

Design for Manufacturing, Reliability, and Economics

Team 13

Tabletop Torsion Machine



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ABSTRACT

This report discusses the importance of our design and why the Air Force Research Laboratory has a need for a small scale torsion tester. This report outlines how the torsion tester was manufactured and the necessary components used for the design. A breakdown of the potential problems with the design and how it may fail is also presented in this report. Fortunately, the torsion tester should not experience any problems, but as with all things, there is potential for things to break or go wrong. Finally, the budget for this design was \$2,000, so a comprehensive breakdown of how much each piece of the design cost to procure and how the build compares to other torsion testers on the market is discussed.

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1. Introduction

Material testing is an essential part of designing new and improved products. It ensures reliability, efficiency, and safety. Knowing how a material acts under certain conditions allows engineers to create an optimal design. Without proper material testing an idea would never become reality. The Air Force Research Laboratory (AFRL) Munitions Directorate at Eglin AFB is currently testing materials to use with their products. These products range from warheads to the frame of a fighter jet. In order to ensure optimal performance and user safety, many material tests are performed. The current torsion machine at Eglin AFB is very large and is only effective when testing large specimens. They have a need for smaller, tabletop torsion testing machine. A smaller machine will lead to more accurate data when testing small specimens. These small specimens are used in order to test materials that are similar to the geometry of the product in the field. The data that will be gathered from the new machine will more accurately characterize the materials and how they react under torsional loads. This will result in more accurate models and simulations used by the AFRL.

In general, there are 4 major components of a torsion machine. These components include load generation, load application, load measurement and housing or frame. Additionally, the Air Force sponsor has requested that the free end of the specimen has 1 degree of freedom in the axial direction. This will ensure accurate results even if the specimen expands or contracts during testing. An AC gear motor and variable frequency drive (VFD) are being used in order to generate the load required to twist the specimen. The specimen will be held in place using two 6-jaw chucks. A strain rosette will be placed on the transmitting shaft in order to output the applied load on the specimen. Finally, the frame will be made out of steel and will utilize a 2 rail ball bearing guide in order to allow the free end to have 1 degree of freedom in the axial direction.

This paper will focus on 3 main sections including design for manufacturing, reliability, and economics. Each section will go into detail discussing these 3 topics by utilizing pictures, diagrams, charts and results. This paper is essential to understanding how the final product was designed and eventually fabricated.

2. Background and Literature Review

The Munitions Directorate at Eglin Air Force Research Laboratory (AFRL) has tasked the team with designing and building a small scale torsion tester that can be used in their labs to help characterize different materials. The AFRL currently uses a torsion tester that is roughly three meters in length, to test samples that are no greater than eight centimeters long. Due to the large size of the machine in comparison to the samples being tested, the data collected from testing on the current apparatus is not ideal. Therefore, a smaller testing machine will be proved to the AFRL which will allow for more accurate results, while taking up much smaller space in the lab.

To further understand the task assigned to the group, the fundamentals of torsion testing will be discussed in detail. A torsion test measures the strength of a material against a twisting force. This is a very common test which is used to determine how a specimen of a specific material will interact when subjected to a torque. Through these laboratory tests, the behavior of these materials under specific loading conditions can be characterized, and although the geometries may change from test to real world application, important characteristics of the material can be determined which are independent of geometry.

In a typical torsion test, the specimen is gripped on both ends firmly so that no slippage may occur during the experiment. Then, once the specimen is secured, a motor and gear drive is used to apply a torque. One end of the specimen remains stationary during testing, while the other is rotated by the motor. The twist experienced by the specimen is recorded. By using the twisting information as well as the applied torque, many material properties can be determined.

The data collected from a torsion test can be represented in a shear stress vs. shear strain plot like the one shown in Figure 1. The shear stress applied to the specimen can be determined by using the equation

$$\tau = \frac{M_T r}{J} \quad (1)$$

where M_T is the torsional moment applied, r is the radius of the sample, and J is the polar moment of inertia. The shear strain applied can be calculated with

$$\gamma = \frac{r\theta}{L} \quad (2)$$

where θ is the angle of twist, and L is the length of the sample.

