MSE 3380 B
Drill Gearbox Design Interim Report
Team 1

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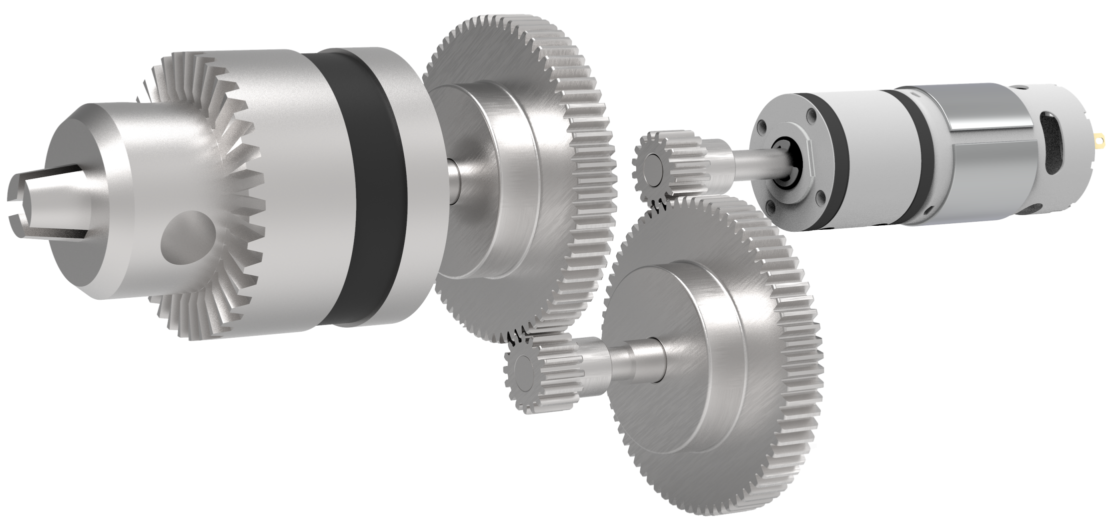


Contents

Preface

MATLAB code and SolidWorks files are available on Github here:

github.com/andrewrichardr/MSE3380BGearBoxProject/

1 Scope/Introduction

This report covers the design of a gearbox for an electric drill. The purpose of the gearbox is to reduce the speed of the drills' motor while increasing the torque applied to the drill bit. The gearbox will have a single ratio and a two-stage design. The gears will be selected from Boston Gear. As a result, the specifications should match industry standard values. The main design problems addressed are: Gear Dimensions and Materials, Shaft Dimensions and Materials, Bearings and Seals, and Connections between Components and Shafts. This interim report covers the specification of the gears. The topics covered are: stage ratios, system ratio, torque in shafts, speed of shafts, forces between gears, bending stress, contact stress, and factors of safety.

2 Specifications and Performance Criteria

2.1 Required Specifications

The given requirements are as follows:

Table 1: Requirements

Required Output Torque:	55 Nm
Required Output Speed:	575 rpm
Required Duty:	2000 hours
Gearing Efficiency:	90%

Additionally, the gearbox must be a two-stage design using spur or helical gears and the input pinion of the gearbox must be directly connected to the motor.

2.1.1 Motor Specifications

Motor specifications are as given:

Table 2: Motor Specifications

Nominal Operating Voltage:	40 VDC	Torque Constant:	8.474 Nmm/A
Body Length:	73.025 mm	Voltage Constant:	1125 rpm/V
Overall Length:	88.90 mm	No-load current:	2.6 A
Diameter:	46.831 mm	Armature Resistance:	0.072 Ohms
Mass:	443.67 g		

2.2 Assumptions

The following assumptions have been made for this design:

