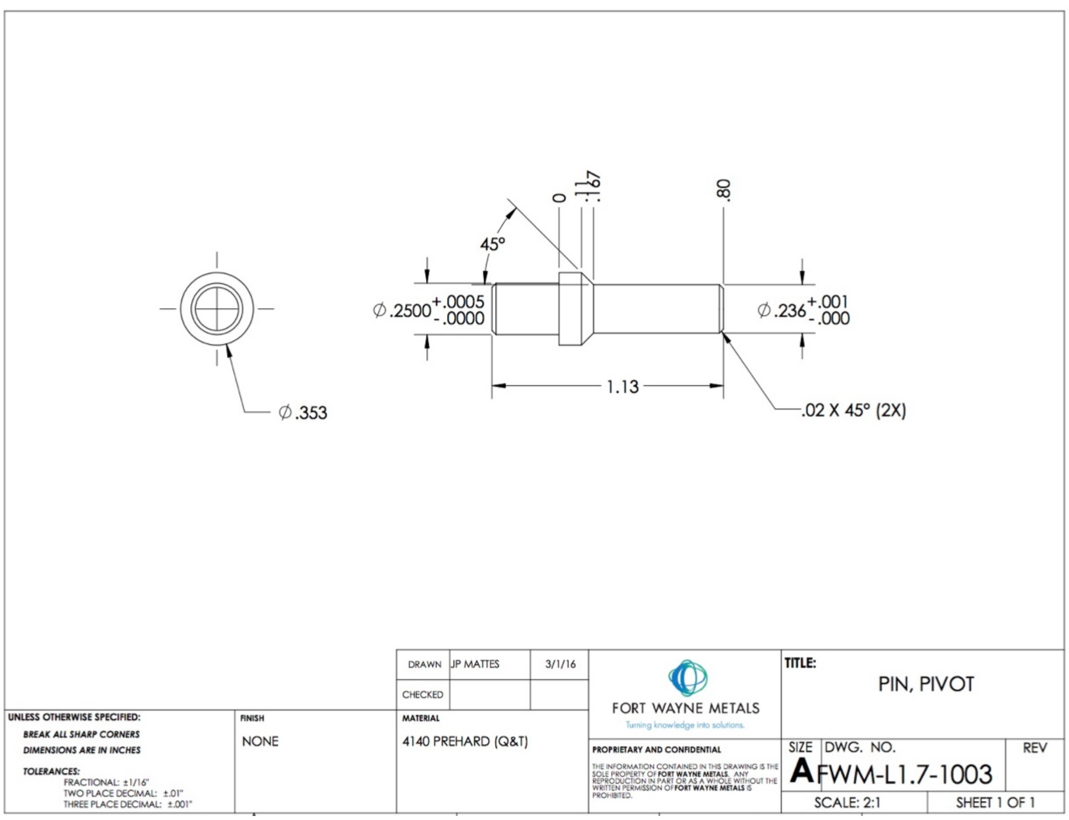
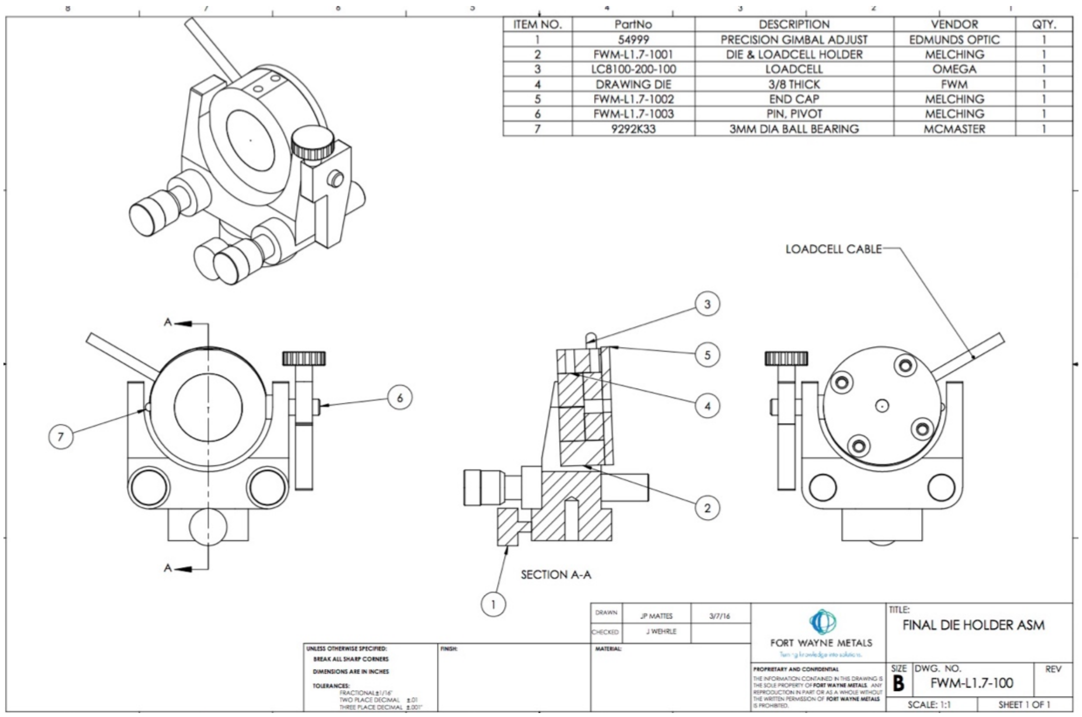


Figure 8 new pivot pin

The load cell cable also proved to be a challenge, as it is permanently fixed to the cell and sensitive to bending and flexure. With the cell embedded in a tight fitting diameter, the cable restricted easy removal of the cell. By bolting a cap (Item 5 in Figure 9) onto the holder (Item 2), we were able to mill a slot for the cable that makes the load cell easily removable with little risk of damage to the cable.



ITEM NO.	PartNo	DESCRIPTION	VENDOR	QTY.
1	54999	PRECISION GIMBAL ADJUST	EDMUNDS OPTIC	1
2	FWM-L1.7-1001	DIE & LOADCELL HOLDER	MELCHING	1
3	LCB100-200-100	LOADCELL	OMEGA	1
4	DRAWING DIE	3/8 THICK	FWM	1
5	FWM-L1.7-1002	END CAP	MELCHING	1
6	FWM-L1.7-1003	PIN, PIVOT	MELCHING	1
7	9292K33	3MM DIA BALL BEARING	MCMASTER	1

Figure 9 completed die holder assembly

The slot was angled to direct the cable safely away from the machine lid. The die is removable from the front side for inspection and replacement. The back plate is attached with a symmetrical pattern of (4) #8-32 UNC flat head screws and creates the assembly shown in Figure 9. Tensile force and pull out strength calculations for the screws are shown in Appendix A1. These calculations show that 2 screws would easily handle the expected load but we wanted to keep the back plate tight and flat against the ring. With 4 screws, even a slightly warped back plate would be pulled flat every time.