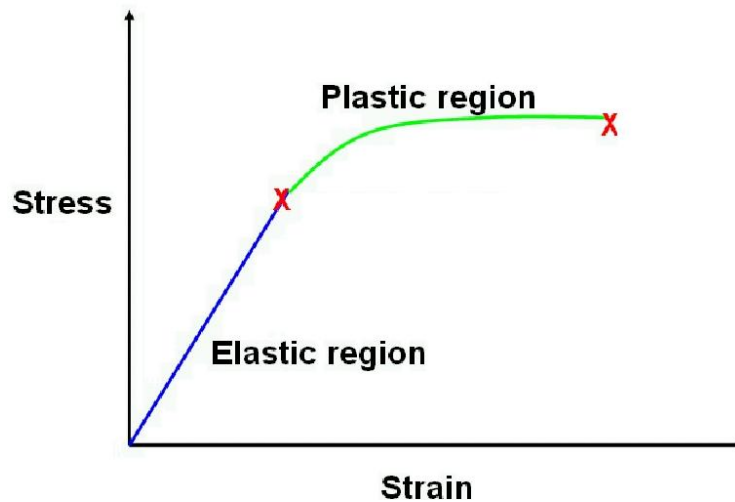


Figure 1: Example of a shear stress vs. shear strain plot for a sample undergoing a torsion test

In the elastic region of the plot, there is a linear relationship between the shear stress and shear strain experienced by the sample. This linear relationship leads to the determination of the shear modulus, G , of the material which can be determined using the equation

$$G = \frac{\tau}{\gamma} \quad (3)$$

When undergoing torsion, brittle and ductile materials will fail in different ways. A brittle specimen will break along surfaces 45° to the shaft axis. However, a ductile material fails along a plane of maximum shear, resulting in a fracture surface on a plane perpendicular to the shaft axis. [1]

Torsion testing machines have been around a very long time so the fundamental goal of this project is not new. What separates this project is the sponsor's special customization requests such as its low cost, small size, free end axial motion, and its ability to accurately test very small specimens. Tinius Olsen and Instron are two of the main companies that manufacture material testing equipment. These companies make great torsion testing machines for general applications but are very costly.

Although many material properties are already known from previous engineers performing tests and posting their results, the sponsor of this project benefits from performing these tests himself. Due to the nature of the products made for the Air Force, the tests performed at the AFRL are

unique and require new tests. Also, since the AFRL is interested in unconventional specimen geometries data is not known for much of their testing.

3. Design for Manufacturing

The manufacturing and assembly aspect of this project is very involved. The frame, free end, and couplers had to be machined from raw stock material. This process took time and required accurate and clear engineering drawings from CAD. The other components of the machine such as the motor, VFD, chucks, pillow blocks, and linear rails were ordered from various vendors and took time to be delivered. Once all of the parts were completed in the machine shop and delivered assembly began.

First the group selected to machine the free-end due to it being such a critical part in the alignment of the machine. The baseplate was cut with clearance holes in the OMAX waterjet in the school's machine shop, followed by the free-end stand which was also cut in the waterjet. Upon press fitting these items with six tons of force it became time to mount the already purchased pillowblock bearings. It was decided in the shop to tap each of the holes in the pillow blocks, and use the baseplate as alignment. To aid in strength the baseplate was countersunk to make the series more rigid. Upon assembling the pillowblocks it was time to broach the free-end shaft to make way for the key. With the free-end assembly complete, the already purchased precision rails, and support blocks were ran through the pillow blocks to complete that section of the machine.

The next major phase of machining consisted on the motor side of the machine. This assembly consisted of the 304 SS support tubes which ran through the entire frame. Cutting these down to size and milling in the various slots and clearance holes allowed the second major assembly to get started, while still continuing the first. Once these were cut the motor shims and motor baseplate were machined using a press drill, and a mill. Assembling these items along with the support bars completed the motor subassembly.

After both of the subassemblies were complete it was time to construct the frame. The remaining members were cut to size on the Do-all band saw in the school's machine shop. After the tubes were cut, they were cleaned and prepped for welding. Laying out the frame and subassemblies on the welding table it became important to insure everything remained straight. Considering the slots on the support bars it was deemed that having a precision bar locked into the assemblies would make the machine straight enough to tack together. Once the frame was

tacked together, the machine was completely deconstructed in order for final welding. Upon completing the welding it was necessary to grind down each of the welds to make the frame flat. This need was due to the fact that it had to sit flat on the table, and have each assembly bolted to it. After grinding it was prepped for paint, which completed the machining, and assembling of the tabletop torsion machine.

