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Design and optimization of CNC based polishing process

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DESIGN AND OPTIMIZATION OF CNC BASED POLISHING PROCESS

By

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BEng in Aerospace Engineering, Ryerson University
Toronto, Canada, 2006

A thesis

Presented to Ryerson University

In partial fulfillment of the requirement for the degree of

Master of Applied Science

in the program of

Aerospace Engineering

Toronto, Ontario, Canada, 2008

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Abstract

Design and Optimization of CNC Based Polishing Process

MASc 2008, James Lambie, Aerospace Engineering, Ryerson University, Toronto

In recent years many aerospace manufacturing corporations have taken an initiative to eliminate the manual interaction of workers and moving work pieces. At the same time there is an ever-increasing demand for efficiency in the manufacturing sector. The research performed investigates the design and development of passive compliance polishing tools for both external and internal polishing of parts on a CNC turning center. The goal of this thesis is to develop tools that meet new safety demands while at the same time optimizing the tools through the Taguchi method and process planning in order to meet quality standards cost effectively. Experiments on both test pieces and production parts were conducted not only at Ryerson University but at Messier-Dowty as well.

Keywords: Passive compliance, automated polishing, CNC polishing

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Nomenclature

F	F Ratio
$MS_{\text{Treatment}}$	Mean Square of Treatments
MS_{Error}	Mean Square of Error Terms
N	Number of Samples
$N_{\text{Factors_Pooled}}$	Number of Factors Pooled as Error Term
$N_{\text{Treatments_Not_Pooled}}$	Number of Factors Not Pooled as Error Term
S	Standard Deviation
S/N	Signal to Noise Ratio
S / N_{xi}	Signal to Noise Ratio for Experiments with Factor X
SS_x	Sum of Squares Treatment for Factor X
SS_E	Sum of Squares Error
$SS_{\text{Treatments_Not_Pooled}}$	Sum of Squares for Treatments Not Pooled as Error
$\bar{y}$	Mean Surface Roughness
y_i	Surface Roughness Measurement
η_{Opt}	Optimized Signal to Noise Ratio (Multi-Objective Taguchi Tests)
η	Optimized Signal to Noise Ratio from Previous Test
ω	Weighting Factor

Glossary of Terms

ANOM:	Analysis of Means
ANOVA:	Analysis of Variance
CAD:	Canadian Dollars
CAD-Model:	Computer-Aided Design Model
CMM:	Coordinate Measuring Machine
CNC:	Computer Numerically Controlled
ID:	Inner Diameter
MSDS:	Material Safety Data Sheets
NAF:	Nylon Abrasive Filament
NC:	Numerically Controlled
OD:	Outer Diameter
PERT:	Program Evaluation Review Technique
PVC:	Polyvinyl Chloride
RMS:	Root Mean Square
RPM:	Revolutions Per Minute
SFM:	Surface Feet Per Minute
S/N:	Signal To Noise
STEV:	Short Term Exposure Value
TWA:	Time Weighted Average
USD:	United States Dollars

1. Introduction

This chapter provides a background on metal finishing and the tools and techniques to automate the process. Subsequently, the problem-statement and scope of the thesis are given followed by a thesis outline to provide the reader with an overview of the thesis layout.

1.1 Background

In recent years there has been a push by many companies to eliminate the interaction between operators and moving machinery, even ahead of government safety regulations. One major aerospace conglomerate, Safran, has reported that over the past decade manual polishing operations on moving parts has been directly related to 7 serious accidents throughout their companies; all incidents involved medical leave [1]. The accidents that have arisen from manual polishing operations, and injuries range from multiple fractures and severed fingers to other serious injuries [2]. The result of the injuries was in the form of a complete ban of manual polishing operations on moving parts throughout the Safran owned companies. Without the interaction between an operator and a moving part other polishing methods must be used or developed in order to compensate.

Manual polishing (not on moving parts) is one conventional method of polishing parts. The parts are taken from the machines and polished generally using hand tools and grinders. In the case of manual part polishing Guvenc and Srinivasan report that in the mold making industry 37% of manufacturing time is allotted to manual polishing [3]. Other studies such as the one done by Huissoon et al. state that 37% is a lower bound and that in fact 37%-50% of mold manufacturing is spend on finishing operations [4]. In many aerospace manufacturing settings parts are machined rather than produced via a mold, this means that each part would require a considerable amount of polishing time and may lead to a backlog in production. It is necessary to polish aerospace components and more specifically landing gear components, for many reasons. The two most

prominent reasons for polishing parts are to eliminate stress concentrations and to ensure geometric accuracy. Stress concentrations that arise at sharp corners during machining are a serious concern and cause problems including reduced fatigue life. One method of eliminating a sharp edge is through the creation of a chamfer. Many studies have been conducted, as illustrated in a summary table by Hua et al. [5] regarding the residual stresses after chamfering and other edge preparation techniques. In a study by Kihui et al. [6] on high stress components (pressure vessels) the authors mentioned that little work has been done in determining optimum chamfer geometry and that a radial edge is preferred. The notion of using a radial edge over a sharp corner is one that is used in the manufacturing of landing gears, the idea being that a chamfer simply eliminates one corner for two. Results of the study by Kihui et al. [6] on the optimization of chamfer parameters indicates that further studies are still required. Geometry accuracy is important in aerospace components for several reasons, one being aerodynamics the other being to allow for proper tolerance fits between components such as the fit between a landing gear piston and a bushing. One landing gear specific reason for polishing is to remove sharp edges from components that would cut open rubber seals, such as those on pistons if not properly removed [7].

Increasingly in manufacturing industries a push towards automated polishing is occurring. While there exist several ways that researchers are attempting to automate the process, the two most commonly studied and promising methods are robotic [1,8,9,10] and computer numerically controlled (CNC) based automation [11,12,13]. Benefits of automating the polishing process include increasing productivity and eliminating the need for highly skilled labour to manually polish parts [14]. Further benefits of automated polishing include a more consistent quality on finished parts [8] as well as optimal use of polishing tools. The use of robotic polishing has been found to significantly reduce the number of abrasive belt and pad changes required to polish aerospace components, this is due to optimizing tool paths [15].

With the realization of the benefits of turning to automated polishing techniques many researchers choose to investigate the development of compliant polishing tools. Many existing robotic and CNC processes use non-compliant tooling, briefly this means that these tools cannot adjust to un-expected irregularities in the surface geometry or tool

wear. While compliance is discussed later on, researchers have generally broken this field down in to two main categories of study: passive compliance and active compliance.

