Senior Project

Final Report for

Torque-Limiting Tapping Head

in the partial fulfillment of

TECH 4945

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Executive Summary

This project developed a robust, adjustable tapping head that reduces or eliminates damage caused when excessive torque is applied to taps. The tool's output is adjustable from 20 to 300 inch-pounds, and can drive taps from size #0 to 1/2-inch. It can be driven by a variety of machine tools using a set of custom adapters.

The device was designed in CAD and rapid prototyped with 3D printing. The finalized design was machined from O1 tool steel and 17-4 PH stainless. Careful insert selection and machining techniques were required to complete the fabrication. CNC operations proved challenging, but were ultimately successful.

The prototype tapping head met or exceeded its initial requirements. It successfully met its torque specifications, and the adapters worked correctly.

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Introduction

Tap breakage often ruins both tooling and expensive workpieces. Despite this, there are very few products on the market designed to avoid overloading machine-driven taps. Nearly all of the available options are designed with a fixed torque value in mind. While these fixed torque value tapping collets are compact and quick to interchange, they quickly become a very expensive investment due to the fact that one entire clutch assembly must be purchased for each size of tap. This project produced a compact and modular torque-limiting device with more drive options than commercially available products. While not as quick to change between different tap sizes as traditional interchangeable torque-limiting tapping collets, this device allows for a single tool to cover a wide range of tap sizes. The tool is also more versatile than commercially available torque-limiting tapping collets. It has a series of drive adapters that allow it to be driven by lathes, drills, vertical mills, drill presses, and even by hand if needed. While not designed for mass production work, the tapping head is well suited for job shops and other low-volume work.

The torque range for the tapping head is based on values sourced from tap breakage torque tables created by Parlec and Tapmatic. A range of 20 to 300 inch-pounds was chosen in order to keep the device as compact as possible while still being able to drive taps from size #0 to 1/2-inch. Extending the range beyond 1/2-inch taps would require an extremely powerful spring, making the tool excessively bulky. This would also cause poor low-torque performance when threading small holes. Designing the tool for taps above 1/2-inch would also not be very beneficial for many machines. The Haas TM-1, for example, has a maximum spindle torque of 33 lb-ft (396 in-lbs) (Haas Automation), while a high strength 1/2-inch tap can have a breaking torque as high as 600 in-lbs (Tapmatic).

Review of Objectives

The primary objective of this project is to develop a robust, adjustable device that reduces or eliminates damage caused when excessive torque is applied to taps. The secondary objectives are to develop drive adapters for various machine tools as well as tap holders for a set of common tap sizes.

Review of Deliverables

The deliverables of the project are:

1. A functional prototype tapping head that has an adjustable output torque from 20 to 300 inch-pounds
2. Prototype drive adapters for use with T-handles, drill chucks, and collet chucks
3. Prototype tap holders for #0, 1/4-inch, and 1/2-inch taps

Technical Implementation

Data on tap failure torque proved difficult to find. Two documents, one from Tapmatic and the other from Parlec, were found and used as a basis for all future design goals. Initial clutch designs were drawn in Onshape. Select designs were rapid prototyped using a Creality Ender 3 Pro 3D printer and tested for smoothness, wear, and torque performance. A separate design that employed a cam mechanism was developed and tested, but was abandoned due to the complexity involved in providing the variable preload needed. After 16 prototypes, the final design was chosen due to its ability to operate smoothly while generating 33 in-lbs of torque with only 25 lbs of preload.

Further design work was conducted in Siemens NX where decisions about the tool body and preload mechanism had to be made. The tool needed to be as compact as possible while still utilizing off-the-shelf components. Geometries that would require complicated and time-consuming machining operations were also avoided. Particular difficulty was faced in the design of the preload mechanism which had to mount atop the clutch housing, remain as compact as possible while still using an off-the-shelf spring, and allow for the tool to be driven by a machine. Several iterations were developed in NX until the design was finalized.