Table 3: Assumptions

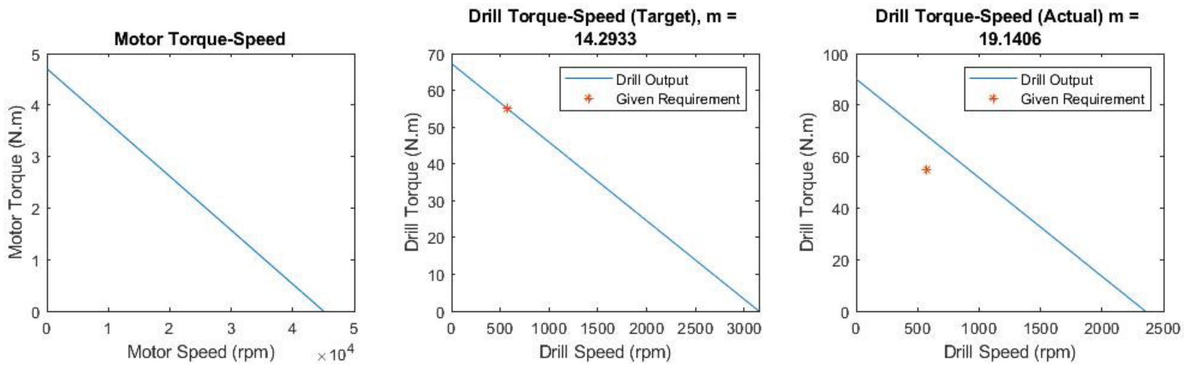
1. Torque-Speed specification for the motor is linear. See Figure 1.
2. No-Load Speed is 45000 rpm. $\omega_{no-load} = K_v V_{operating}$
3. Stall Torque is 4.71 N.m. $T_{Stall} = K_t \frac{V_{operating}}{R_{Armature}}$
4. Inertia of gears and shafts is not accounted for in motor specification.
5. The motor has an infinite duty cycle
6. Factors of Safety were calculated with grade 3 steel, hardened and carburized.

2.3 Gear Ratio Specifications

2.3.1 Overall System Ratio

The motor produces peak power of 5.546 kW at 22500 rpm. The required task requires a power output of 3.31 kW. Since the motor is overpowered for the given application, there is a large tolerance for the overall system gear ratio. Any ratio between 14.3:1 and 64:1 would produce an output which satisfies the required output specifications assuming 100% efficiency. In reality, this range of ratios is slightly smaller due to the 90% inefficiency. A secondary objective: minimize the gear ratio, has been put in place to reduce the overall size of the gearbox. The lowest theoretical system gear ratio which would produce the required output is 14.3:1 as seen in plot 2 of Figure 1. This ratio is unrealistic to achieve with standard off-the-shelf parts. The overall gear ratio which has been selected is 19.14:1 as seen in plot 3 of Figure 1. The point marked with * is below the Torque-Speed line which indicates that the system output is exceeding the output requirement.

Figure 1: Torque-Speed Plots



2.3.2 Stage Ratios

Both stages will have the same ratio of 4.375:1 which results with a system ratio of 19.14:1. Table 4 summarizes the gear ratios and the number of teeth used in the stages. These ratios were specified by an iterative process used to determine the optimal Diametrial Pitch; specific gears were then chosen from Boston Gear's catalog with the final specifications.

Table 4: Stage Specifications

Stage 1 Number of Teeth			Stage 2 Number of Teeth			Stage Ratios		
Pinion	Gear	Gear Ceiling	Pinion	Gear	Gear Ceiling	Stage 1 Ratio	Stage 2 Ratio	System Ratio
16	**70**	101	**16**	**70**	101	4.375:1	4.375:1	19.141:1

3 Concept

3.1 Model

The gearbox consists of three shafts; the shafts are connected as follows: Shaft A connects the rotor to Pinion 1, Shaft B connects Gear 1 to Pinion 2, Shaft C connects Gear 2 to the Drill Chuck. See Figure 2 and 3 for a render and 3D model of the concept.