The torsion machine assembly took more time than the team initially thought it would. This is partly due to the fact that some parts were ordered late and took a while to ship. Also, during the machining process some of the pieces had to be cut multiple times in order to ensure they were the desired size. Furthermore, the actual assembly and machining caused delays in the production of the build. The assembly took longer than expected due to our first machine being our only machine produced. This meant that when alignment issues arose, they had to be machined a second, or third time to keep the necessary alignment. Some noted issues throughout the machining process: the free-end stand stock was mounted incorrectly in the waterjet and skewed the final product. This meant that the stand had to be recut in the waterjet which took extra material, and extra time. The next major flaw in the machining was the dimensions on the pillowblocks did not exactly match the ones that were in the CAD assembly on the computer, so that part had to be recut as well. This put major emphasis on the parts being ordered may not be exactly the specs they said they were when purchased. After those two instances the rest of the project went smoothly other than the machine shop being backed up. We still managed to plow through the project by working on site in the machine shop. Lastly the welding of the frame, and final machine assembly took an entire day, this was much longer than expected. Throughout the advising of the machine shop, the actual machining hours, and the assembling in the machine shop, the total time spent in the machine shop was accounted to be approximately 150 hours. When considering the idea of constructing a final product as a prototype, it can easily be seen how the addressed problems drastically extended the time to design, machine, and construct the torsion machine.

Figure 2 shows an exploded view of the assembly with dotted lines showing where each part goes. This figure shows the relative size of each part and gives a good representation of all of the parts required to build this tabletop torsion machine.