The new die holder will be used in a continuous production environment. If successful, it will be used for decades to come, so a material with excellent mechanical properties is required. Routine die changes can cause wear to the internal surface of the holder. The pivot point where the ball interacts with the holder is also susceptible to wear and deformation. The existing holder is manufactured from brass, but a better choice for this would be an alloy of steel. FWM routinely builds machine components from an alloy known as 4140 pre-hard. This material provides a good combination of hardness and toughness without the need for a secondary heat treat process, therefore, we chose this as the material for the design. Alro Steel supplied the 4140 pre-hard used by our machine shop for these components [7]. This completed the mechanical design and analysis of our testing device. The full package of detail prints and BOM is shown in Appendix B.

The logic and process of data collection

I. How the load cell and logger function

Our method uses a load cell to measure the force applied to the die as the wire is drawn through it. The load cell is a strain gauge configuration known as a Wheatstone bridge. The manufacturer's schematic for the internal wiring of the load cell is shown in Figure 10 [4]. This bridge circuit also includes compensation for temperature changes that might normally cause drift in measurements.

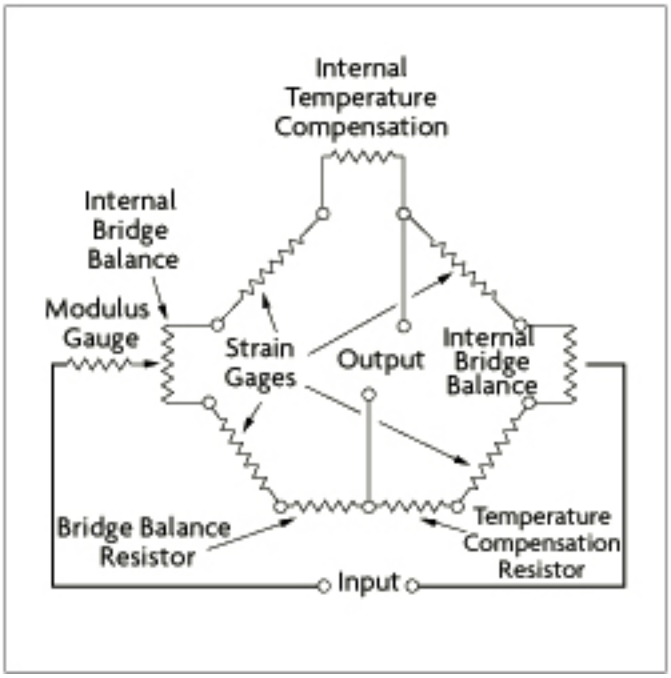


Figure 10 load cell internal circuit

As the wire was drawn, we expected the force on the die to vary. The rate that wire is drawn is theoretically constant and controlled by a PLC on the machine. If we could track the load on the die versus time during the run, we would be able to approximate the footage location on the wire where the load changed. Inspecting the wire at this location might reveal a quality change that correlates to the increase die force.

To log the die force measurements, we ordered an Omega data acquisition module [3]. This unit outputs a 12 VDC excitation signal to the load cell that is returned to the module as a signal in the millivolt range. This module, shown in Figure 11, accepts the output from the load cell and uses a USB connected laptop to track the mV reading from the load cell in relation to elapsed time. We could then convert these mV readings to a load in pounds using the load cell calibration values.

Figure 11 data acquisition module

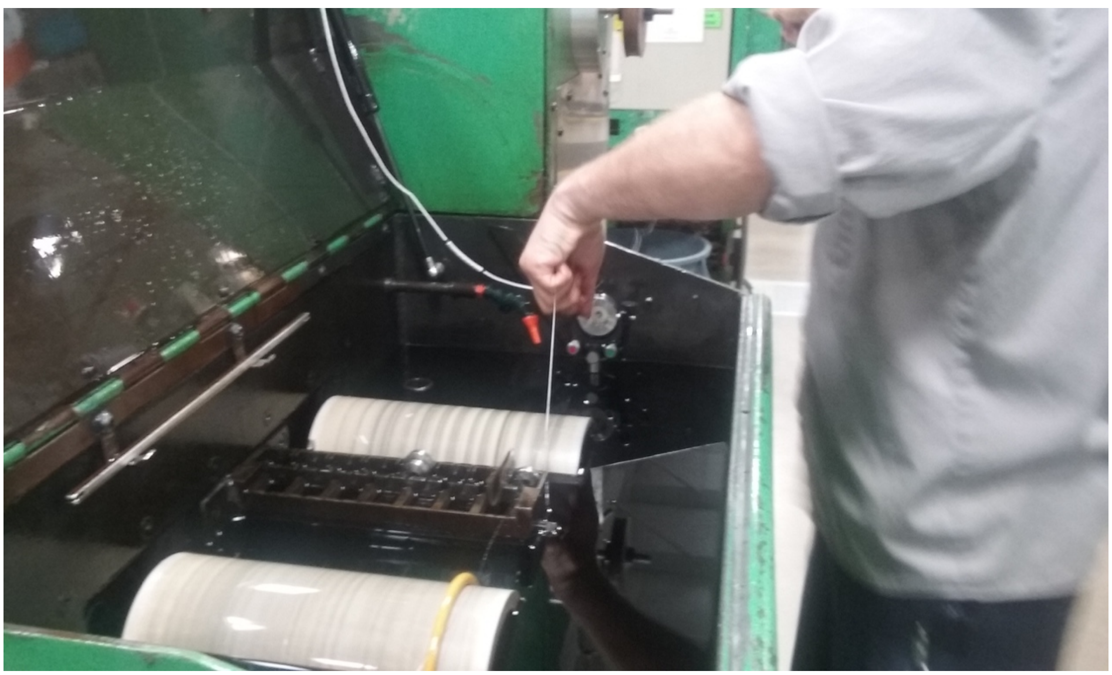
II. Calibration and setup

We applied weights of 5, 10 and 15 pounds to the cell and recorded the output voltage for each weight as shown in the chart below.

	10lb	5lb	15lb
Avg Reading V	0.007188324	0.006017887	0.00843429
Minus Tare	0.00237038	0.001199943	0.00361635
mV/LB	0.237037999	0.239988637	0.24108987

We then used these values to develop a spreadsheet that would convert a mV reading into a load in lbs. We had thousands of data points to convert and Excel proved very helpful.

We next installed our device and ran a test to ensure that the fine wire machine and the data logger wouldn't electrically interfere with each other. We allowed the logger to run at the machine without the die in place. This kept the known load at zero while letting us watch for variations or other signs that there was interference. No interferences were observed. We enlisted the assistance of a wire drawer to string up the wire in the machine. Wire drawers are the highly skilled professionals who set up and run the wire drawing machines at Fort Wayne metals. We were then ready for our first attempt at gathering data.