Figure 2: Gearbox Assembly

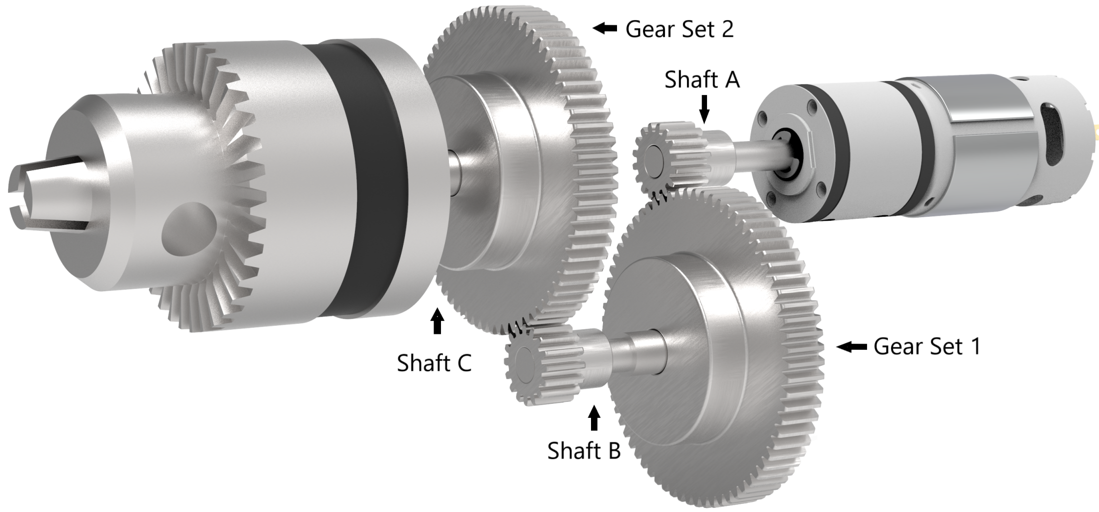


Figure 3: Gearbox Assembly 3D Model (Interactive if Viewed in Adobe)

3.2 Iterative Design Process

3.2.1 Ratio Selection

Initially, an overall gear ratio of 40:1 was desired. This ratio matches the peak power output of the motor with the operating speed. This was thought to be a good starting point as the motor would not be required to operate at 100% capacity to meet the required output speed and torque. However, a gear ratio of 40:1 was determined to be infeasible due to the physical size of the gears required to achieve this ratio. The second iteration used stage ratios of 5:1 and 4:1 resulting with a system ratio of 20:1. This iteration was scraped due to gear Boston Gear's limited gear selection. The final iteration is described in the sections above. The final ratio was chosen by directly selecting gears from the catalog.

3.2.2 Diametral Pitch Selection and Pressure Angle

The tables in the appendix contain varying Diametral Pitches to serve as sensitivity analysis to help determine the optimal Diametral Pitch. One of the design goals is to minimize the physical size of the gearbox, this implies the use of the largest possible diametral pitch. A diametral pitch of 20 was determined to be adequate for the required task and was selected. This Diametral Pitch does not produce a very large factor of safety. If a larger factor of safety is needed in future iterations, reducing the Diametral Pitch to 16 is feasible. A pressure angle of 20 is chosen due to the lower number of teeth and the reduced interference concerns.

3.2.3 Material Selection

A drill is required to be robust and reliable. Hardened and carburized steel is selected as the preferred material choice as it offers a very robust option for the gears and shafts.

4 Analysis

The bending and contract stresses were calculated to analyse the system. The Standard ANSI model was used for this calculation. Contact Stress is determined by Equation 2 and Bending Stress is determined by Equation 1. The adjustment factors are listed in Table 8 with justification.

$$\sigma = W^t * K_o * K_v * K_s * \frac{P_d}{F} * \frac{K_m * K_b}{J} \tag{1}$$

$$\sigma_c = C_p \sqrt{W^t * K_o * K_v * K_s \frac{K_m}{d_p * F} \frac{C_f}{I}} \tag{2}$$

4.1 Shaft Torque, Speed, and Power Estimations

Table 5 summarizes the torques and speeds which are developed in each shaft. From inspecting this table, it can be seen that Shaft C meets the specified output requirements. From inspecting Table 6, it can be seen that gearing efficiency is 90% which meets the specifications.

Table 5: Shaft Torque and Speed Estimations

Shaft A		Shaft B		Shaft C	
Torque	Speed	Torque	Speed	Torque	Speed
3.19	11005.86	13.25	2515.63	55.00	575.00

Table 6: Power Estimations (Watts)

Input Power	Output Power	Efficiency
3679.73	3311.76	0.9

These tabulated values were determined from power estimations of each shaft. The required output specifications were assumed on Shaft C, then the state of Shaft B was determined via Equation 3. The state of Shaft A was determined from Shaft B in the same method. The efficiency of each gear set is $\sqrt{0.9}$ as there are two gear sets which result with an overall efficiency of 90%. The Torque was determined from dividing the transmitted power in each shaft by the shafts' rotational speed, see Equation 5. This method gives torque values which are coincident with the efficiency requirement. The rotational speeds of the shafts were determined via Equation 4.

$$P_{out}(Efficiency) = P_{in} \tag{3}$$

$$\omega_{out} = \frac{\omega_{in}}{m_g} \tag{4}$$

$$T = \frac{P}{\omega} \tag{5}$$

4.2 Contact Forces and Diameters

Table 7 summarizes the contact forces between the pinions and gears as well as the pitch diameter of said pinions and gears. See Appendix Table 10 for forces and dimensions of varying diametral pitch.