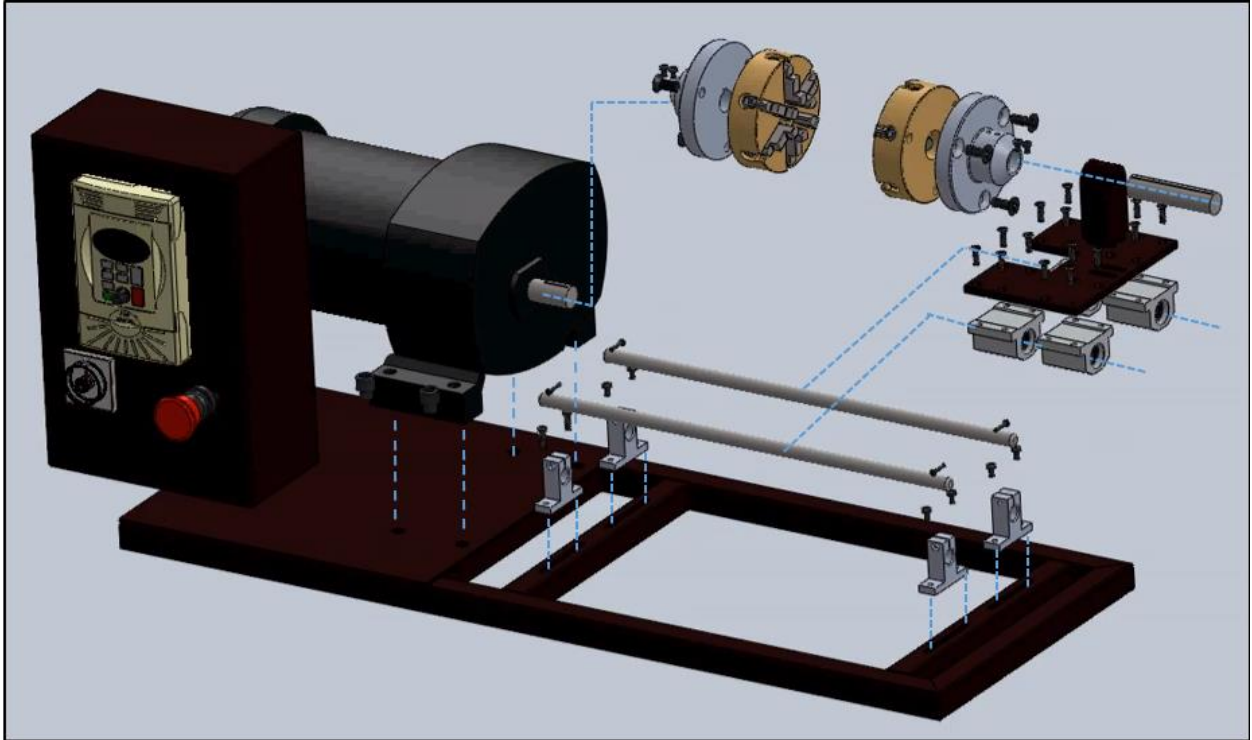


Figure 2: Exploded View of Assembly

Table 1 lists all of the components in the assembly. The final design chosen was reviewed multiple times by the team to ensure sponsor satisfaction and simplicity. The team believes this design is as simple as it could be while still abiding by the sponsor's requests. Each part of the assembly acts as a critical component and cannot be removed without jeopardizing the integrity of the machine. On the other hand, adding more complexity to the design would not be justified. Torsion machines are meant to be easy and quick to use. The team made sure that it is clear how to operate the machine even if the user has little experience in materials testing.

Table 1: Bill of Materials

Part #	Part Name	Description	Quantity	Unit Cost	Supplier	Cost
Load Generation						
6Z404	Motor	AC Gear Motor, 18rpm, TEFC, 208 - 230/460V	1	\$601.56	Grainger	\$601.56
GS2-10P5	VFD	Variable Frequency Drive, 0.5 HP, AC Drive	1	\$166.00	Automation Direct	\$166.00
Load Application						
2276	Lath Chuck	6-Jaw, 4" Outer Diameter	2	\$174.95	Little Machine Shop	\$349.90
Linear Motion						
2HXB4	Rails	0.5in Thick(Annealed Shaft, Steel, 0.500in D,16in)	2	\$41.80	Grainger	\$83.60
2CNL6	Pillow Blocks	0.5in. (PillowBlock, 0.500 in. Bore, 1.690in L)	4	\$41.83	Grainger	\$167.32
2CNU7	Shaft Support	0.5in. (Shaft Support, 0.500 in. Bore, 1.625in. H)	4	\$25.99	Grainger	\$103.96
Frame						
2HHP8	Motor Shim	0.75in stock (Bar, Rect., Steel, 1018, 3/4 x 1in, 1Ft. L)	1	\$9.05	Grainger	\$9.05
3DRT8	Motor Baseplate	0.125in Sheet (Flat Stock, LCS, Hot Rld., 1/8in T, 1Ft. L)	1	\$16.49	Grainger	\$16.49
3DRU7	Free End Baseplate	0.25in Sheet (Flat Stock, LCS, Hot Rld., 1/4in T, 1x1 L)	1	\$22.59	Grainger	\$22.59
3DRR5	Long Support Tube	0.125in Th (Tubing, Sq, 1015 LCS, 1OD x 1/8in T, 6 Ft. L)	2	\$19.71	Grainger	\$39.42
4YUL5	Small Thick Support	0.25in Th (Sq Tube, 304SS, 1 OD Sq x 3/4 ID Sq 6ft)	1	\$47.48	Grainger	\$47.48
2HHW5	Free End Stand	1in Stock	1	\$25.55	Grainger	\$25.55
2EYG6	Rod	Aluminum 6061, 4in D x 12in L	1	\$105.70	Grainger	\$105.70
8290T15	Rod	Unpolished, 1117 Carbon Steel, 0.75in D x 12in L	1	\$7.79	McMaster	\$7.79
Miscellaneous Costs						\$98.54
Total Cost						\$1,844.95

4. Design for Reliability

Although the team only had 1 semester to fully design the torsion machine, it is expected to last a long time. Each part of the design was analyzed and chosen carefully based on theoretical calculations. As long as specimens do not exceed the shear strength of the materials the team was told it would be testing the machine should not yield or fail. However, almost every machine has the potential to malfunction due to unforeseen circumstances. See Appendix A for a FMEA (failure modes and effects analysis) the team has created for the torsion machine. This diagram is important to understand because it highlights the major ways the machine could fail and gives prevention steps to avoid this.