With the development of passive and active compliant tools the Taguchi method has often been used to determine optimal tooling conditions [4,14,16] over empirical approaches [8]. The Taguchi method is a method to ensure robust design through a design of experiments. Traditionally the Taguchi method has been applied to quality engineering in the following three steps [17]:

- 1) Under standard conditions we design a product or system that each of us consider optimal.
- 2) To find design problems, we test the system under various conditions.
- 3) We change the design of the product or system (called tuning, a counter-measure based on cause and effect relationships) such that it functions well even under conditions where the original design does not work properly.

In today's quality engineering often improvements are made prior to problems occurring, this is done by examining the effect of changes on the functionality using signal to noise calculations [17]. Through the examination of signal to noise ratios it is possible to determine how the system parameters (often called control factors) affect the variance and mean system outputs.

1.2 Scope

This thesis research documents the design of various CNC based polishing tools for use in an aerospace manufacturing environment. Polishing tools designed in the following chapters are limited to CNC control due to the extensive use of CNC machines in manufacturing and the less extensive use of robotic systems.

The tools designed were then tested and optimized using a Taguchi method analysis in order to determine optimal polishing conditions to be used on various aerospace materials. Materials selected for testing are limited to aerospace metals, and generally those used in the production of landing gear components. These materials include various types of steels and aluminums.

Once the tooling parameters have been optimized, process planning is conducted in order to determine the cost and time effectiveness of the tools developed. The tools are compared to specific manufacturing operations in existing process plans that are used

in the production of various landing gears. By using the process plans of existing landing gears an element of realism is introduced into the analysis.

1.3 Thesis Outline

There are 6 chapters ahead. Chapter 2, literature review provides an overview of the scholarly works that have already been performed on areas pertaining to the research and design herein. Chapter 3, Design and Methodology provides an introduction into the polishing tools that were designed and the reasons why there were designed as such. Chapter 4 is the Parameter Optimization chapter which first discusses the materials used for the optimization and why those materials were chosen. The core of Chapter 4 involves the use of various Taguchi tests as a means to optimize each of the tools tooling parameters for different metals. Once a set of tooling parameters is developed Chapter 5, Process Optimization looks at how long each method will take when compared to other possible solutions. With an optimized tooling solution developed, the costs (either reductions or increases) are analyzed to determine the feasibility of the new solutions. The final chapter (Chapter 6) is a discussion and conclusion chapter about what can be drawn from the tool designs and process optimization. After all of the Chapters the references cited and appendices appear (respectively).

2. Literature Review

Before going in depth as to the research performed, this chapter will outline research works that have been conducted on pertaining matters. This chapter will cover active and passive compliance, research into the methods of polishing automation, the tools used and what has been done to investigate the effects of operating parameters. Lastly this chapter will provide information regarding the types of materials used for testing purposes, including their properties and the rational behind their selection.

2.1 Compliance

As briefly mentioned in chapter 1.1 the compliance of a tool (especially a polishing tool) has often been the focus of research.

Compliance is a trait meaning that the end effector (in this case the polishing tools) has the ability to compensate or comply in a particular axis when a contact force or positional error is present; in other words it is a means to accomplish force or position control [18,19].

An example of a non-compliant tool would be a regular cutting (or any machining) tool. A non-compliant tool is not flexible and cannot change to fit the geometry of a given part, nor can it adjust to shape or force changes should it encounter any [18].

Compliance is important in tasks where errors could be present in a work piece's tolerances, position or orientation [20]. The sources of errors in position, force, tolerance etc. has been the focus of many studies. The general consensus is that errors are intrinsic in many systems due to structural flexibility, finite actuator resolution (for active compliance), and uncertainty in the part geometry, environment or measurements [21,22].

Uncertainty in part geometry can arise from many different situations, in the case of turning on a lathe a common source of geometric uncertainty is the total indicator run-out. After machining, inspections often will show that if there is any eccentric loading present, a dial indicator will show that a part will have a slight elliptical shape rather than

a perfectly round shape. Another source of positioning error is explained by Schneider et al. [10] in their study on the feasibility of passive compliant robotic deburring; they stated that any multi-link structure (such as a robot) has will have an inherent accumulation of static and dynamic errors which must be accounted for.

One study conducted by Tian-Soon et al. [22] found that often situations arose where tasks were conceptually possible using only motion control; however, in reality these tasks required compliance to compensate due to the achievable tolerances and accuracies.

Research conducted by Huang et al. [8] focused on the fact that during the overhaul and repair of used turbine vanes, discrepancies of up to 2mm were found between the nominal and actual part geometry. Huang et al. [6] mentioned that without the use of some form of compliance each individual turbine vane would require its own individual tool path for repairs.

Some studies such as the one by Roswell et al. [23] stated that a compliant tool will have the ability to compensate along various axes and that the most compliance is necessary normal to the application of polishing force. In the study of passive compliance conducted by Schneider et al. [10] it was found that a lack of rigidity in other directions could lead to vibrations that would appear as chatter, and as such the tool should be constrained to move only in a direction normal to the work piece.

As mentioned in chapter 1.1 it is common for researchers to classify compliance as being either active or passive. Passive compliance is a purely mechanical form of compliance that is not controllable [24]. One commonly cited example of a passive compliant tool would be a spring loaded tool. As mentioned about previously, compliant tools are used for a variety of reasons, including overcoming position and force errors; however, passive compliance is also being used for other purposes such as overcoming tool wear, by maintaining contact between the part and tool as the tool begins to degrade, and to improve disturbance rejection capabilities [10,22]. Other benefits of passive compliant tools are that they can allow for increased flexibility and dexterity that is required for many polishing and deburring operations [10].

In their study of passive vs. active control in robotic applications Wang et al [20] mentioned that there are in fact few results available regarding passive compliant

experimental studies when compared to those of active compliance. In their study Wang et al [20] considered the mechanical structure of their robot, due to the finite stiffness of the links, joint drive mechanisms etc. to be an intrinsic source of passive compliance and modeled this compliance by deriving a stiffness matrix.

Tian-Soon et al. [22] mentioned that a chamfer may be used as a means of passive compliance for positioning during robotic assembly. Their study showed that the forces during the crossing of the chamfer can be used to move a peg sideways into position [22]. This compliance by using chamfering is demonstrated in the figure below.

Figure 2.1: Chamfer Compliance [22]

This method of compliance can be applied to many other areas as the technique is often employed for machining techniques such as drilling and boring. In order to ensure accurate hole positioning often a center drill has first been used so that further drilling operations will locate to the center of the hole.