Table 7: Contact Forces and Gear Diameters

Diametral Pitch	Stage 1: Force 1 (N) Tangential	Stage 1: Force 1 (N) Radial	Stage 1: Diameter (cm) Pinion 1	Stage 1: Diameter (cm) Gear 1	Stage 2: Force 2 (N) Tangential	Stage 2: Force 2 (N) Radial	Stage 2: Diameter (cm) Pinion 2	Stage 2: Diameter (cm) Gear 2
20	314.25	114.38	2.03	8.89	1237.35	450.36	2.03	8.89

4.3 Bending and Contact Stresses

4.3.1 Selected Stages

Table 8 summarizes the Bending Stress, Contact Stress, Factors of Safety, and the stress alteration factors and their justifications. See Appendix Table 9 for this data with varying diametrial pitches.

Table 8: Parameter Summary

	Pinion 1	Gear 1	Pinion 2	Gear 2	Justification
DP	20.00	20.00	20.00	20.00	(teeth/inch)
Contact Stress	764.00	358.75	1430.27	671.60	(MPa)
Bending Stress	124.05	78.80	434.74	276.17	(MPa)
Contact FOS	1.89	4.37	1.10	2.53	(x)
Bending FOS	3.56	5.88	1.07	1.76	(x)
K_o	1.25	1.25	1.25	1.25	Uniform source, moderate shock
K_v	1.29	1.29	1.15	1.15	Eq. 14-27, AGMA Quality 9 Rating
K_s	0.98	0.98	0.98	0.98	Eq. 14-10
K_m	1.09	1.05	1.09	1.05	Eq. 14-30, Crowned Teeth
K_b	1.00	1.00	1.00	1.00	No Rim
K_t	1.00	1.00	1.00	1.00	< 250 °F
K_r	1.00	1.00	1.00	1.00	Eq. 14-10, 99%
C_f	1.00	1.00	1.00	1.00	Standard
J	0.27	0.41	0.27	0.41	Fig. 14-6
I	0.13	0.13	0.13	0.13	$mn = 1$ for Spur Gears

The appendix contains a sensitivity analysis of each pinion and gear which evaluate the feasibility of different diametral pitches.

4.4 Diagrams

Figure 4 gives a cross sectional view of the gearbox, as well as relevant dimensions. A more detailed view of each gear can be found in appendix 7.3.