As shown in the FMEA the main reliability concerns for the machine are the grip strength of the chucks, misalignment of the linear rails, and fastener failure. In order to ensure proper grip strength over time, the team recommends using an attachment to the key to increase the applied moment when tightening down the chuck teeth. It is expected that after some time the linear rails will become misaligned. In order to prevent this their alignment should be checked before and after each use with a straight bar. The nuts that hold the rails in place should also be checked in case they loosen due to loading or vibration. The last major reliability concern the team has for the machine is fastener failure, particularly on the free end. It is possible for any of the screws to fatigue after multiple uses. In order to prevent this the user should check the fasteners before every use and replace them if any yielding is observed.

In order to ensure the structural integrity of the frame and machine, FEA was performed on the critical parts of the frame as shown in Figure 3. These analyses proved that the team's theoretical calculations were accurate and the machine should hold up perfectly under the expected loads. As seen in the Figure, the highest stress felt by the frame is approximately 18 MPa which is well under the yield stress of the material which is 620 MPa. Therefore, the frame will be more than adequate to handle the stresses being applied throughout the system. Further FEA analysis can be found in Appendix B.

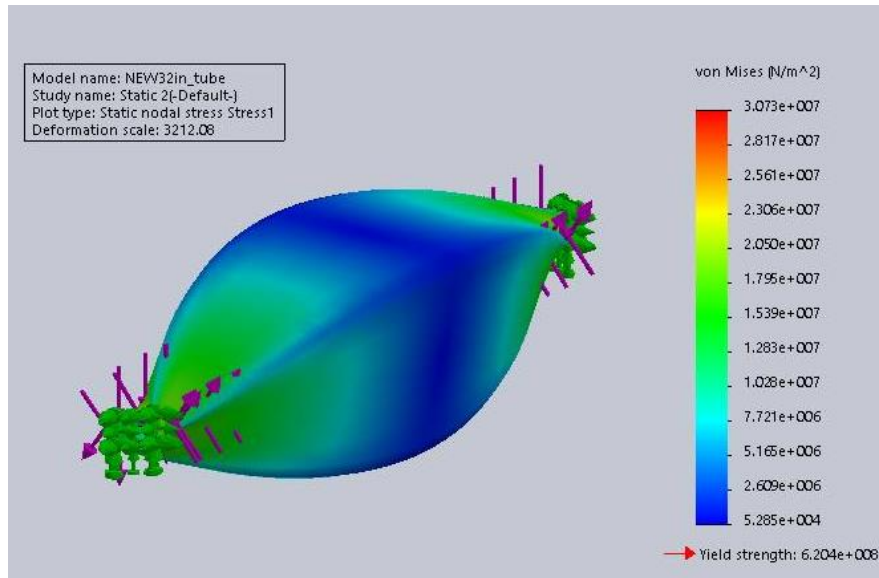


Figure 3: FEA Analysis performed on a support bar

During performance testing, the machine was able to break an aluminum specimen without any complications. The only issue with the tester was that the chucks were unable to grip the cylindrical specimens without slip. Therefore, it was necessary to use specimens with hexagonal grips that allowed for the chucks to firmly grasp. This issue was expected and one of the prominent issues already faced by the AFRL. Moving forward the team is looking into way of inducing friction between the chuck jaws and the specimen grip lengths to allow for the cylindrical specimens to be tested accurately.

Due to the components selected for the design, and the materials used, as long as the proper maintenance is performed, this machine is expected to last as long as the sponsor requires. This is expected because after an analysis of the forces and stresses applied throughout the tester, it was determined that all components have a high safety factor. Therefore, as long as the machine is used for the job it was designed for, it should perform that task with little to no problems.

5. Design for Economics

When tasked with building this tabletop torsion tester for the AFRL, the team was constrained to a budget of \$2,000. With this constraint, the team was tasked with delivering a finished product that could be implemented with little to no extra effort from the employees at Eglin Air Force Base. Taking a look at Figure 4 below, a breakdown of how the budget was allocated can be found.