In their study comparing robotic manipulator compliance Shirey et al. [21] mentioned that passive compliant tools are in general naturally stable as there is no control system. Shirey et al. [21] went on to mention that the fixed geometry of passive compliant tools cannot be easily modified and that there exist compression limits to elastic components; once the compression limit is reached there is no further compliance in the tool as additional loading will not result in further deflection. This has led many researchers such as Migliore et al. [24] to focus on the development of non-linear elastic compliant systems (something which has been found to be very difficult passively).

A further limitation of passive compliant systems brought up by Migliore et al. [24] is that a passive system is un-able to simultaneously and independently control both angular and linear joint compliance, and that an active compliant system is required.

Active compliance systems achieve compliance through joint, servo and actuator stiffnesses that can be controlled via a controller [20]. The simplest form of active feedback use is a system that can be considered is as a spring with a variable spring coefficient [20]. For the most part active compliance systems use a closed loop feedback in order to sense and correct the force that is exerted on the work piece [4]. Using the control laws it is also possible to vary the apparent stiffness of the end-effector to suit different part needs [21]. The two principle methods used to generate control laws for active feedback systems are stated by Shirey et al. [21] to be either explicit force control or impedance control. The control law generated uses the only the force to determine the actuator input for explicit force control while the position is also needed from impedance control [21]. Shim et al. [25] further mentioned that other control strategies that have been used included discontinuous control, input command shaping and jump impact control. In order to determine the forces between the end-effector and the work piece sensors can be place either on the moving joints, close to the end-effector or on the supports that contain the work piece [21]. As Shirey et al. [21] explained it is more beneficial to place sensors on or near the end-effector because it is easy to translate the measurements directly into forces in the end-effector's coordinate frame, as well as eliminating any un-certainty in the forces produced by a joint or link.

One benefit of using controlled active compliance over passive compliance is the force feedback mentioned above. In their study on the robotic probing of PCB's, Shim et al. [25] discovered that 70-80% of plastic deformation arising from impact between the tool and the work piece was the result of the initial impact. Shirey et al. [21] remarked in their studies that active force control was a method that could reduce the effects of large contact forces between an end-effector and work piece.

Even with active compliance tools there are drawbacks that need to be addressed; the most commonly reported issue with active compliance is the control laws used [10,20]. The response in an active compliance system is not instantaneously generated (as in passive compliance) but rather the response rate is determined by the sampling rate

and control law of the system [20]. Often in parts with tight tolerances and small feature sizes the lag time of the control law is attributed with producing errors [21].

One other problem with automating polishing techniques that was observed by this author was in the robotic polishing of a landing gear component with a belt driven tool. In some instances when an active compliance device was in need of maintenance (arising due to wear of normal production uses) the system behaved as an under-damped system. The system in question began oscillating when the belt of the polishing tool was placed on the work surface; the oscillations continued rather than dissipated which would lead to un-even polishing force.

In their studies Wang et al. [20] composed a comparison of active control vs. passive control, which is summarized in Table 2-1 below.

Table 2-1: Active vs. Passive Compliance [20]

Active Control	Passive Control
Mainly Software Achievable	Mainly Hardware Achievable
Easy to regulate and compute, and can be of general use	Hard to regulate, compute and usually dedicated to particular applications
Dynamic Compliance	Static/Quasi-Static Compliance
Instability is often observed in active compliance system. Careful attention is needed	Guaranteed overall stability due to its passive nature
For position control, there is an upper limit on the desired stiffness to avoid the oscillation or instability	Can be set with a very high stiffness
Limited response rate	Fast response rate
Relatively expensive (for most applications)	Relatively cheap (for most applications)

After researchers began studying active and passive compliance systems a third category of compliance has begun to emerge. In recent studies many researchers have begun developing tools that they consider to have hybrid compliance. Some researchers have classified hybrid compliance as being passive compliance tools that have sensors to determine the contact force and then modify the tool trajectory accordingly [4]. Most researchers however, viewed the situation from the opposite angle; since automation is typically done via active compliance it is becoming apparent that there is still a need for at least some passive compliance in the (active) system [19]. Researchers have found

that “no single scheme of interaction control has been successfully implemented” and that adding some passive compliance to active systems enhanced disturbance rejection and increased the systems stability [19,21].

One of the benefits of hybrid compliance was studied by Wang et al. [20] and that benefit was to reduce jamming during insertions in robotic assembly. In their studies Shirey et al. [21] found that by using a hybrid compliance device it was possible to reduce the end-effector size from that of a purely passive device due to the fact that the majority of the compliance was active and only a small amount of passive compliance is needed. Shirey et al. [21] also reported in their studies that hybrid compliance tools were capable of achieving high accuracy.

2.2 Motion Methods

The previous chapter described the types of compliances that are available and have been studied for an automated end-effector. This chapter will discuss the options that are being studied to mount and automate the motion of an end-effector.

As can be inferred from the studies above one of the more popular methods of automating polishing is through the use of a robotic motion system, such as the ABB robot in use at Ryerson University.

In his study on the economic benefits of robotic polishing Saad [26] examines the benefits of using a robotic manipulator on cast aluminum automotive rims during grinding on a buff wheel. Saad [26] found that not only does the use of a robotic manipulator yield highly repeatable results with a high throughput but also that the contact efficiency, constant pressure and repeatable cycle time yielded 2-4 times the media life (abrasive belts, brushes, wheels, etc.). The ability of a robotic polishing system to improve media life has been observed by this author in polishing studies carried out in the aerospace industry; however, more conservatively that the 2-4 times increase stated above.

In terms of polishing with compliance devices as focused on in the previous chapter Guvenc et al. [3] reported that the use of an articulated robot arm to hold a polishing tool was a better option than other control methods due to a larger reachable

workspace and the ability at a relatively low cost to add additional degrees of freedom. Guvenc et al. [3] reported that relying on a conventional NC machine tool structure placed limits on maneuverability which is directly related to the part complexity that can be polished. In their report Huang et al. [8] mentioned that in operations with well defined conditions (such as deburring and finishing) industrial robots have been proven to be an economical solution and that advantages over conventional CNC systems include a greater capability to integrate sensors.

Shih et al. [27] discussed some of the issues surrounding the use of robotic motion systems in their report. Robotic systems tend to have a low structural stiffness which reduces the ability to suppress chatter during polishing and deburring and also limits the speed of the tool as it traces a part [27]. Another issue when using robotic systems for polishing and deburring is a large positional uncertainty [27]. In their study Shih et al. [27] used a GE P50 and a Puma 560 robotic system and found that the systems exhibited positional uncertainties of 0.35 mm and 0.1 mm respectively.

It is the high positioning accuracy and rigidity of the machine tool structures that Guvenc et al. [3] reported make CNC systems both attractive and effective for finishing operations. Further benefits of using CNC motion systems for the automation of polishing tasks also includes the availability of cutter path data in order to generate polishing tool paths [3].