Figure 4: Cross Section Assembly Drawing

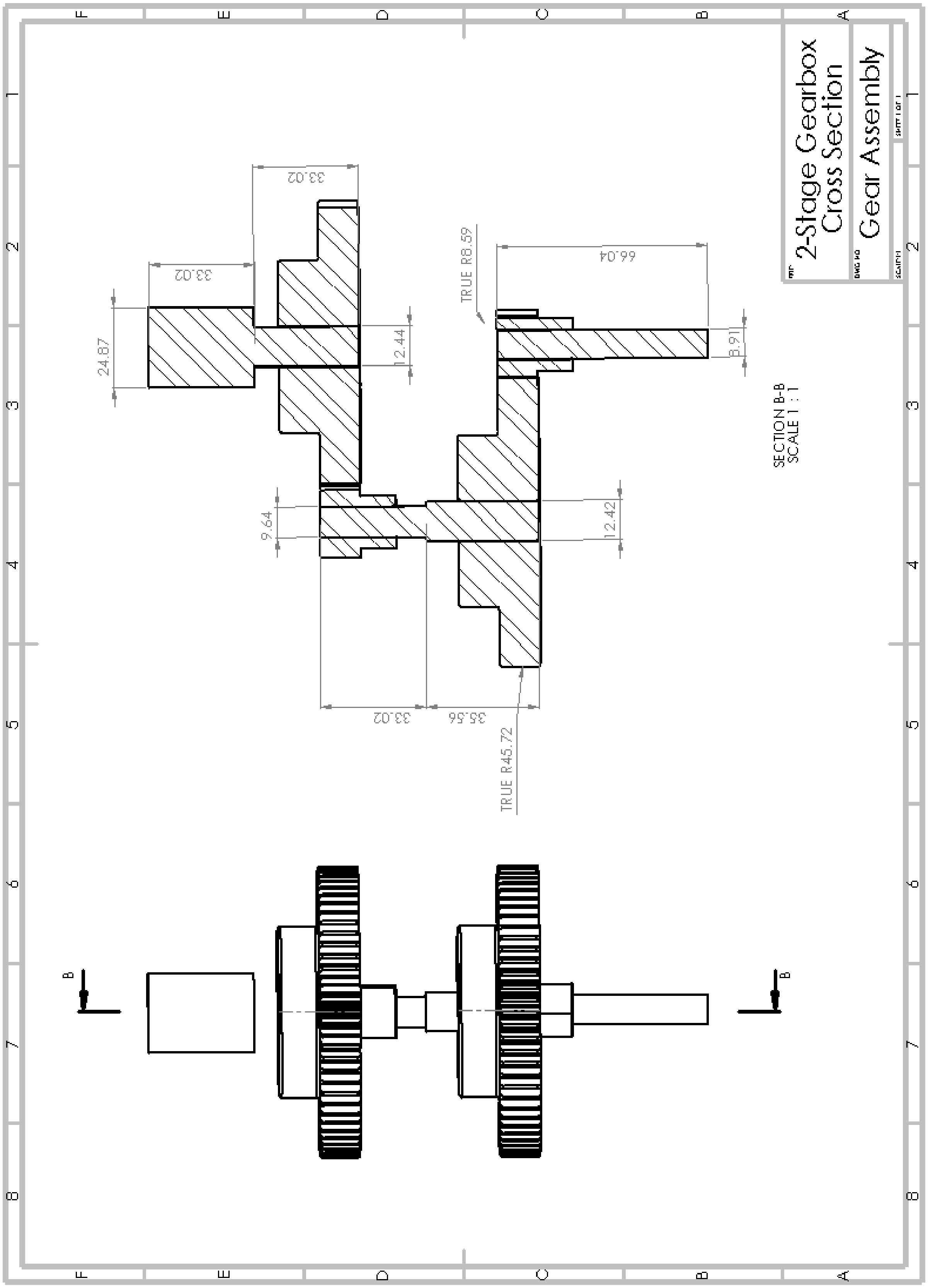
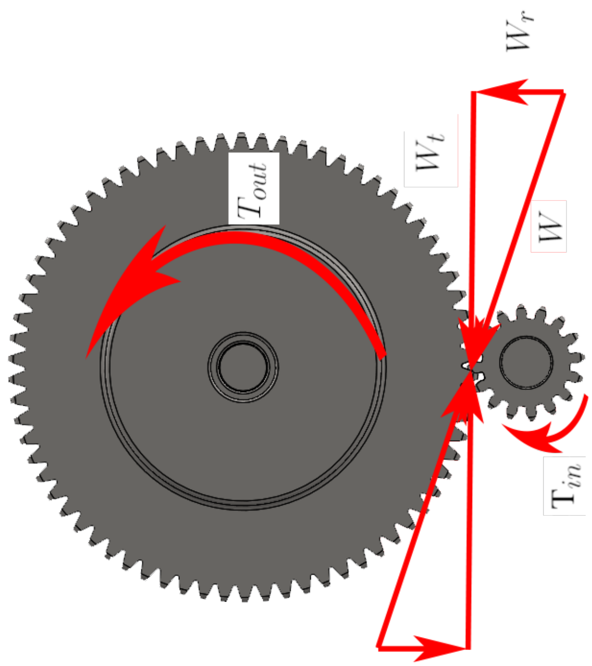


Figure 5 shows one set of a pinion and gear. The red arrows represent the forces and torques which act on the set. The gearbox contains two of these gear sets.

Figure 5: 2nd Pinion and Output Gear



4.5 Component material and properties

All the gears and pinions that will be used for the gearbox are made from 0.20 carbon steel, also known as alloy 1020. This alloy has a nominal carbon content of 0.20% with approximately 0.50% of manganese. This combination offers both strength and ductility. For the gears in the system, the alloys will undergo carburization and case-hardening treatments, this is a common process that produces a wear resistant, durable surface with a strengthened core. Due to the nature of the speed drill, wear resistance is a crucial variable to consider due to the rotational speed at which the system is operated at. The selection of steel offers excellent wear resistance and is able to withstand a good measure of shock loads.