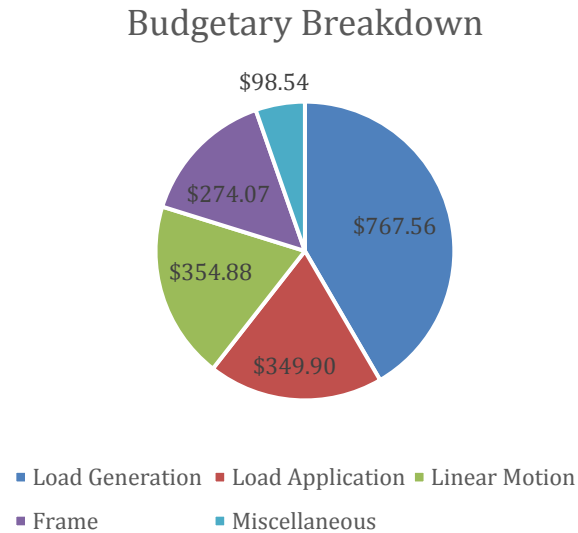


Figure 4: Breakdown of budget by category

Overall, the entire design cost \$1,844.95 which is greater than \$150 under budget. Figure 4 breaks down the budget into 5 categories: Load Generation, Load Application, Linear Motion, Frame, and Miscellaneous. Load Generation required the largest chunk of funding due to the high cost of the motor and variable frequency drive (VFD) purchased to control the motor. The Load Application aspect of the design consist of the two 6-jaw chucks used to hold the specimen during testing. The Linear Motion includes everything necessary to allow for the one degree of freedom on the non-twisting end of the machine. The Frame costs are due to the materials necessary to build the structure of the tester, and Miscellaneous accounts for all other expenses. Looking back at Table 1, the cost of each specific component is listed.

Currently, there are many torsion testing machines on the market that are comparable to the one designed by the group. However, these machines are typically very expensive. Figure 5 shows a

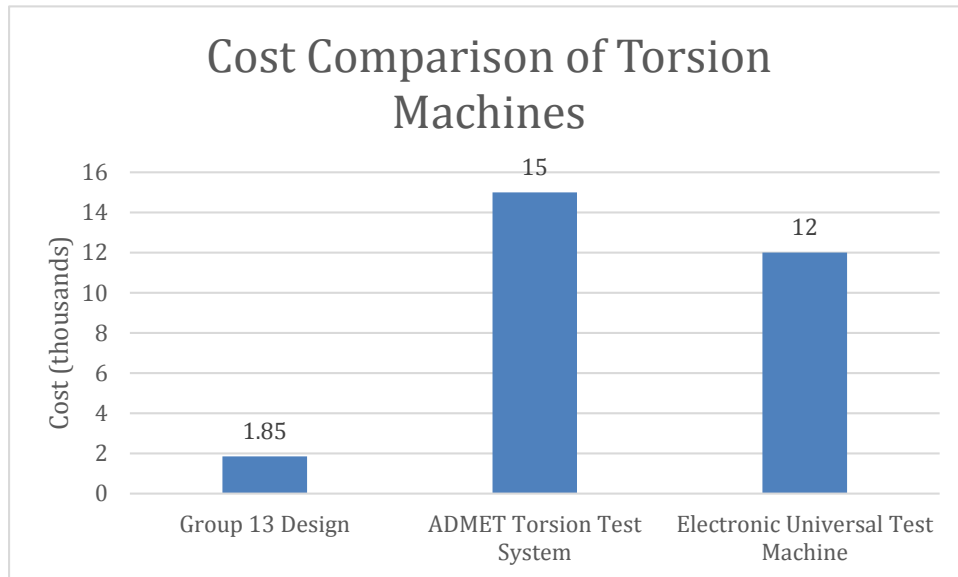


Figure 5: Comparison of similar torsion machines on market

price comparison between our machine and those readily available on the market. Two machines similar to the one designed by the team were used to compare how much cheaper our design was. The Group 13 machine costs a fraction of those found on the market. One of the main reasons for such a reduced cost is that our design does not need to provide a way to measure the strain applied to the sample, and the tools used to measure the stress applied are already in place at the AFRL. This significantly reduced the cost of the machine and allowed for the majority of the budget to be spent on the mechanical aspects of the design.

6. Conclusion

Materials testing is a very important field in engineering. It allows engineers to create the best possible design for a product. Knowing how a material reacts under certain conditions can lead to higher cost efficiency, reliability, and safety. The AFRL at Eglin AFB uses material testing when improving or creating new products. One of the many tests they utilize is the torsion test, which involves applying a torque on a specimen until failure. Their current torsion machine is very large and inaccurate when testing small specimens. They have a need for a smaller, tabletop torsion machine in order to better characterize certain metals for their models and simulations. Aside from the fact that the new torsion machine must be small enough to fit on a table, it must allow the free end to move freely in the axial direction and stay within the \$2000 budget.