As mentioned earlier a conventional CNC motion system is less maneuverable than a robotic system, limiting the maneuverability and complexity of part that can be polished.

One interesting study that was performed by Baptista et al. [11] was on comparing 3 and 5 axis milling operations in order to improve the surface finish and reduce the overall polishing that was required. Studies found that in milling operations with a ball nose end mill the maximum roughness is perpendicular to the feed direction and that if the ball nose mill is replaced with an end mill inclined in the feed direction the scallop left (and hence roughness) is reduced [11]. This milling technique to reduce roughness was also found to be faster than ball nose milling and it is only possible with a 5 axis system and not a 3 axis system [11]. The figures below illustrate both what is meant by scallop and the results.

Figure 2.2: Scallops after Milling [11]

Figure 2.3: 5 Axis End Milling Solution [11]

The motion systems mentioned above were either tested on flat, inclined/declined or in one case a sinusoidal surface. In their report on bottle polishing Nagata et al. [28] pointed out that no advanced polishing robots have been able to polish bottle molds on a commercial basis as of yet. Nagata et al. [28] mentioned that issues such as difficulty in creating curved geometries with teach pendants, and lack of proper control schemes for curved surfaces, limit bottle polishing abilities; which is why it is still largely manually performed, as seen in the figure below.

Figure 2.4: Manual Bottle Mold Polishing [28]

In their research Nagata et al. [28] attempted to develop a CAD/CAM system that can be implemented in robotic polishing, in order to automate bottle mold polishing. The study performed by Nagata et al. [28] yielded good results (seen in the figure below); however, it was found that on a case by case basis the robotic bottle polishing was not capable of a force resolution as fine as that of a skilled worker.

Figure 2.5: CAD/CAM Robotic Polishing Results [28]

Further limitations to the CAD/CAM system developed include the fact that the system is designed with the specific work surface material, robot, jig, force sensor etc. as opposed to a more generic approach suitable for many cases [28].

There is one further type of motion control that has been studied in polishing operations, one which attempts to overcome limitations in tool path generation and surface following; that method is magnetic polishing. Magnetic polishing controls the polishing pressure via an internal magnet which is always normal to the work surface, eliminating complex tool paths [29,30]. Two types of magnetic polishing were studied by Kim et al. [30] the first used an abrasive wheel which reduces initial roughness and a second which used a wire brush to further enhance the surface finish. The figure below depicts the magnetic polishing apparatus that was used by Kim et al. [30].

Figure 2.6: Magnetic Polishing [30]

2.3 Types of Automated Polishing Tools

After having discussed the motion systems and compliance schemes used in polishing automation, this chapter will examine different tools that have been studied.

Zhang et al. [16] classified the abrasive tools used in polishing as generally falling into one of three categories: fixed abrasives, filamentary brushes and loose abrasives.

Fixed abrasives are classified as generally being spherical, rectangular or cylindrical in shape, which can vary in grit, binding strength and flexibility [16]. In their report on die and mold polishing Guvenc et al. [3] reported that some German sources prefer to use reciprocating stones because of a high surface integrity and the fact that wider stones have reduced susceptibility to force variation effects. However, in their study regarding turbine blade repairs Huang et al. [8] have found that grinding wheels were not suitable because the hard alloys led to rapid tool wear and longer cycle times. Huang et al. [8] reported that in turbine repair operations it was advantageous to use a belt driven polishing tool because it yielded the highest material removal rate and lowest cycle time. Drawbacks to using belt abrasives included the fact that the contact area is larger than some other existing methods which led to less accurate positioning [8]. Another drawback to using belt abrasives was that in some instances an undesirable vibration was present leading to non-uniform polishing force [8]. Huang et al. [8] summarized their comparison between milling, grinding and belt polishing in Table 2-2, where it is evident that based on their results belt polishing is the most economical of the three approaches.

Table 2-2: Comparison of Milling, Grinding and Belt Polishing [8]

Process	Surface Finish	Removal Rate (g min ⁻¹)	Cycle Time (min/vane)	Tool Life (vanes)	Tool Cost (US\$/unit)	Machine Cost (US\$)
5-axis CNC Milling	Micrometer level	0.8	>56	0.22	6	350000
5-axis grinding with wheel	Submicrometer level	0.15	300	<3	150	>500000
6-axis robot belt grinding	Micrometer level	15	2.5	3	7.5	<300000

Other studies on the use of fixed abrasives for automated polishing include the study done by Tsai et al. [14] where a rotary tool with a foam sponge and emery paper was used to perform the polishing operations. The idea behind the foam was to allow the tool to conform somewhat to the surface of the part. The tool developed by Tsai et al. [14] can be seen in the figure below.

Figure 2.7: Conforming Polishing Tool [14]

Another common way in which researchers are using fixed abrasives to automate polishing was by mounting conventional tools to fixtures attached to motion stages, rather than developing new tools altogether. In order to test their concept of a hybrid compliant polishing device Schneider et al. [10] mounted a die grinder on both a milling machine and a robotic manipulator. In their test of a hybrid compliance device Shih et al. [27] used a die grinder to perform automated deburring operations. It was found that the grinder worked well on small burrs but was less effective on large burrs due to the constant motor speed [27].

Regarding brush polishing, Huissoon et al. [4] studied its potential for use in automated polishing applications. Huissoon et al. [4] found that the filamentary nature of the brush could in some ways act as compliance and conform to complex parts and shapes reducing the need for precise control. In his report on Nylon Abrasive Filament (NAF) brushes Mahadev [31] also mentioned that brushes with nylon filaments

impregnated with abrasives, commonly silicon carbide or aluminum oxide, have been used in CNC and robotic polishing. Mahadev [31] mentions that common examples of automated NAF brush polishing include automotive cam shafts, cylinder heads and wheel rims to name a few. Mahadev [31] reports that in tests comparing NAF brushes to belt abrasives with identical grits, the belt abrasives left deeper scratches and removed more material.

Loose abrasive polishing operations, such as lapping have had little research performed in the area of aerospace manufacturing (with the exception of some magnetic operations). Loose abrasive polishing techniques are more commonly studied for their application to optical manufacturing automation, such as the research performed by Hallock et al. [32].