Based on the diametral pitch and pressure angle, other material alternatives were available, such as cast iron. Using cast iron will also provide an effective wear resistant material, however carbon steel has a long useful life which is very beneficial for a speed drill application.

4.6 Factors of safety

After analyzing the contact and bending stresses and factor of safety, the results for the contact factor of safety ranged from 1.08 to 4.32, while the bending factor of safety ranged from 1.03 to 5.69. Overall, the factor of safety for each component fell within the acceptable range of >1. (See Appendix Tables for all Factors of Safety) The minimum contact and bending factor of safety of 1.10 and 1.07 both fell on Pinion 2. This is mainly due to the 1237.35N and 450.36N tangential and radial forces acting on the pinion making it a critical component. Due the material choice, the components are inexpensive to replace and repair. Even though the factor of safety fell within the acceptable range, typical product designs aim for a factor of safety between 2 - 3 (which aligns with majority of the factor of safety calculated in the other gears and pinions). Since the application of the gearbox is enclosed in a case, the speed drill will have low odds in causing any injury should the component fail. For Gear 1, the contact and bending factor of safety of 4.37 and 5.88 fell well above a factor of 3. Even though this suggests a very safe component it may be cost inefficient to manufacture a gear using that material. By not compromising the wear resistance and strength a cheaper material for Gear 1 may be viable. Materials such as cast iron, bronze or a plastic material such as Delrin, Acetal or Minlon are possible alternatives which are offered by Boston Gears.

5 Conclusions

Overall, the drive system for a speed drill was designed. The design assumptions and constraints were outlined and analyzed to calculate the required output power. Each stage in in the system had a ratio of 4.375:1, this results in a system ratio of 19.14:1. The specifications and dimensions of the gears and pinions were established based on a diametral pitch of 20 and pressure angle of 20°. To strengthen the components, the steel gears and pinions were carburized to reduce wear and increase core strength. After analyzing the bending and contact stresses, the biggest threat is from contact and bending factor of safety on Pinion 2. While this factor of safety fell within the acceptable range, further steps will be taken to ensure full safety of this section. The layout of the gear system was modelled and assembled.

6 References

References:

[1] Coburnmyers.com. (2019). Materials: Carbon Steel. [online]. Available:https://www.coburnmyers.com/materials-carbon-steel/ [Accessed 21 Mar. 2019].

[2] Boston Gear, ”Rotary Drive Products: Gears, Bearings, Couplings and Shaft Accessories,” P-1930-BG, 2019.

[3] R. G. Budynas and J. K. Nisbett, Shigley’s Mechanical Engineering Design. New York, NY: McGraw-Hill Education, 2015.