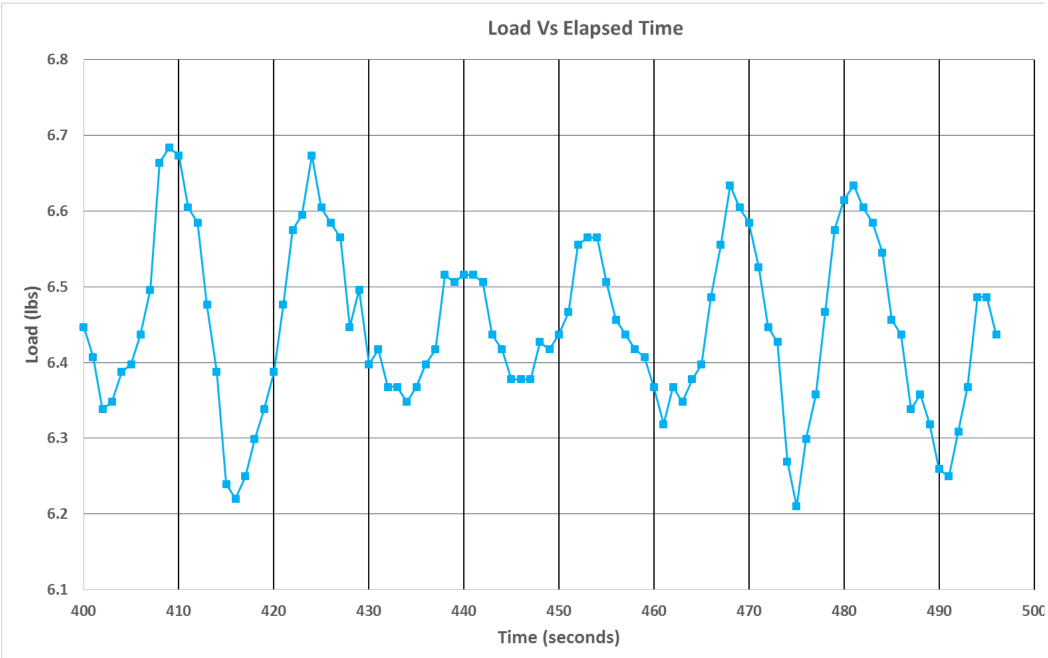
Stringing up wire for testing

III. Collecting the data

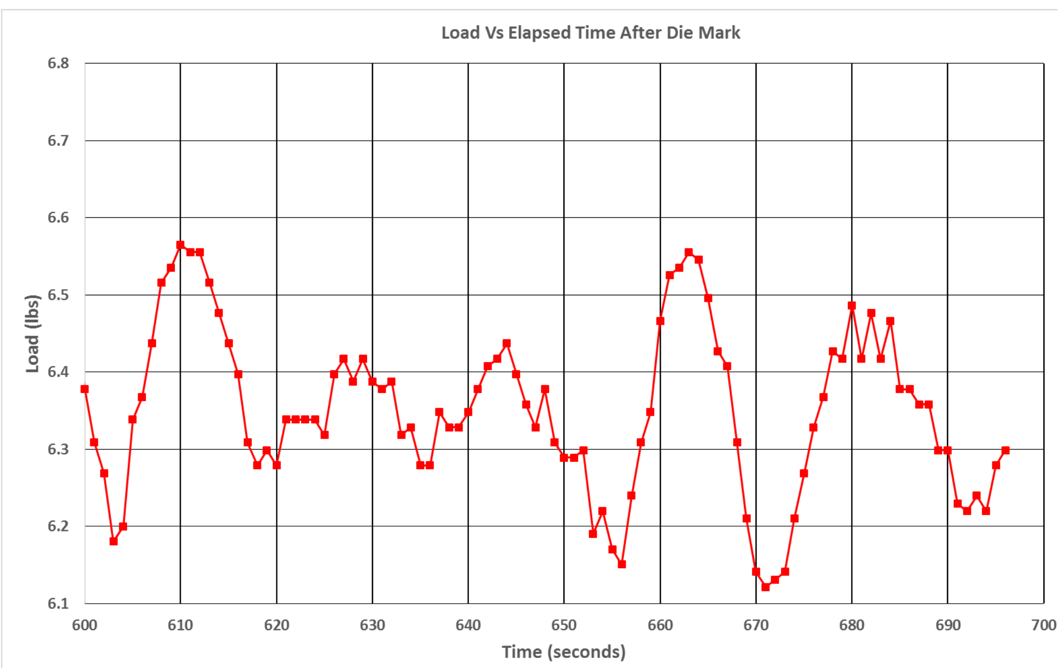
We were able to observe 4 hours of wire production with the data logger in place, and monitor the computer in real time. The wire drawers ran the test set up for 4 more shifts of production, setting up both the hardware and software, unaided by engineering. The total footage of wire run with the logger equates to about 80 miles. This is equivalent to the length of 3 Boston Marathons!

IV. Analysis

The chart below shows the load versus elapsed time for one of the drawing tests using a wire known as Nimonic 90, which has a history of wearing dies. This material was selected for the test in an attempt to show results quickly. The first chart is a sample of the data during a known good section of wire.



The second chart shows the data collected just after a die mark was observed in the wire. The data does look slightly different than the first chart, but no glaring variations appear.



The die mark is shown under magnification in Figure 12.