Up to this point all the methods examined have focused on the polishing of outer surfaces, including flat, incline/decline and sinusoidal; none however, have focused on internally polishing of a part. While no research directly pertaining to the automation of internal polishing of aerospace components could be found, possibly applicable solutions include the development of tools for polishing free-form surfaces. Free form surfaces commonly exist in mould manufacturing as well as in optical manufacture. In their study on free form polishing Tam et al. [33] examined computer modeling of a material removal profile of a tool path that varies depending on the local and global geometries of the surface. Other studies on the polishing of freeform surfaces include the development of the Precessions CNC Polishing Process which used a spinning inflated membrane tool “the bonnet” to conform to part geometry [12]. The bonnet was covered with a detachable polishing surface such as polyurethane and could be positioned so its axis of rotation is normal to the part surface which eliminated the center-zero of removal that is common with pole down rotating tools [13]. The Precessions process used a seven axis motion system and by using dwell times could be used to fix errors in part geometries [12,13]. Currently the Precessions process is used on lenses and dies for coin production [12]. One further example of free form polishing was a gravity loaded polishing tool developed by the Steward Observatory that used actuators to conform to spherical lenses; issues with this tool included the fact that it is complex and must be re-built for every part [12].

2.4 On-Line vs. Offline Programming

With all of the methods of motion control and all of the different tools available there currently exist two methods of programming the automation technique: on-line programming and offline programming.

On-line programming is accomplished by teaching the robot the motions it is to perform in order to carry out a task. Teaching tool paths to a robot is typically done by a teach pendant near the robot work station and requires an actual part or scrapped part in order to achieve proper positioning. On-line programs can be written away from the robot but requires the specific points to be taught to the robot before the program can be run. Typically teaching requires extensive tests by programmers to generate proper trajectories [34]. On-line programming benefits from the fact that as teaching continues programmers can compensate for tool wear by positioning the tool closer to the part. On-line programming can also compensate for un-expected compliances such as tensioners in the tool that flex in order to allow belts and abrasives to be changed.

Offline programming is an attractive method of robotic programming for automation because it is faster than using a teach pendant and it is done and verified away from the robot [26]. Offline programming is also faster physically than on-line programming which is done in slow motion [26]. Typical robotic controllers are restricted in teach or manual modes in order to avoid possibly injuring programmers, in the case of the ABB robot at Ryerson University the traverse speeds of the robots is restricted to 250mm/s or less. Offline programming further benefits from the fact that a robotic cell does not need to be taken out of production in order to create new programs or update existing ones [26]. While there are software packages that are now commercially available to perform offline robotic programming researchers continue to develop tool path programs for offline programming more complicated free-form surfaces. Research conducted by Basanz et al. [35] developed a graphical interface offline program to generate crash free tool paths optimized for time. Other researchers also have attempted to develop offline programs for free-form surfaces optimized for

time, such as Chen et al. [34] who also attempted to optimize other parameters such as coverage.

2.5 Parameter Optimization

Once an automated polishing system is developed and a tool path generated determining the optimal polishing parameters is an important task which has been the focus of considerable research. Optimal polishing parameters ensure consistent material removal that is neither overly aggressive nor not aggressive enough when it comes to material removal.

The most popular method of parameter optimization as mentioned earlier is the Taguchi method. The Taguchi method is an attractive method for researchers based on the reduced number of tests required to determine optimal conditions. In their research Lin et al. [36] performed Taguchi testing on magnetic abrasive finishing with a 60% iron, 40% aluminum oxide (by weight) abrasive. The test by Lin et al. [36] used an L_{18} orthogonal array with 4 factors: lubricant, revolution, feed rate, working gap and abrasive; the analysis was performed using a larger the better signal to noise ratio. It was found that the working gap was the most influential factor, along with the feed rate and abrasive; it was further found that the lubricant and spindle speed had no effect on the finish [36]. The main focus of the study by Huissoon et al. [4] was to optimize parameters for a disk polishing tool in a fixture attached to an NC motion system. Each test performed by Huissoon et al. [4] used an L_8 orthogonal array and was based on a single polishing pass. The parameters used were inclination angle, feed rate, applied force and polishing direction [4]. It was found that the normal force had the greatest effect on the surface finish, the highest force resulting in lowest roughness [4]. None of the other factors tested had a significant impact on the roughness; however, the smallest inclination angle and slowest feed rates did yield the best signal to noise ratios [4].

In recent studies few researchers have attempted to modify the Taguchi method in order to optimize multiple objectives. In their study on drilling Gaitonde et al. attempted to minimize the height and thickness of burrs in stainless steel [37]. After performing regular Taguchi tests a fitness function was developed for each of the 2 parameters to be

optimized, the fitness function in essence was a method of linearizing the results [37]. With the two equations describing the results an average of the two functions was taken and a larger the better signal to noise comparison is performed [37]. In a more recent study performed by Gaitonde et al. the Taguchi method was again used in an attempt to optimize multiple drilling parameters [38]. In this study the signal to noise ratio of each factor was determined without the use of a fitness function, the average signal to noise ratio is obtained and used to determine the optimal system parameters [38]. The fitness function approach was not adopted for this study because there was not a sufficient explanation in the study to support a similar study.

Another approach to determining the optimal polishing parameters is the one used by Zhang et al. [16] which was to mathematically derive an equation for the material removal. Zhang et al. [16] derived an equation for the material removal done by an elastic spherical tool on a cylindrical surface when the tool path is parallel to the cylinder center axis and the tool's axis is normal to the part. The results of the mathematical modeling were that the material removal profile was a parabolic shape with a depth proportional to the polishing force, contact modulus and spindle speed, and inversely proportional to the hardness and feed rate [16]. Test results also indicated that the width of the polished area was proportional to the force applied and inversely proportional to the contact modulus [16].

A less scientific approach to determining optimal polishing parameters is to empirically determine them. Schneider et al. [10] mounted a die grinder to both a robot and a milling machine to test both conventional and piloted cutters on 4140 steel. Results from the test found that on a milling machine regardless of which cutter was used in deburring the surface roughness ranged from 60-70 $\mu\text{in Ra}$ and seemed independent of speed and damping [10]. During robotic testing results showed that the straight cutter had finishes in the range of 130-200 $\mu\text{in Ra}$ while the piloted cutter had a finish of 70-90 $\mu\text{in Ra}$ [10]. Huang et al. [8] also used empirical methods to optimized robotic belt grinding. Results of testing found that the fastest belt speed (that is stable), the slower the feed rate and greater the spring force the more material was removed [8].

3. Design and Methodology

The tools developed and tested in the following chapters were designed with the primary goal of safety in mind. With the realization of the dangers of manual interaction with machining centers solutions must be developed to ensure operator safety. Other goals of the tool designs are to improve the manufacturing process of landing gears in terms of quality, cost and time by focusing on the polishing operations.

The polishing studies conducted focused on both outer diameter (OD) and inner diameter (ID) polishing tools developed for use in landing gear manufacturing. The majority of the tests were performed at Ryerson University; however, some tests were performed on real landing gear components to show realistically how feasible the newly designed tools are.