7 Appendices

7.1 Gear and Pinion Stress Tables

Table 9: Pinion and Gear Stresses

Diametral Pitch (teeth/inch)	Contact Stress (Mpa)	Bending Stress (Mpa)	Contact Stress FOS	Bending Stress FOS	Ko	Kv	Ks	Km	Kb	Kt	Kr	Cf	J	I
Pinion 1														
8	170.36	17.77	9.99	27.34	1.25	1.22	1.09	1.07	1.00	1.00	1.00	1.00	0.41	0.13
10	228.40	31.94	7.45	15.21	1.25	1.20	1.07	1.06	1.00	1.00	1.00	1.00	0.41	0.13
12	300.52	55.30	5.66	8.79	1.25	1.18	1.04	1.06	1.00	1.00	1.00	1.00	0.41	0.13
16	450.44	124.23	3.78	3.91	1.25	1.16	1.01	1.06	1.00	1.00	1.00	1.00	0.41	0.13
20	671.60	276.17	2.53	1.76	1.25	1.15	0.98	1.05	1.00	1.00	1.00	1.00	0.41	0.13
24	1103.36	745.38	1.54	0.65	1.25	1.13	0.93	1.04	1.00	1.00	1.00	1.00	0.41	0.13
32	1657.43	1681.97	1.03	0.29	1.25	1.12	0.91	1.04	1.00	1.00	1.00	1.00	0.41	0.13
48	2954.56	5344.81	0.58	0.09	1.25	1.10	0.87	1.04	1.00	1.00	1.00	1.00	0.41	0.13
Gear 1														
8	92.82	5.28	16.88	87.81	1.25	1.43	1.09	1.07	1.00	1.00	1.00	1.00	0.41	0.13
10	123.82	9.39	12.65	49.35	1.25	1.39	1.07	1.06	1.00	1.00	1.00	1.00	0.41	0.13
12	162.26	16.12	9.66	28.74	1.25	1.36	1.04	1.06	1.00	1.00	1.00	1.00	0.41	0.13
16	241.71	35.77	6.48	12.95	1.25	1.32	1.01	1.06	1.00	1.00	1.00	1.00	0.41	0.13
20	358.75	78.80	4.37	5.88	1.25	1.29	0.98	1.05	1.00	1.00	1.00	1.00	0.41	0.13
24	587.26	211.16	2.67	2.19	1.25	1.26	0.93	1.04	1.00	1.00	1.00	1.00	0.41	0.13
32	877.42	471.37	1.79	0.98	1.25	1.23	0.91	1.04	1.00	1.00	1.00	1.00	0.41	0.13
48	1553.20	1477.07	1.01	0.31	1.25	1.19	0.87	1.04	1.00	1.00	1.00	1.00	0.41	0.13
Pinion 2														
8	363.97	28.15	4.30	16.45	1.25	1.22	1.09	1.11	1.00	1.00	1.00	1.00	0.27	0.13
10	488.44	50.70	3.21	9.14	1.25	1.20	1.07	1.11	1.00	1.00	1.00	1.00	0.27	0.13
12	642.16	87.63	2.44	5.29	1.25	1.18	1.04	1.11	1.00	1.00	1.00	1.00	0.27	0.13
16	962.55	196.90	1.63	2.35	1.25	1.16	1.01	1.10	1.00	1.00	1.00	1.00	0.27	0.13
20	1430.27	434.74	1.10	1.07	1.25	1.15	0.98	1.09	1.00	1.00	1.00	1.00	0.27	0.13
24	2333.27	1156.96	0.67	0.40	1.25	1.13	0.93	1.07	1.00	1.00	1.00	1.00	0.27	0.13
32	3505.11	2610.91	0.45	0.18	1.25	1.12	0.91	1.07	1.00	1.00	1.00	1.00	0.27	0.13
48	6248.12	8296.36	0.25	0.06	1.25	1.10	0.87	1.07	1.00	1.00	1.00	1.00	0.27	0.13
Gear 2														
8	170.36	17.77	9.99	27.34	1.25	1.22	1.09	1.07	1.00	1.00	1.00	1.00	0.41	0.13
10	228.40	31.94	7.45	15.21	1.25	1.20	1.07	1.06	1.00	1.00	1.00	1.00	0.41	0.13
12	300.52	55.30	5.66	8.79	1.25	1.18	1.04	1.06	1.00	1.00	1.00	1.00	0.41	0.13
16	450.44	124.23	3.78	3.91	1.25	1.16	1.01	1.06	1.00	1.00	1.00	1.00	0.41	0.13
20	671.60	276.17	2.53	1.76	1.25	1.15	0.98	1.05	1.00	1.00	1.00	1.00	0.41	0.13
24	1103.36	745.38	1.54	0.65	1.25	1.13	0.93	1.04	1.00	1.00	1.00	1.00	0.41	0.13
32	1657.43	1681.97	1.03	0.29	1.25	1.12	0.91	1.04	1.00	1.00	1.00	1.00	0.41	0.13
48	2954.56	5344.81	0.58	0.09	1.25	1.10	0.87	1.04	1.00	1.00	1.00	1.00	0.41	0.13