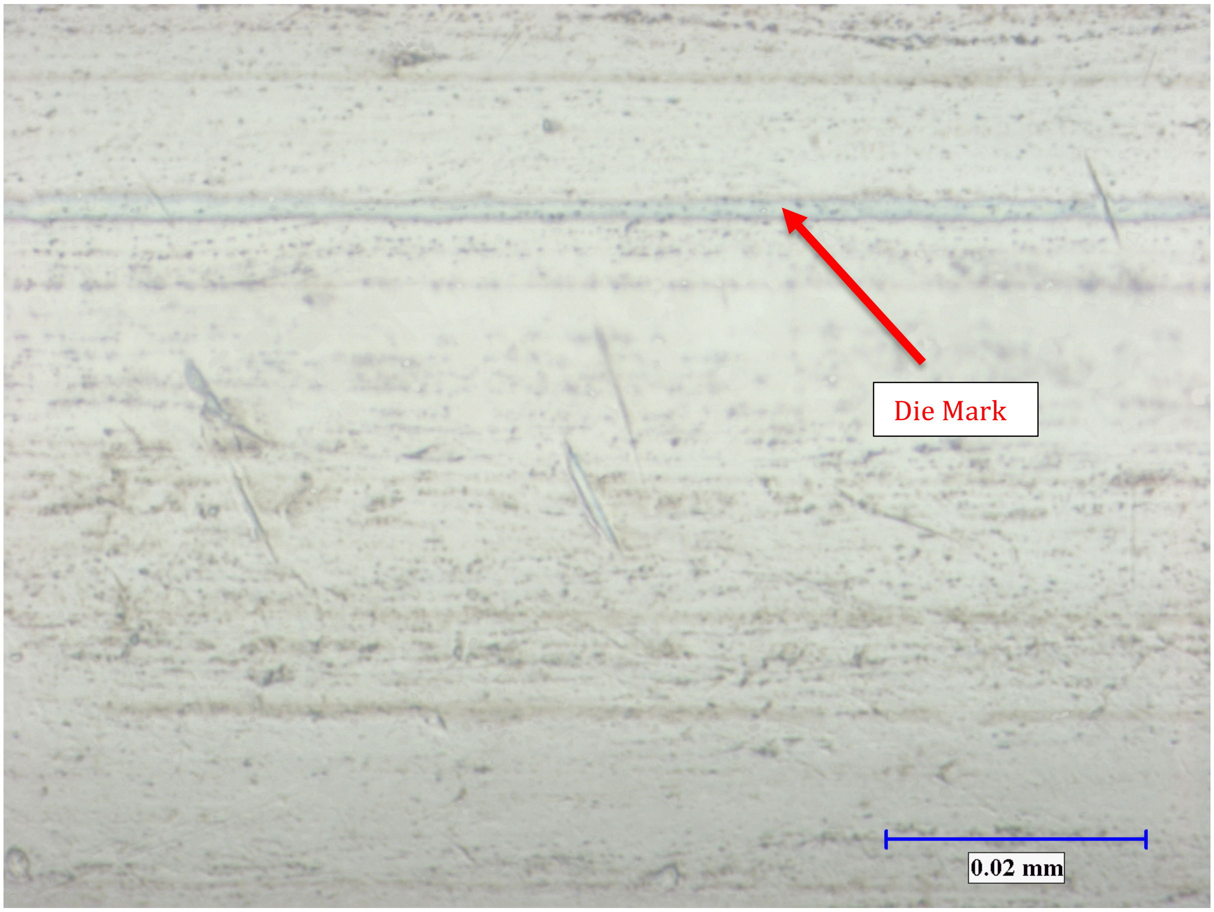


Figure 12 magnified view of .0079" diameter wire with die mark defect

Our limited analysis of this data doesn't show obvious correlation between defects and draw force, but the design group lacks the experience and knowledge of wire drawing to understand the intricacies of the process. Further testing is required to prove or disprove this correlation. This testing should include a design of experiments by those experienced with the drawing process in order to measure and catalog other variables that we are not familiar with. These controlled tests will provide more valuable information than our preliminary runs.

Comparison to initial specs

Double checking the Fort Wayne Metals outlined criteria:

1. Force is to be measured with a load cell.
   - ✓ Successfully integrated a load cell
2. Device should fit in a fine wire drawing machine without modification to the machine.
   - ✓ Fits in both a fine wire and intermediate wire drawing machine
3. Apparatus should collect data for an entire 8-hour shift.
   - ✓ Capable of collecting 277 continuous hours at one data point per second
4. Should be easy to use so that engineers are not required to operate.
   - ✓ Used for 4 shifts without engineering support
5. Needs to withstand the environment of wire drawing. This includes heat, drawing oils and accidental drops and bumps.
   - ✓ Designed to achieve these specs, longer test period is required to prove out

Failure and the unexpected

Die fit in the holder turned out to be an issue. During one of the load tests, a final die became lodged in the holder. The load cell showed almost no change in force during that run so something was obviously wrong. We found out the die was stuck after the run. This die was slightly oversize from the specifications. We have developed an improvement on the holder that should account for a die that is oversize or even one that becomes wedged in the holder. As seen in the Figure 13, the new design would have a sliding flanged bushing (in red) between the die and the die holder. This bushing would be sized to allow movement regardless of the die fit. This should prevent the issue we experienced.

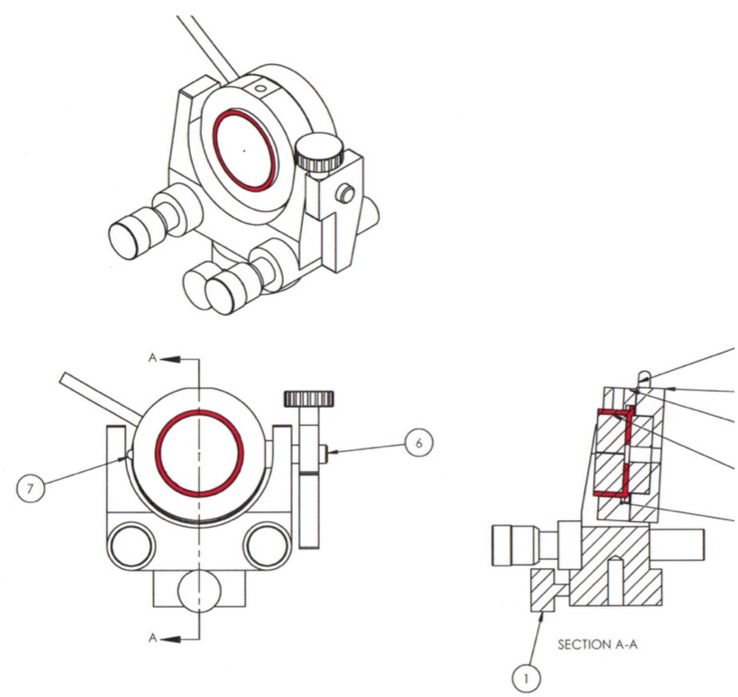


Figure 13 proposed design improvement

Budget and ownership

Fort Wayne Metals sponsored this project and committed to financially supporting its success. In light of their full financial support, the resulting research and products developed are the property of Fort Wayne Metals. The project budget shown below was approved to fully develop and build a prototype unit.

Project Budget			
Item Purchased	Budget	Actual Cost	Notes
Die Holder (3 details)	$550.00	$ 515.00	
Precision Gimbal Mount	$360.00	$ 360.00	
Load cell	$495.00	$ -	Loan from R&D
Logger	$550.00	$ 550.00	
Computer	$500.00	$ -	Loan from IT
Electrical Connectors	$65.00	$ -	Included in logger
Freight	$135.00	$ 57.00	
Total	$2,655.00	$1,482.00	

Reflection & conclusion

Our project was a very specific design that Fort Wayne Metals had requested for their fine wire drawing machines. They desired to have a device to attempt to establish a correlation between die drawing force and wire quality. We successfully constructed and implemented a system to begin testing the correlation.

We see other potential uses for the device aside from detecting defects. During our time on the floor, a supervisor expressed interest in using the device for his upcoming tests of new die designs. Many other variables in the drawing process can affect die draw force and our project could help to measure the difference in this force as those variables are changed.

Although our project won't revolutionize any aspect of wire production, it is another small stepping stone in the continuous improvement process. This type of incremental innovation is one of the reasons FWM leads the medical wire industry and is a growing locally owned business.

References

[1]2016. [Online]. Available: http://www.omega.com/pressure/pdf/LC8100.pdf. [Accessed: 17- Feb- 2016].

[2]P. George, "UTS fine wire" e-mail containing wire UTS data and sizes, 2016.

[3]2016. [Online]. Available: http://www.omega.com/das/pdf/OM-DAQ-USB-2400.pdf. [Accessed: 17- Feb- 2016].

[4]2016. [Online]. Available: http://www.omega.com/prodinfo/loadcells.html. [Accessed: 17- Feb- 2016].

[5]2014 Barry Dupen. Applied Strength of Materials for Engineering Technology. 6 ed. http://opus.ipfw.edu/mcetid_facpubs/35

[6]E. Oberg and R. Green, *Machinery's handbook*. New York: Industrial Press, 1996.

[7]*Alro.com*, 2016. [Online]. Available: http://www.alro.com/datacatalog/008-alloys.pdf#page=7. [Accessed: 17- Mar- 2016].

[8]"McMaster-Carr", *Mcmaster.com*, 2016. [Online]. Available: http://www.mcmaster.com/#91253a193/=11nkbih. [Accessed: 17- Mar- 2016].