After thorough calculations and design selection the team has come up with an optimal design that satisfies all of the sponsor's requirements. The parts used were ordered from various vendors and machined if necessary before they were all welded and put together to form the final product. The team has performed FMEA and FEA on the assembly and individual components in order to ensure high reliability. Like any other machine, this torsion tester has the potential to fail due to overuse or some unexpected occurrence but the team will provide recommended precautionary actions to the sponsor.

The team was able to keep the total cost for the torsion machine to just under the \$2000 allocated for this project. This is significantly lower than similar torsion testers on the market. The team is confident that the sponsor will be satisfied with the final product the team has made due to its low cost, simplicity, and reliability.

References

- [1] Kalu, N., and A. Joseph. *WiseGeek*. Conjecture, n.d. Web. 24 Mar. 2015.
- [2] "EXpert 9000 Torsion Tester." *ADMET*. N.p., n.d. Web. 24 Mar. 2015.
- [3] <http://www.alibaba.com/showroom/torsion-testing-machine.html> (Pricing Reference)

Appendix A

Key Process Step or Input	Potential Failure Mode	Potential Failure Effects	Severity (S)	Potential Causes (C)	Occurrence (O)	Current Controls (C)	Detectability (D)	RPN	Actions Recommended	Responsible (Resp.)
What is the Process Step or Input?	In what ways can the Process Step or Input fail?	What is the impact on the Key Output Variables once it fails (customer or internal requirements)?	How Severe is the effect to the customer?	What causes the Key Input to go wrong?	How often does cause or FM occur?	What are the existing controls and procedures that prevent either the Cause or the Failure Mode?	How well can you detect the Cause or the Failure Mode?		What are the actions for reducing the occurrence of the cause, or improving detection?	Who is Responsible for the recommended action?
Load Application (Gripping of Sample)	Slippage of sample during operation	Inaccurate data	6	Not enough clamping force	7	Tighten with adequate force/tool	5	210	Use proper tool to apply the proper holding force	User/Tech Expert
Load Generation (Motor)	Overheat or burnout	Renders machine unusable. Large cost of replacement	10	Overuse/misuse of VFD	2	Proper motor settings put into VFD. Also limitations of motor known by operator	4	80	Read motor/VFD manuals. Don't use for extended periods of time. Be aware of motor temperature during use.	User/Tech Expert
Motor Control (Variable Frequency Drive)	Loose connections	Unable to properly control the motor	8	Moving the apparatus; constant use	3	Tightened connectors	5	120	Check connections before use	User/Tech Expert
Linear Motion (Free end)	Deflection in rails	Introduction of other stresses (false readings)	9	Improper material chosen	2	Material selection followed, FEA performed	4	72	Check rails before and after use, noting any changes	User/Tech Expert
	Misalignment	Introduction of other stresses (false readings)	9	Improper assembly, fasteners loosen over time	5	Proper measures taken during assembly	4	180	Use proper measuring tool to ensure alignment before use	User/Tech Expert
	Fastener Failure	Require replacement and reassembly	7	Improper selection of fasteners	3	Material selection procedures followed	6	126	Perform routine maintenance/check	User/Tech Expert
Frame	Yielding	Require replacement and reassembly	9	Improper selection of materials used	2	Material selection procedures followed, FEA performed	6	108	Clamp to optical table and also perform routine checks	User/Tech Expert
	Failure at joints	Require replacement and reassembly	9	Stress analysis at welding was miscalculated	2	Stress analysis performed	6	108	Perform routine maintenance/check	User/Tech Expert
Load Measurement (Coupler & Strain gauges)	Coupler plastic deformation	False stress measurements and eventual failure	8	Underestimated max stress being applied	2	Theoretical calculations performed to ensure reliability	3	48	Ensure specimen tested does not require a higher load than what the machine is rated for	User/Tech Expert
	misalignment of strain gauges	Inaccurate measurements	6	User error	5	Expert installation	3	90	Ensure proper placement, compare values to expected values	User/Tech Expert
	Loss of strain gauge sensitivity	Inaccurate measurements	6	Wear & tear	6	Recommended after a period of time	3	108	Perform routine maintenance/check	User/Tech Expert

Appendix B

FEA analysis on the support frames