In preparation for machining, O1 tool steel was chosen for the clutch plate and the die spring washer, and 17-4 PH was selected for all other components. Tool steels are typically shipped in an annealed state, and fall within the Rockwell B hardness range. This hardness was inadequate for all components of the tapping head, so heat treatment would be necessary for all of the tool steel components. For the vast majority of the components, 17-4 PH was ideal due to its hardness without further heat treating. Its corrosion resistance was considered important given that the tool will be routinely handled and may be exposed to coolant when tapping. 17-4 PH is commonly supplied in conditions H1150M or H1150D, which typically have a hardness of 29 Rockwell C. This hardness is adequate for most components of the tapping head. This selection reduces the heat treatment processes required for production. Heat treating components poses multiple risks. The first is dimensional stability. Parts meaningfully distort during heat treating, causing fitment issues. To avoid this problem, workpieces are typically machined oversized, heat treated, and then undergo a final machining process to bring the parts down to their specified dimensions. Given the timeframe for this project, this approach was impractical. If a mistake was made that required remachining a major component, there would not be adequate time to complete it. Machining numerous components after heat treatment was also impractical given the capabilities of the University's machine shop. Machining hardened components would have required specifically designed inserts to be purchased for every machine used, as well as a wide array of carbide drill bits and reamers. 17-4 PH proved to be the best choice given these restrictions.

A Jet E-1236VS manual lathe was used for the majority of the machining operations. The University's machine shop and its associated tooling is primarily set up to work with aluminum. Because of this, the lathes were equipped with Iscar WNMG 3-2 NF inserts with a carbide grade of IC-20, an uncoated and unsuitable grade for turning stainless steel. Extensive research was done into turning insert carbide grades, coatings, chip breakers, and geometries in order to find suitable tooling before machining could begin. During this process, it was discovered that the existing inserts were an unusual geometry. Most WNMG inserts are size code 332, but the inserts in the shop read 3-2. Further research revealed that this was an Iscar-specific code denoting an insert that is thinner than the standard size. The tool holders were equipped with a seat designed to account for this difference. While a different tool holder was available to accept standard inserts, it proved difficult to source and was deemed impractical. Instead, insert selection was limited to Iscar products made to this internal standard. For general turning, an Iscar WNMG 3-2 TF907 insert was selected due to its blend of hardness and toughness. Its large nose radius improved its durability, and its chip breaker was suitable for many tasks. A second insert, an Iscar WNMG 3-0 NF807, was chosen for finishing operations. This insert had the same carbide characteristics of the 907 grade, but a slightly different coating. Both of the chosen inserts were among the hardest available for stainless steel turning and were capable of some hard turning if the project called for it. The inserts were also tough enough to handle interrupted cuts. The second and more delicate 0.0079" nose radius insert was not strictly necessary to complete the project, but was purchased due to a lack of operator experience. It allowed for the operator to slowly approach final dimensions with light depths of cut to reduce the chances of scrapping parts. It provided an excellent surface finish that the WNMG 3-2 TF907 could not at low depths of cut. Another key consideration in insert selection was minimum order quantity. Turning inserts are typically sold in packs of ten, making them prohibitively expensive. Only inserts that were sold individually were considered during this process.

Once the correct turning inserts were selected and obtained, machining began with the rough turning of the upper and lower body ODs. Initially, speeds and feeds were based on the insert packaging from Iscar. These parameters proved to be much too fast, which caused excessive heat buildup that resulted in the carbide degrading. Research was done to find tailored speeds and feeds for the application. Generalized numbers were expressly avoided, as they often assumed a production environment. Upon further research, the Walter Tools' GPS application was discovered. It offered good customizability and flexibility in its parameters. The new speeds and feeds based on Walter's program greatly extended insert life and allowed for one cutting edge to be used for several days instead of a single machining session.

A 1.25" drill was used to remove the bulk of the material from the upper and lower body. During drilling, it became evident that cutting oil was inadequate. Progress was unacceptably slow due to heat buildup in the drill. Additionally, two out of the six available cutting edges on the TF907 insert were worn out. Because of this, a lathe was set up with flood coolant that was utilized for all future operations. This change made machining processes much faster and greatly extended tool life. Switching from oil to coolant extended the life of inserts from days to weeks.

The upper body has a feature that required a three-inch deep bore to be cut, but the shop was only equipped with a boring bar designed for a maximum stickout of 1.25". This posed a major challenge due to how unstable the setup was when the boring bar was extended beyond its designed stickout. Purchasing a longer boring bar was considered, but decided against due to cost and the fact that the project proposal specifically stated that fabrication would not require the purchase of one. Instead, the issue was minimized with insert selection. Boring the upper body started with a TCMT 21.52 insert that was already installed in the tool. Chatter and harmonics made boring excessively slow. The process was stopped, and research was conducted. It was decided to switch to a TCMT 21.51 and a TCMT 21.50 insert. The reduced nose radius lowered the radial cutting forces and therefore chatter. Like before, insert selection was limited to those which were sold individually. The TCMT 21.50 insert gave the best performance and allowed for spindle speeds to be increased by approximately 300% over the TCMT 21.52 insert.