Appendix A

A1

Stripping of the internal threads are a concern so we needed to calculate the required length of engagement of the screws into the die holder ring. The variables used are:

E_s= Min pitch diameter of internal thread

L_e= Length of thread engagement

A_s = Shear area of external threads

D_s = Min major diameter of external threads

UT_n = UTS of female threads

A_t = Tensile stress area of screw threads

P = Load required to break screw at threads

K_n = Max minor diameter of internal thread

n = Threads per inch

A_n = Shear area of internal threads

E_n = Max pitch diameter of the internal thrd

UT_s = UTS of screw material

J = Relative strength of internal to external thd

Formula 1:

$$Le = \frac{2*At}{\pi*Kn[.5+.57735*n(Es-Kn)]}$$

Formula 2b:

$$At= \pi(\frac{E_s}{2} - \frac{.16238}{n})^2$$

Formula 3:

$$J = \frac{A_s - UT_n}{A_n - UT_s}$$

Formula 4:

$$P = UT_s*A_t$$

Formula 5:

$$As =\pi * n * L_e * K_n[\frac{1}{2n} + .57735(E_s - K_n)]$$

Formula 6:

$$An =\pi * n * L_e * D_s[\frac{1}{2n} + .57735(D_s - E_n)]$$

First we must find out if the internal threads will strip before the screw breaks.

Formula 5 and 6 are solved using the proposed L_e value.

Next equation 3 is solved. If the value is less than 1, the screw will break before the threads pull out.

This is the case for our die holder, the J value is less than 1. With this known, we can use equation 1 to find the smallest L_e required to break the screw.

Formula 2b is used to find the smallest area of the screw (the smallest part of the thread profile)

This A_t value is finally used in Formula 4 to give the maximum load that a single screw will withstand in pure tension.

We created an excel spreadsheet to perform these calculations. The values of its output are below:

Es	0.1399	IN	Ds	0.1571	IN
Kn	0.139	IN	En	0.14	IN
Le	0.328	IN	Utn	110000	PSI
n	32		Uts	120000	PSI
As	0.074	IN^2	At	0.0132	IN^2
An	0.13208	IN^2			
J	0.51354		If J is greater than 1, use formula 4.		
			If J is less than 1, use formula 1.		
Formula 1					
Le Required	0.12099	Inches			
Load to break bolt using only direct tension, no shearing forces					
P	1586.7	Lbs			

The value P of 1586.7 LBS is the limiting factor. Formula 1 shows that the minimum thread engagement is .121 inches. This means a thread engagement of more than .121 inches will lead to the bolt breaking in tension before the internal threads will strip out of the material used.

Thread values from machinist handbook [6]

Screw material values from source [8]

Material strength values from vendor [7]

A2

Stress is given by the formula: $\sigma = \frac{F}{A}$

Rearranging the equation we can solve for the force F. The equation becomes:

$$F = \sigma * A$$

The units for this equation are: F (lbs) = σ $(\frac{lbs}{in^2}) * A(in^2)$

The wire is round so its area is found by the formula: A= (PI * D^2)/4

A3

Breaking Strength Calculations		
FWM Name	Hyten	Spring Condition
UTS	450KSI	360KSI
Wire Diameter	Load Required (lbs)	Load Required (lbs)
0.010	35.3	28.3
0.009	28.6	22.9
0.008	22.6	18.1
0.007	17.3	13.9
0.006	12.7	10.2
0.005	8.8	7.1
0.004	5.7	4.5

A4

Stress is given by the formula: $\sigma = \frac{F}{A}$

Rearranging the equation we can solve for the allowable force F. The equation becomes:

$F = \sigma * A$

The units for this equation are: F (lbs) = σ $(\frac{lbs}{in^2}) * A(in^2)$

The pin is round so its area is found by the formula: A= (PI * D^2)/4

Using our values for the actual material and pin diameter:

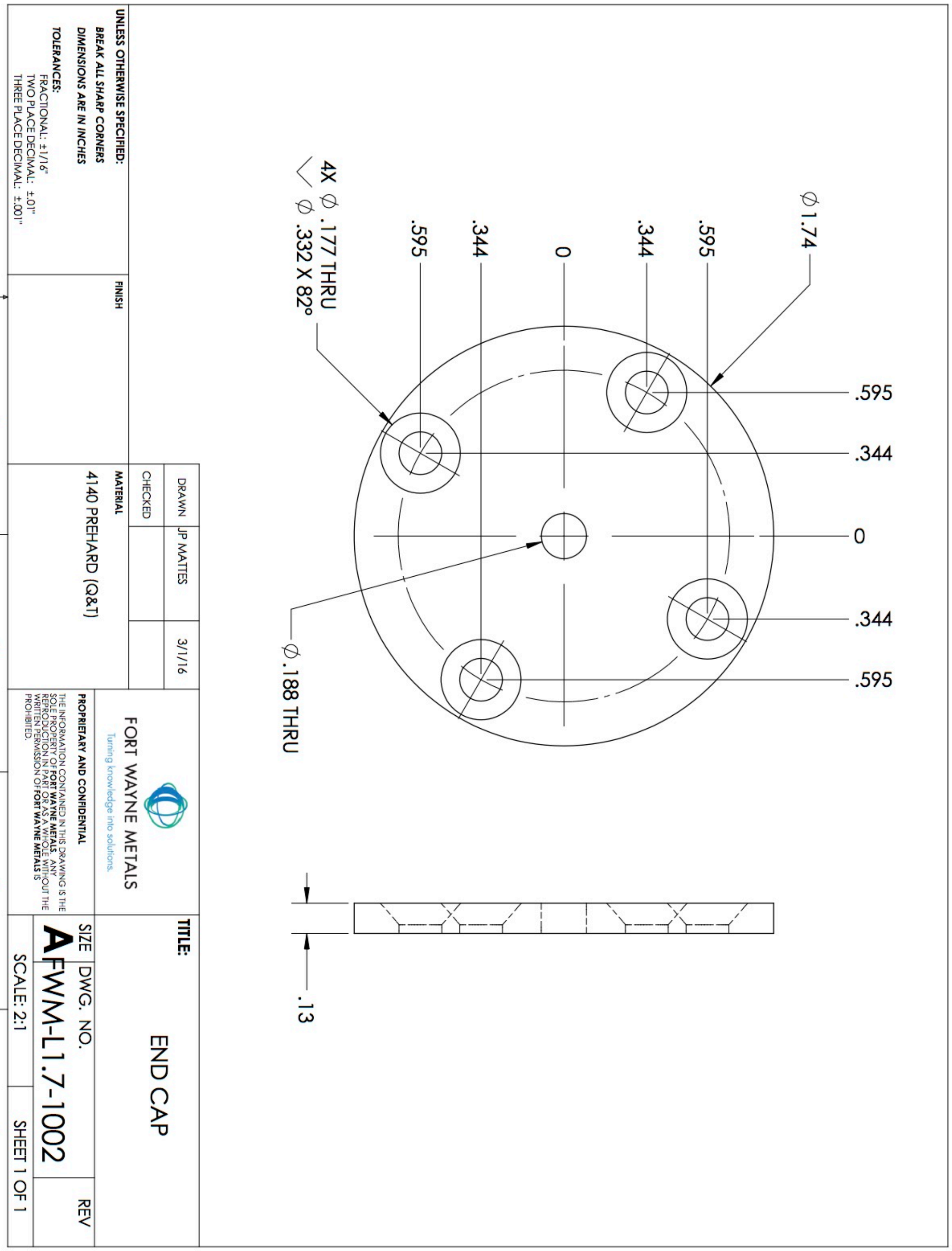
.0437 in^2= (PI * $.236^2$)/4

4811.8 (LBS) = 110,000 $\left(\frac{lbs}{in^2}\right).0437(in^2)$

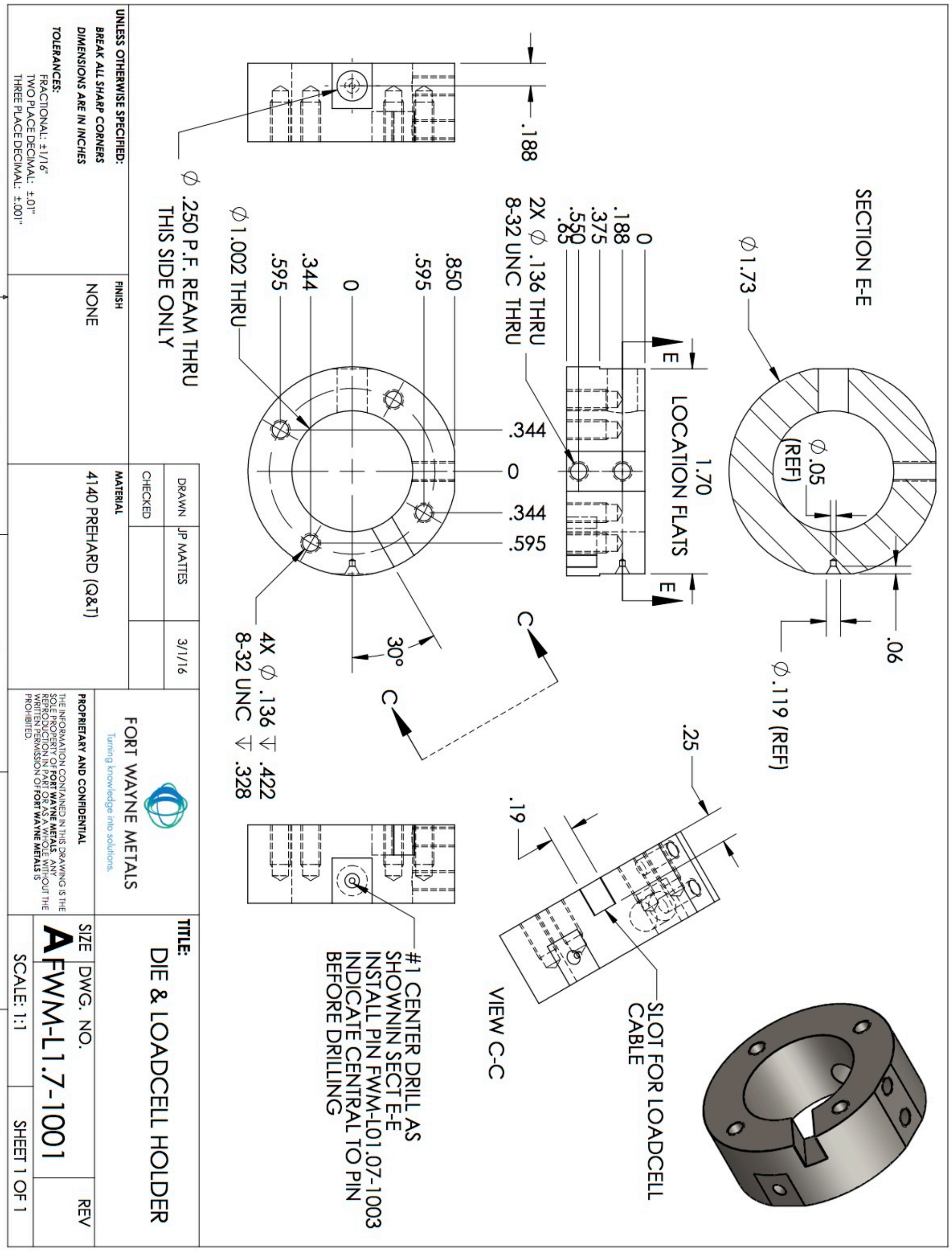
The allowable force on the pin is thus 4,811.8 LBS in shear.

The pin is significantly stronger than our anticipated drawing forces of less than 100 LBS.