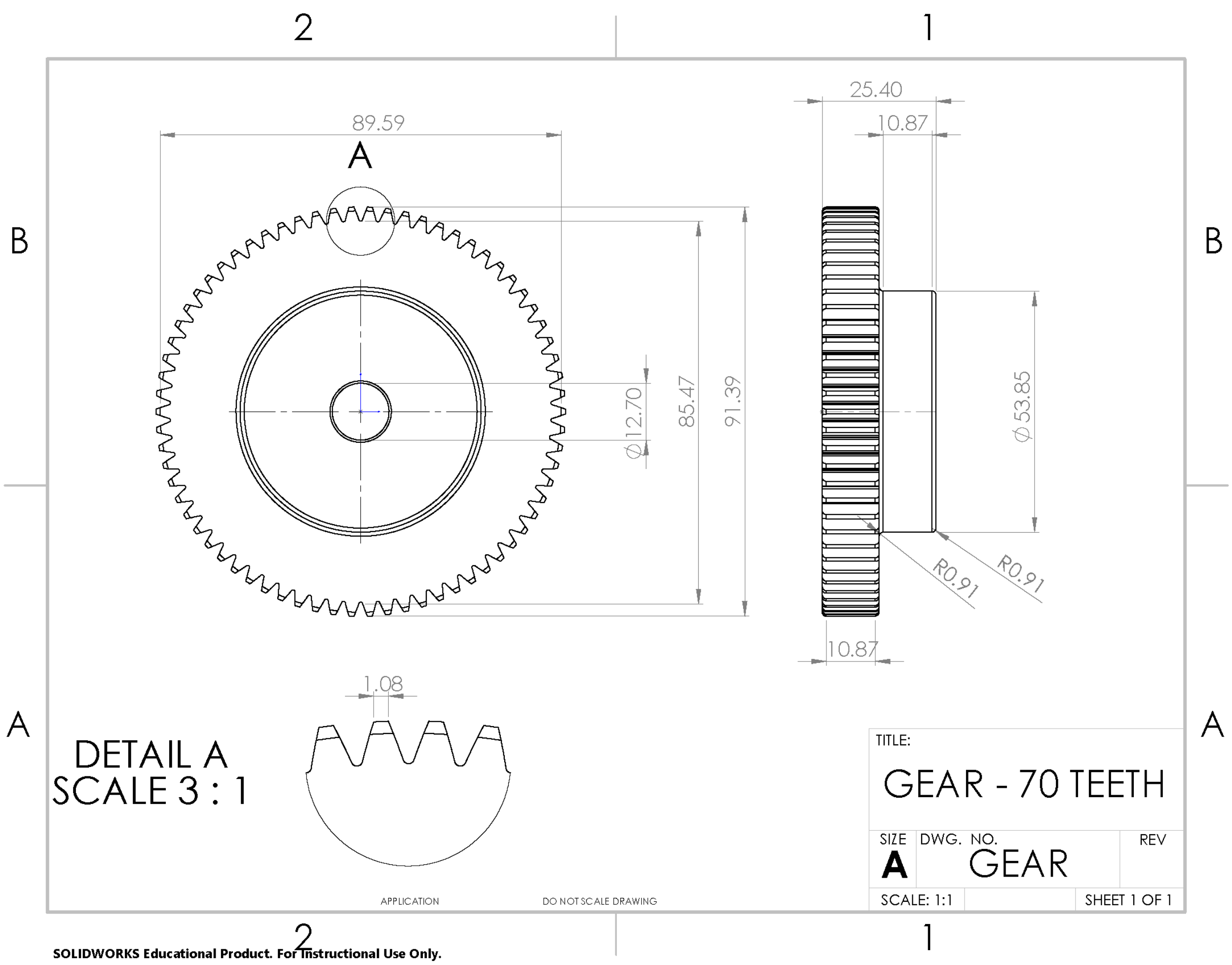
7.2 Gear Diameter and Force Tables

Table 10: Contact Forces and Gear Diameters

Diametral Pitch	Stage 1				Stage 2			
	Force 1 (N)		Diameter (cm)		Force 2 (N)		Diameter (cm)	
	Tangential	Radial	Pinion 1	Gear 1	Tangential	Radial	Pinion 2	Gear 2
8	125.70	45.75	5.08	22.23	494.94	180.14	5.08	22.23
10	157.12	57.19	4.06	17.78	618.67	225.18	4.06	17.78
12	188.55	68.63	3.39	14.82	742.41	270.21	3.39	14.82
16	251.40	91.50	2.54	11.11	989.88	360.29	2.54	11.11
20	314.25	114.38	2.03	8.89	1237.35	450.36	2.03	8.89
24	377.10	137.25	1.69	7.41	1484.81	540.43	1.69	7.41
32	502.79	183.00	1.27	5.56	1979.75	720.57	1.27	5.56
48	754.19	274.50	0.85	3.70	2969.63	1080.86	0.85	3.70

7.3 Part Drawings

Spur Gear, 20 DP, 20 PA, 70 Teeth, Steel



Spur Gear, 20 DP, 20 PA, 16 Teeth, Steel