Further machining processes went smoothly from this point until the drive adapters were being made. At this point, it was discovered that the lathe was cutting a taper on all components. Upon further investigation, it was found that the lathe would cut a taper of about 0.0012" over 3 inches, which was unacceptable for the components being produced. A straight bar of steel was set up in the lathe as a reference surface between the chuck and live center. The carriage was moved back and forth between the chuck and live center with a dial indicator reading the distance from the tool post to the reference bar. The tailstock was then slowly adjusted to align it with the centerline of the spindle. The tailstock being in correct alignment was indicated by the dial indicator having the same reading across the reference surface's entire length. After adjustment, the amount of taper being cut was reduced to approximately 0.0003" over 3".

Once the manual machining on the lathe was completed, work on the Haas TM1 vertical mill began. Before parts could be loaded into the CNC machine to be cut, all required tooling had to be documented. This documentation was critical in selecting correct speeds and feeds. Walter's GPS application was invaluable for this process. However, calculations could only be performed on tooling from Walter's catalog. All documented shop tools were compared and cross-referenced with Walter products. After equivalent tooling was found in the program, speeds and feeds close to the minimum rates suggested were chosen for machining operations. The quick release tap holder required holes of a specific depth to be reamed for the ball bearing lock. Because of this, the point length of the 0.1885" reamer had to be determined for use in the CAM software. To do this, a Mitutoyo PH-A14 optical comparator was used to characterize the tool.

Once CNC milling began, there were issues obtaining the correct dimensions on critical features due to worn and reground end mills. To avoid this issue in the future, a 0.250" and a 0.125" square end mill were purchased to reduce the complexity of machining operations. Parts were milled on-size after the change to new tooling.

The post processor used to convert the CAM tool paths to G-code would not work with the 4th-axis. This was a completely unexpected issue and caused several days of delay. This time was largely spent attempting to create a new post processor that would work with 4th-axis movements. Documentation for creating a new post processor was poor, and the time required to prepare and test a complete implementation was unrealistic for the project timeline. Instead, a workaround was created where everything would be modeled as a 3-axis operation in the CAM software, and a short program was written in the manual data input of the CNC machine to rotate the A axis when needed. This was slower than true 4th-axis machining, but it was a quick and functional alternative for the necessary 4-axis operations.

Once the 4th-axis was operational, it was discovered that the mount for it was not machined with all the correct features required to secure it properly. A single bolt secured the unit in place. Because of this, it could not withstand the feed force required to drill parts and would rock and pivot. Some workpieces were damaged due to the 4th-axis rocking, but they were not unusable. This was a second significant and unexpected issue with the 4th-axis and required several days of work to address. In order to fix this issue, a new mount for the 4th-axis was designed. The new mount uses two bolts to rigidly secure the 4th-axis to the machine in alignment with the X-axis of the table. A piece of S7 tool steel of suitable size that was already in the machine shop was used to create the mount. The exact type of steel for this application was not of great importance. S7 was selected simply because it was the most readily available. The edges of the block were surface ground to be parallel to each other. After this, the ground faces were clamped by the vise in the CNC mill and used as reference surfaces for all other operations. Then, the top and bottom of the block were cut with a face mill in single passes until all surface imperfections were removed. The workpiece was then brought back to the surface grinder and the top of the block was ground to be parallel with the bottom. All subsequent features were machined on the CNC mill. The keyway that locates the 4th-axis on the mount ended up being within 0.0001" of parallel with the sides. This eliminates the lengthy alignment process required with the original mount.

When tapping the threads in the center shaft, the tap broke and was not removable. This was the only part that had to be remade during the entire project. Before making a new center shaft, more research was done on tapping stainless steel and on tap drill sizes. The design of the center shaft was changed to have a through hole instead of two blind holes, allowing for a spiral point tap to be used instead of a spiral flute tap. A spiral point tap requires a through hole, but keeps the cutting edges clear of chips and is stronger due to its larger cross sectional area. Additionally, the hole size was enlarged from a letter F drill to 7mm, reducing the thread engagement from approximately 77% to 51%. This reduced the tapping torque. After these changes, the process worked without issue.