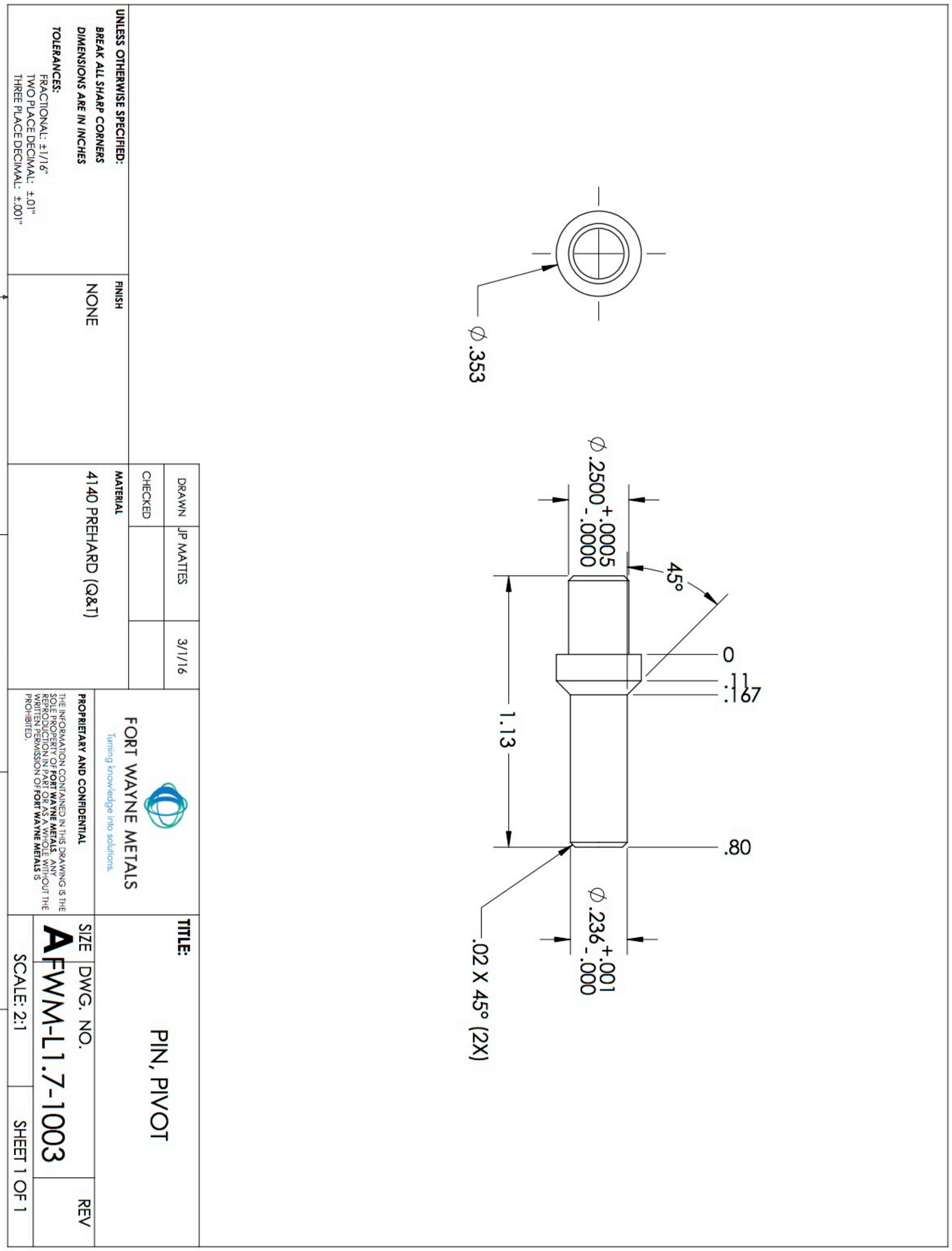
Appendix B



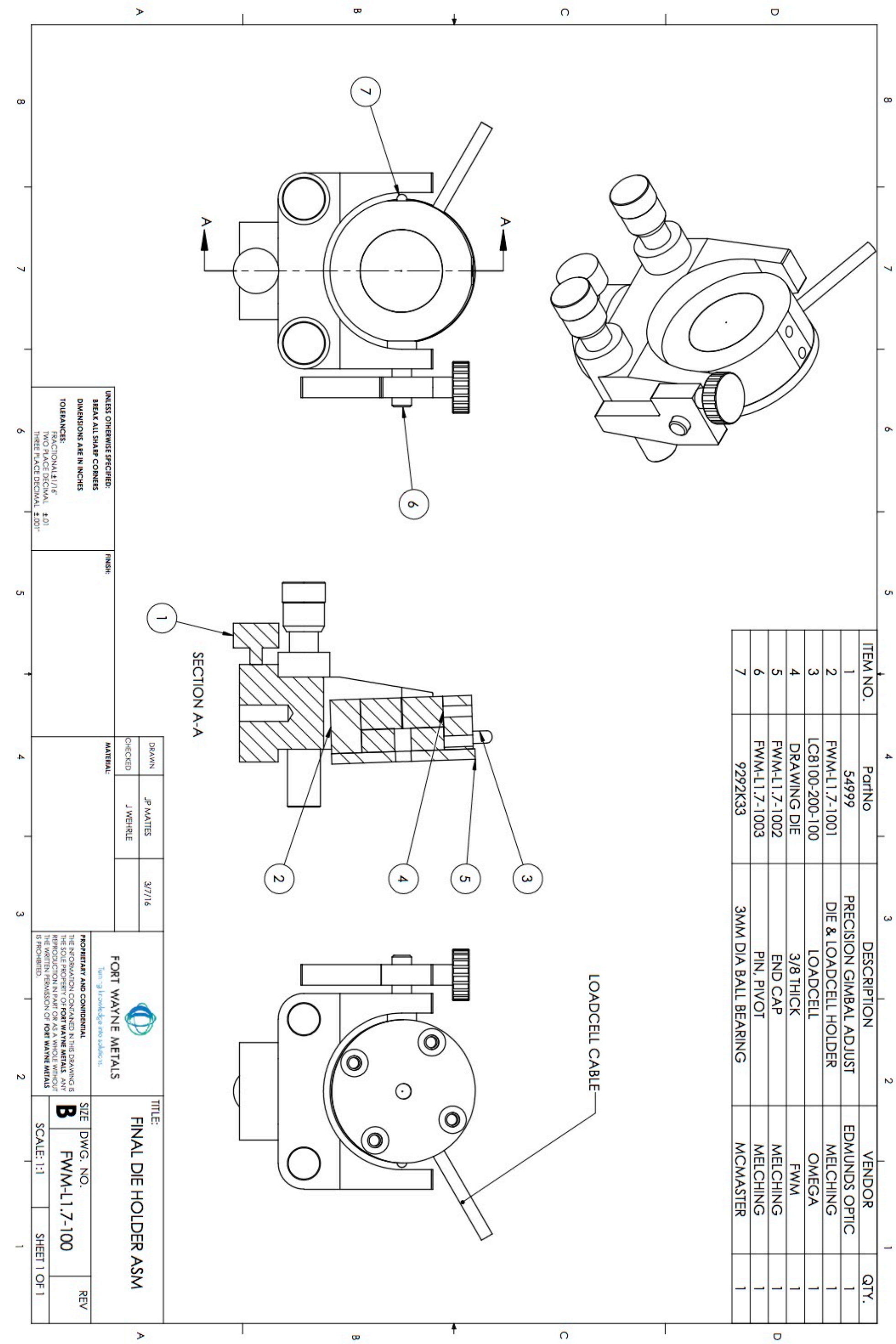
End cap, allows for load cell removal



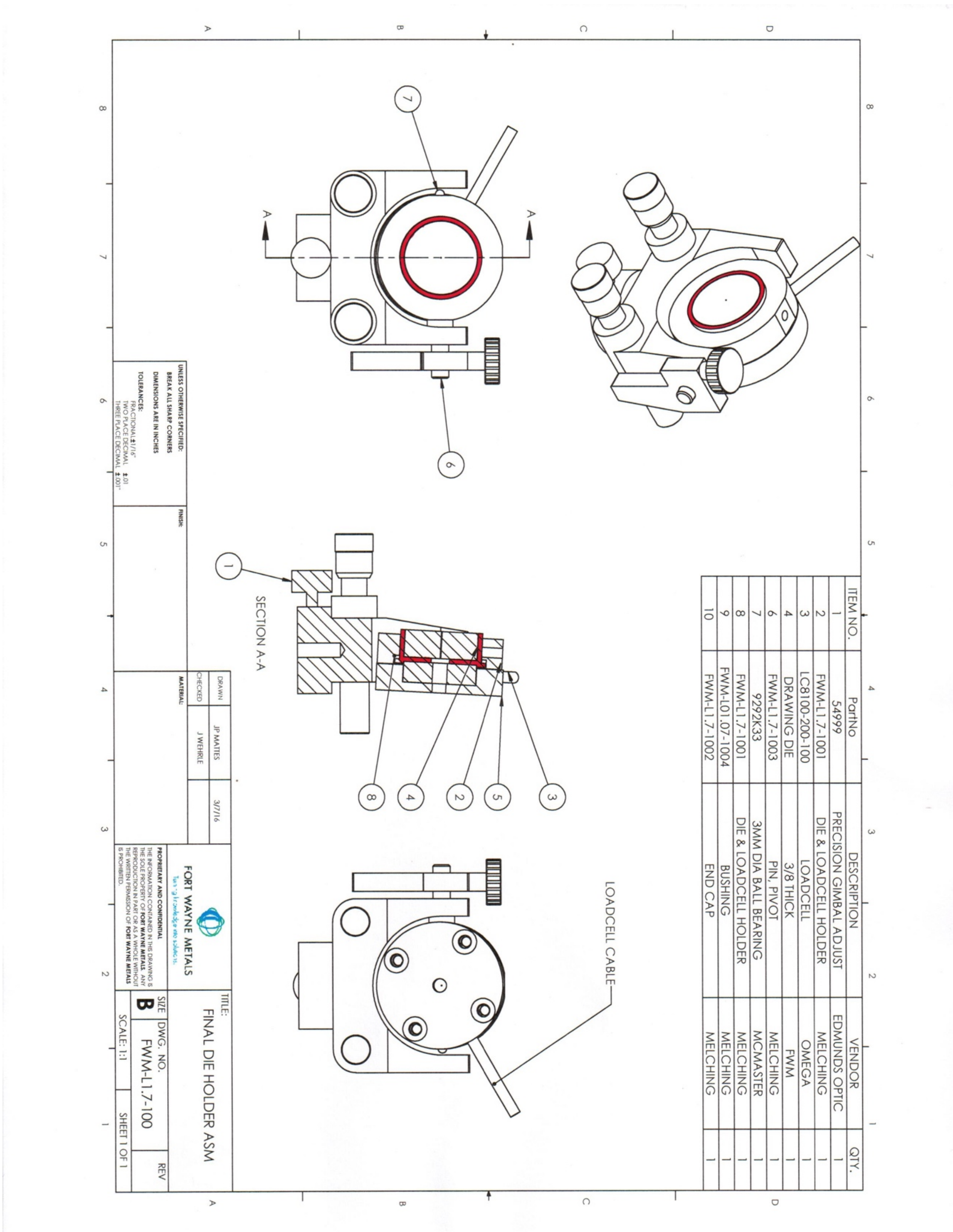
Load cell and die holder ring



Pivot pin for die holder ring

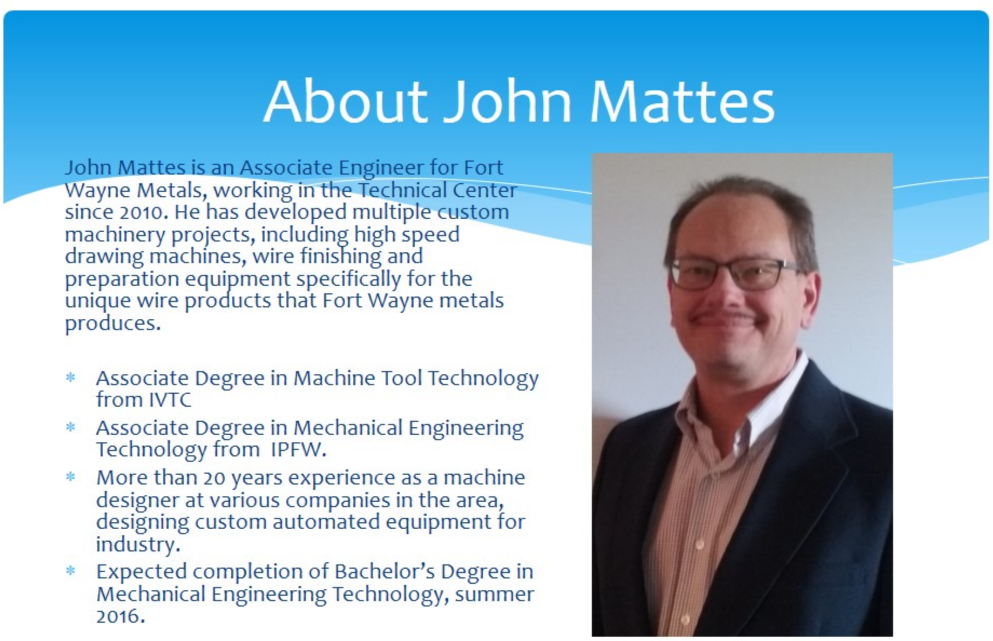


As built die holder design



Improved design with new bushing feature

Meet the team



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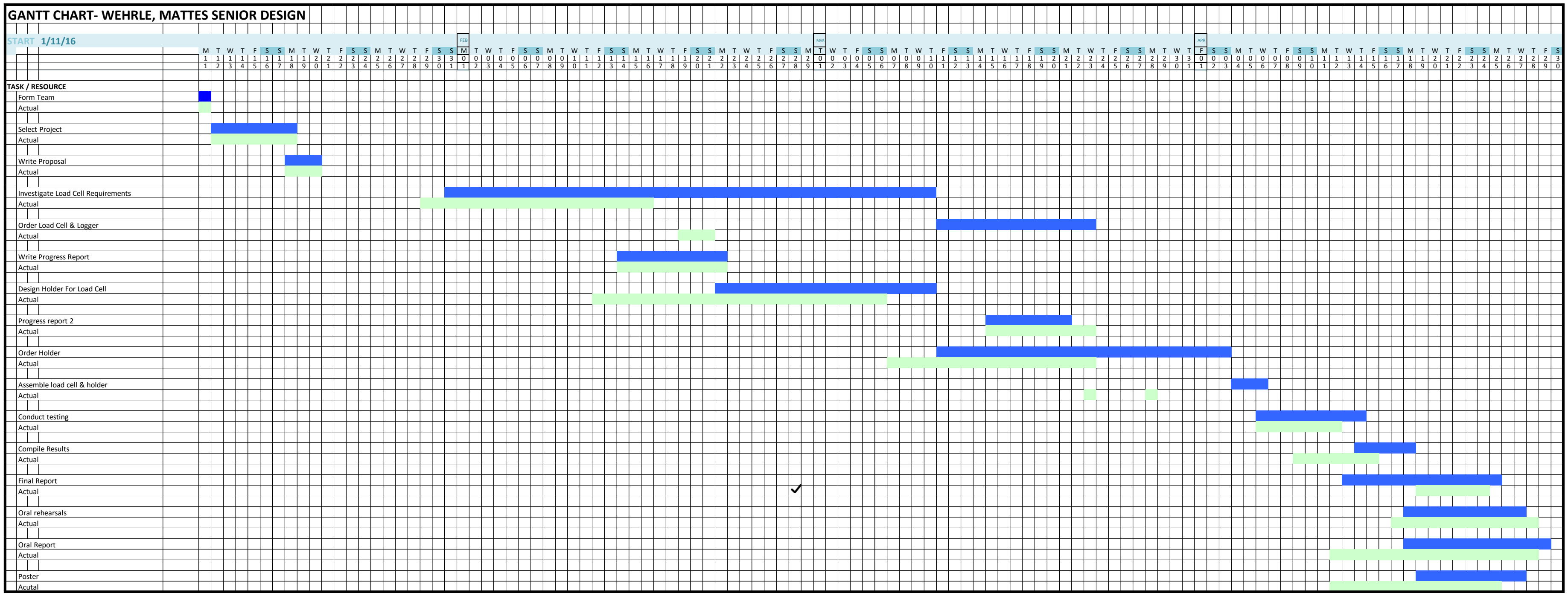
GANTT CHART- WEHRLE, MATTES SENIOR DESIGN
START 1/11/16
FEB
MAR
APR
TASK / RESOURCE
Form Team
Actual
Select Project
Actual
Write Proposal
Actual
Investigate Load Cell Requirements
Actual
Order Load Cell & Logger
Actual
Write Progress Report
Actual
Design Holder For Load Cell
Actual
Progress report 2
Actual
Order Holder
Actual
Assemble load cell & holder
Actual
Conduct testing
Actual
Compile Results
Actual
Final Report
Actual
Oral rehearsals
Actual
Oral Report
Actual
Poster
Acutal