The methodology developed in order to obtain robust polishing tools is described in the flow chart found in Figure 3.1 below.

Figure 3.1: Robust Design Process

The first step in developing the optimized polishing tools was to actually formulate a tool design (discussed later in this chapter) based on the polishing problem. After the polishing tools were manufactured they were tested in order to determine the optimal polishing parameters. The optimal parameters were then applied to a process plan for an actual landing gear component where they were compared to other possible solutions. Iterative changes were then made in order to find an optimal set of parameters that would also optimize the process plan in terms of time (and as a result cost).

3.1 Spring Loaded NC Tool

For the creation of a CNC polishing tool the use of a spring-loaded device is necessary in order to compensate for tool wear, ensure fairly consistent polishing force as well as minimizing any damage caused due to tool crashes between the tool and the part. Because an NC program cannot directly compensate for tool wear other methods must be used. The use of a spring-loaded device is a simple example of a passive compliance system, eliminating the need for more complicated and more expensive compensation systems. Further benefits (asides from the low cost) of designing a CNC controlled passive compliant polishing tool, are that the tool can be indexed in the turrets or tool carriages of many different lathes such as those used and moved from one machine to the other with ease. The main body of the polishing tool was designed to mimic the rectangular dimensions of the tool holders for existing carbide cutting tools. A computer aided design model (CAD-model) of the tool can be found in the figure below.

Figure 3.2: CAD-Model of Spring Loaded NC Tool

The CAD-Model that was developed was used to ensure that there would be no tool crashes between the tool and the part during use. In order to avoid tool crashes (as well as to hide the shoulder screws) the Delrin piece (shown in white) was extended several inches, this ensured that lugs and other features on the landing gear would not be able to hit the wider metal plating at the base of the Delrin.

On the tool seen in Figure 3.2 the polishing abrasive (not shown), is wrapped around the polishing head made out of Delrin. The abrasive is then held in place by two 1/8" front plates that are screwed into place with cap screws. Delrin was chosen for the

polishing head because it is a material that is readily available commercially and is more ductile than steel or other metals. A relatively ductile material was chosen in order to reduce the possibility of part damage in the event of a tool crash with the part or the application of excessive polishing force. The Delrin itself has a radius of 0.5" on the leading edge to match end-profiles to be blended on a specific part. The Delrin head is itself replaceable, being held to the back plate by cap screws, should a different part with a different profile need polishing in the future.

The spring loading is achieved by using two commercially available music wire springs with a free length of 0.63" and a solid height of 0.16", allowing for 0.47" of travel. The length of the spring was selected from available standard spring sizes with respect to a tapered landing gear component, which required just over 0.100" of travel distance. A spring with a low spring rate was chosen, as this process is required for edge blending not material removal and excessive force would lead to dimensional inaccuracies.

When the produced part came back from manufacturing it was discovered that the springs used were not of the specified stiffness. Testing was performed and it was determined that each spring had a stiffness of 64 lb/in. Because of the fact that the spring stiffness is far greater than specified, care will have to be taken in manufacturing to ensure that there is not too much material removal or excessive force on the work piece.

The springs are constrained by a pair of shoulder screws, which also act as a guide for the bushings mounted in the back plate. The shoulder screws are prevented from unthreading via 2 half-dog point set screws. The shoulder screws and setscrews used were selected based on ANSI/ASME standard B18.3-1998 [39].

The design was produced with many counter bored and counter sunk holes; these holes were designed to prevent crashes between the cap screws and the tool base as well as allowing the heads of the shoulder screws to remain out of the way rather than protrude through the Delrin and possibly damage a part. A cross section illustrating the counter bores can be seen in the figure below.

Figure 3.3: Cross Sectional View of Spring Loaded NC Tool

Engineering drawings of the Spring Loaded NC Tool that were produced and used to manufacture the tool can be found in Appendix A: Tool Designs.

The possibility of the head having a 10 deg. range of motion, to allow the tool to follow the part profile (compliance normal to the force application), was also considered. This design was abandoned after computer modeling showed that with the small taper of the intended parts, the contact point on the Delrin's leading edge profile only slightly shifts during use and as a result no further degrees of freedom were necessary. The polishing tool that was produced and used can be seen in Figure 3.4.

Figure 3.4: Spring Loaded NC Tool

As safety is the most important feature with any tool, this tool was designed so that none of the existing machine guarding or safety features needed to be modified/disabled for its use. This tool also complies with safety requirements that the operator is to have no direct interaction with a moving part. One potential safety concern that was also addressed was the dust generated during polishing operations. The Material Safety Data Sheets (MSDS) for the abrasives used for this tool were examined and it was found that the dust generated has no measured short-term (15 min.) exposure value (STEV) because it is deemed to have no harmful effects during that exposure time [40,41]. Due to the small amounts of edge blending/breaking being done and the short duration of these operations, the dust is mostly a “nuisance dust” [41]. Due to the fact that dust is not readily absorbed into the skin but rather inhaled, a regular dust mask which offers 5x the normal protection, can be worn if desired [41].

3.2 *Dynangle Tool*

Originally during this study when the Spring Loaded NC Tool was being tested it was deemed by engineers that it would not be cost effective to develop a pneumatically driven polishing tool for the lathe, given that the spring loaded tool was showing promise for the limited number of parts with remaining OD problems. However, during the course of testing new production parts begun development that will require even greater surface finishes than the spring-loaded tool can obtain (without drastic increases in machining times). In order to keep costs low it was decided that it would be easier to try and use existing tooling rather than create a whole new rotary tool. For this reason the new Dynangle tool was developed. Dynangle is the name of a pneumatic belt driven polishing tool produced by Dynabrade USA. The Dynangle is a tool, which is currently used in the metal finishing department at Messier-Dowty to improve surface finishes on round parts. A picture of the Dynangle tool can be seen in the figure below.

Figure 3.5: Dynangle [42]

As a result the Dynangle Tool developed is a fixture allowing the actual Dynangle tool to be mounted on the tool post of an NC lathe.

As mentioned the design of a lathe mounted Dynangle tool involves the creation of a fixture rather than development of a new polishing tool. In order to create a fixture, measurement of the Dynangle was done using Vernier calipers, a combination set (to measure the angles) and a height gauge to measure some of the more complicated geometry. After recording the geometry of the Dynangle, a CAD-model was generated.

The fixture generated is in essence a tool shank welded to an L-shaped bracket. Again the tool shank is modeled based on the dimensions of existing carbide cutting tool holders to ensure that the tool can be mounted in CNC lathes turrets. The bracket has been machined in order to fit the geometry of the Dynangle. The Dynangle is held in place via a screw in the L-bracket and another in a flange, which has been welded to the bracket. These two screws locate on the Dynangle casing and handle respectively. A photo of the manufactured design can be seen in the figure below.