The clutch and die spring washer were heat-treated at 1500°F and quenched in oil. They were then tempered in order to obtain a hardness of 50-55 Rockwell C. This hardness was selected to give a good balance between toughness and hardness.

Once machining and heat treating was completed, the tapping head was assembled for the first time and testing began. The calculations used to estimate the required preload force and clutch detent depth proved to be inaccurate. The minimum torque output was determined to be 59 in-lbs, roughly triple the desired value. To correct this, the clutch was faced in a lathe to reduce the detent depth in 0.003" to 0.025" increments. These hard turning operations were only feasible due to the toughness of the WNMG 907 insert. Testing was conducted between each facing operation to track the changing output. Ultimately, a minimum torque better than the required 20 in-lbs was achieved without affecting the maximum output torque of 300 in-lbs. Cumulatively, the detent height was reduced from 0.075" to 0.0165".

The original clutch detent depth of 0.075" prevented the clutch from being forced into the lower body if the tapping head was placed under a significant compressive load. After facing the clutch plate, this functionality was lost. To restore this feature, a thrust washer was fabricated out of molybdenum disulfide filled Nylon 6 and placed between the clutch plate and lower body.

Evaluation of Plan of Work

Most of the delays were machining related. Boring operations on the upper body required over seven hours of machine time as well as the acquisition of new inserts. Troubleshooting the post processor for 4th-axis CNC work took several days to resolve. Finally, the design and precision machining of a new 4th-axis mount added nearly a week of delays.

Explicitly budgeting time to troubleshoot CNC operations would have helped to keep the project on schedule. The Gantt chart constructed during the proposal had the project finished by April 12th 2023. This ended up being overly ambitious. The machining phase of the project did not finish until this date and testing was not completed until April 19th. Because of this, there were only two days available to write and edit the report. The quality of the report greatly suffered due to the time remaining to work on it.

Evaluation Results

Extensive testing was carried out to characterize the torque output throughout the device's entire range. The results showed that the tapping head met all of its design goals. The minimum torque setting for the tool averaged 16.7 in-lbs when the goal was 20 in-lbs, and the maximum torque setting averaged 302.7 in-lbs while the goal was 300 in-lbs. These values correspond with Tapmatic's recommended settings for #0 all the way through to 1/2" taps.

The tool was also tested in two different types of machine tools to verify that it could effectively protect taps from overload conditions. The majority of the testing was done on a lathe with the tool held in a 3-jaw chuck mounted in the tailstock. The tapping head effectively protected 1/4” and 1/2” taps but failed to keep #0 taps from breaking. The clutch would begin to slip as the tap would break which indicates that the lowest torque setting is close to being correct. One possible reason for this could be due to purchasing cheaper hand taps for testing. Specially designed machine taps may be higher strength than what was used.

Conclusions

The project, while taking significantly longer to machine than anticipated, was a success. The clutch performance exceeded the performance goals that were set during the proposal and demonstrated that it is capable of performing in a variety of machine tools. CNC operations were the largest obstacle in the completion of this project. Managing software and workholding issues resulted in costly delays and significant troubleshooting work.

Completion of this project required building on a range of skills taught in other coursework. Manual machining required a better understanding of tool selection and materials. CNC machining demanded in-depth knowledge of drafting, workholding and CAM software.

Overall, the project provided intensive experience in planning, machining, and problem solving.

References

Haas Automation. "Torque Chart." *Haas CNC*, 29 January 2016, https://www.haascnc.com/content/dam/haascnc/productivity/spindles/torque-chart-jpg/torque-chart-machine-pdp-binder-/TM_MM%20torque%20binder.pdf. Accessed 19 October 2022.

Parlec. "Tapping Speeds and Torque Requirements." *Parlec*, https://www.parlec.com/Products/Tapping-Tools/Specifications/Tapping-Speeds-and-Torque-Requirements-(1). Accessed 12 July 2022.

Tapmatic. "Tapping Torque & Horsepower Requirements Torque Setting Data For HSS Straight Flute Plug Taps." *Tapmatic*, http://www.tapmatic.com/tapping_questions_torque_setting_data_for_hss.ydev. Accessed 12 July 2022.

Appendix A – Detailed Testing Results

See “Testing Results” folder on USB drive for full results and raw data.

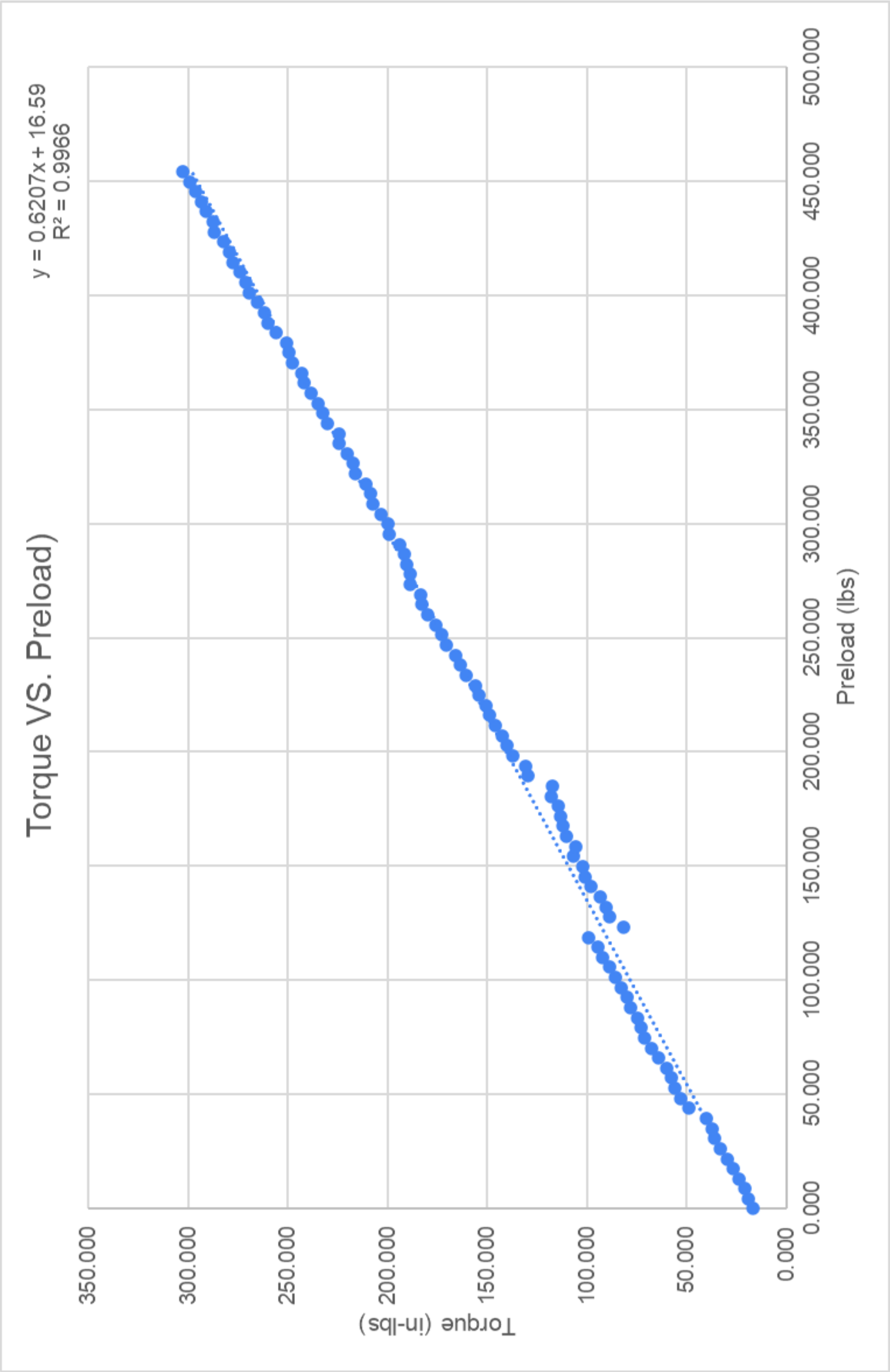

Figure 1 - Chart of Torque Response

Appendix B – Detailed Drawings

See “Drawings” folder on USB drive for all working drawings.

Appendix C – CNC Documentation

See “CNC Programs” folder on USB drive for all program documentation.

Appendix D – Project Pictures

See “Pictures” folder on USB drive for all project photographs.