Figure 3.6: Dynangle Tool Mounted On Lathe

The Dynangle concept was modeled in Catia by modeling an existing fixture and lathe (the one intended for initial use) in order to examine for tool crashes. The following figure was taken from the modeling. The grey rectangular profile is the tool post for the particular lathe in question, the blue object is the tool holder while the cylinder in the bottom left corner is tailstock.

Figure 3.7: Catia Modeling of Dynangle Tool

Typically the handle on the Dynangle is attached to the main body via a revolute joint and as such is free to rotate to suite the operator's desired hand position. The fixture for the Dynangle uses a cap screw in a slot on the flange to secure the handle to a fixed position. With the handle locked in position (so it cannot interfere with machining operations) pneumatic tubing is run from the base of the handle away from the tool post to a manual cutoff valve so that the operator can safely turn air supply to the tool on and off without having to enter the guarded area. The trigger that is normally mounted on the handle is permanently depressed using a metal clamp. After the ball valve a quick connecting fixture is used so that the tool can be attached and removed from the central air supply that is currently found at the lathes at Ryerson and common in industrial manufacturing settings.

Engineering drawings of the fixture created for the Dynangle can be found in Appendix A: Tool Designs.

3.3 *Formed Emery Head*

The Formed Emery Head is the name given to a tool designed for deep bore polishing. This technique uses a polyurethane head that has been machined to form, attached to a boring bar to polish features deep within the bore including the bottom face of the bore. Previous (un-successful) experiences on non-rotating tools had left manufacturing engineers with the impression that a rotating tool would yield better results than a stationary polishing tool. A photograph of the finished Formed Emery Head tool is visible in Figure 3.8, with the abrasives not present.

Figure 3.8: Formed Emery Head Tool

In previous attempts at polishing deep bore features at a die grinder had been wrapped in a rubber shim and inserted into a steel tube via an interference fit. The idea behind using a steel tube was to avoid using other boring bars in order to eliminate the possibility of damage. Boring bars that are used in the aerospace industry which are capable of performing machining operations on the bottom of a landing gear piston can cost upwards of \$70,000 so the manufacturing operations department did not want to risk damaging one [43]. Existing pneumatic die grinders in use in polishing landing gear components (including the one mounted in the steel tube) have standard $\frac{1}{4}$ " collet sizes, for this reason the main shaft of the mandrel was made to a $\frac{1}{4}$ " diameter. The figure below illustrates the different parts of the Formed Emery Head tool and shows a cross sectional view of the mandrel so that the spring is visible.

Figure 3.9: Formed Emery Sectioned View

Due to the fact that the polishing head's position relative to the bottom of the bore cannot be determined during the boring operation (and hence exact tool offset), a spring loading mechanism must be included in order to prevent damage from tool crashes. For the purposes of this design placing a spring inside the mandrel (shown in Figure 3.9) and having the spindle rest on top of it achieved spring loading.

The spindle was arrested from leaving the mandrel via a shoulder screw. The screw was constrained to move only along the centerline of the tool via a slot milled into the mandrel with a RC6 running fit [39]. In order to prevent the nut from loosening off of the screw, a lock nut with a nylon insert was called for.

In order to avoid the spindle from trenching into the polyurethane a large triangular extrusion was milled with the idea being that the large surface area would require forces greater than those applied during polishing to cause any trenching. The large triangular section can be seen in the figure below.

Figure 3.10: Formed Emery Head Tool with Polyurethane Removed

The top of the spindle was threaded with a $\frac{1}{4}$ "-20 UNC left hand thread so that a nut and washer on the top could hold the polyurethane head in position. The purpose of using a left handed thread over a conventional right hand thread was to avoid the nut from coming lose during regular machining operations.

It may seem erroneous to place a nut and washer on the top of a part designed for polishing the bottom of a bore, however, the landing gear components in question have a hole through the center of the bottom face which ensures that there is no contact with the nut/washer and the work piece. Another benefit of the hole in the bottom of the landing gear components is that during polishing the so called zero center, where the work surface sees no relative angular velocity to the polishing tool, is eliminated.

The actual polishing with the formed emery head tool is accomplished by using a heavy weight, adhesive backed 120 grit emery paper. The adhesive backing helps hold the abrasive in contact with the polyurethane. Studies have shown that if the emery is not secure to the polyurethane head it will readily tear. Ensuring that the emery paper is tight to the polyurethane to avoid tearing is why the adhesive backed paper was chosen. In

order to allow the emery paper to conform to the contoured shape of the polyurethane it had to be cut into a special configuration shown in the figure below.

Figure 3.11: Cut Emery Paper Configuration

The hole in the center of the emery paper, seen in the figure above, is to allow the spindle to pass through the paper. Each individual branch of the emery paper has a width of 0.375". The thickness of the emery paper used was measured using a micrometer and the average thickness value that was found, was used to determine the clearance between the polyurethane head and the part, to ensure a proper fit for the polishing tool.

As for the polyurethane head itself, polyurethane was chosen as the material for two main reasons, the first being that any collisions with the bottom of the bore would not result in part damage, the second reason being that the polyurethane is somewhat compliant to conform to the shape of the bottom bore. It was determined that in order to allow the desired conformity as well as to maintain proper form during polishing that the polyurethane was to have a hardness of 60 measured in the Shore A scale. The polyurethane was then machined to a mating profile to the intended landing gear component (with the allowance for the emery cloth).

4. Parameter Optimization

This chapter details the tests that were performed in order to determine the optimal machining parameters for each of the polishing tools.

4.1 Material Selection

The following chapter describes the various metals used in the testing of the each of the tools, their properties and why that material was selected.

As mentioned in earlier chapters the first tool that was developed, the Spring Loaded NC tool, was designed to match the profile of a specific landing gear component. In order to determine how the tool would perform on an actual landing gear the same type of steel was used, 300M. 300M is a modified 4340 steel to give it an even greater strength. In order to obtain some 300M steel for testing purposes a scrap production landing gear part was turned down on the lathe at Ryerson University and used. A comparison between 300M steel and 4340 steel is shown in Table 4-1 below in order to put its properties into perspective. For comparison purposes the composition of the 4340 steel used was based on a 2 inch diameter round (similar to the size of 300M used), that had been oil quenched and tempered (as 300 M is).

Table 4-1: Steel Comparisons [44,45,46]

Property	4340	300M
Carbon (%)	.37-0.43	0.40-0.95
Chromium (%)	0.70-0.90	0.70-0.95
Iron (%)	96	93.4-94.8
Manganese (%)	0.70	0.65-0.90
Molybdenum (%)	0.20-0.30	0.30-0.45
Nickel (%)	1.83	1.65-2.0
Silicon (%)	0.23	1.45-1.8
Modulus of Elasticity, E (ksi)	29700	29700
Ultimate Tensile Strength, UTS (ksi)	180-270	275-300
Yield Strength (ksi)	153-229	230-245

In order to test the capabilities of the Spring Loaded Tool on aluminum, which is another common metal for landing gear components, once again a scrap piece of metal was turned at Ryerson University. The aluminum used for testing the Spring Loaded Tool was Al 7175-T74, again a common landing gear metal. Aluminum 7175-T74 is a type of aluminum that has zinc as the major alloying element and has been solution heat treated. In order to put Al 7175-T74 into perspective in Table 4-2 below it has been compared to pure aluminum.

Table 4-2: Properties of Aluminum [47,48]

Property	Pure Al	Al 7175-T74
Aluminum (%)	100	88.0-91.4
Chromium (%)	N/A	0.180-0.280
Copper (%)	N/A	1.20-2.00
Magnesium (%)	N/A	2.10-2.90
Zinc (%)	N/A	5.10-6.10
Ultimate Tensile Strength, UTS (ksi)	49	76
Modulus of Elasticity, E (ksi)	9860	10400

When testing the Dynangle tool, again 300M steel was used; however, due to a lack of scrap aluminum 7175-T74 and it's very limited availability it was not possible to test the Dynangle tool on aluminum 7175-T4. In order to test the Dynangle tool on aluminum, another aircraft grade aluminum, Al 2024 T351. Aluminum 2024-T351 has copper as the main alloying element and has been solution heat treated and has been stress relieved by stretching. The properties of Al 2024-T351 can be found in Table 4-3 below.

Table 4-3: Properties of Al 2024-T351 [49]

Property	Al 2024-T351
Aluminum (%)	90.7-94.7
Copper (%)	3.80-4.90
Magnesium (%)	1.20-1.80%
Manganese (%)	0.30-0.90
Modulus of Elasticity, E (ksi)	10600
Ultimate Tensile Strength, UTS (ksi)	68

When testing the Formed Emery Head tool it was not possible to obtain any 300M steel for testing and there is a 48 week lead time in order to obtain a sample [50]. In order to determine the feasibility of the Formed Emery Head tool, cut off ends from

forgings made of Hy-Tuf steel were used. Hy-Tuf was selected as it was not only readily available but there exists a production landing gear component with an almost identical bottom bore profile (and hence same polishing problem) as the component made from 300M. The properties of Hy-Tuf are shown in Table 4-4 below.

Table 4-4: Properties of Hy-Tuf [51]

Property	Hy-Tuf
Carbon (%)	0.250
Chromium (%)	0.300
Iron (%)	94.4
Manganese (%)	1.35%
Molybdenum (%)	0.400
Nickel (%)	0.400
Silicon (%)	1.50
Ultimate Tensile Strength, UTS (ksi)	220

It was not possible to obtain an aluminum sample of the required diameter to test the Formed Emery Head tool and such testing was only performed on Hy-Tuf steel.

4.2 Spring Loaded NC Tool Parameter Optimization

The spring-loaded NC tool that was designed was tested in the mechanical and aerospace engineering machine shops at Ryerson University. The part was tested at Ryerson in order to avoid any delays in manufacturing production. Ryerson University does not currently have a CNC lathe so all of the tests were performed on a manual lathe. The test piece was made of 300M steel, as mentioned this is the same material that comprises the production part on which the tool will be initially used.

The first step in determining the parameters to use when polishing features with this tool was to conduct a design of experiment and find the optimal settings. The Taguchi method was used in order reduce the number of tests performed while at the same time determining the optimal solution. Due to the material costs and availability it

was desired to perform as limited number of tests as possible. Due to the fact that the tool design has 4 factors affecting quality (discussed later) and 3 levels were desired per factor, a $L_9(3^4)$ orthogonal array was used [52]. An $L_9(3^4)$ orthogonal array is used based on the assumption that there is little interaction between the factors chosen. Each of the factors and its corresponding level can be seen in Table 4-5 and Table 4-6 below and Table 4-6 shows the $L_9(3^4)$ orthogonal array.

Table 4-5: Spring Loaded NC Tool Factors

FACTOR	LEVEL 1	LEVEL 2	LEVEL 3
A: Spindle Speed (RPM)	115	210	280
B: Polishing Force (Thou)	30	50	100
C: Feed Rate (Thou/Rev)	6	8	10
D: Scotch Brite Grit	Maroon	Green	Gray/Brown

Table 4-6: $L_9(3^4)$ Orthogonal Array

Experiment / Factor	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

The 4 factors that were tested using the Taguchi method can be seen in Table 4-5. The first factor that was used was the spindle speed of the lathe, by speaking to machinists, based on experience the spindle speeds were set to 115, 210, 280 RPM. The manual lathe at Ryerson University can only obtain certain pre-defined spindle speeds; as such the speeds used (mentioned above) are the closest possible values to the ones the machinists mentioned. While these spindle speeds may seem low for polishing operations they are restricted due to the fact that the section that is being polished is only a small portion of the landing gear component and the majority of the part is quite large and clamped inside a fixture rotating about the spindle. Should too fast a spindle speed be used the forces acting on the portion being polished will cause distortions in the part. For the purposes of the Taguchi method a maximum spindle speed of 280 rpm was used

in order to give a wider range on the values to determine their effects on variance. For the purposes of actual machining the spindle speed will most likely be restricted to only slightly more than 200 rpm. In order to accurately perform the Taguchi method it was necessary to take the higher reading in order to get a wide enough range of values to be able to interpret the results.

The second factor was the force that the tool would apply to the work piece during polishing. The force applied to the work piece was determined based on the deflections of the springs. The springs that were prescribed in the design had a spring rate of 5 lb/in; the springs that were used by the manufacturer were tested and found to have a spring rate of 64 lb/in.

The next factor was the feed rate of the actual polishing tool. Again by speaking to the machinists the feed rate was determined based on past experiences.

The scotch-brite grit to be used in the polishing operations was specified by the colour of the abrasive. Each colour of scotch-brite corresponded to a different equivalent grit; for instance maroon is listed as type A very fine and green is listed as type S Medium grit and the gray is type S ultra fine; where the letter indicates the type of abrasive that is impregnated in the scotch-brite. The maroon and green grades of abrasive were chosen as they are currently commonly used in landing gear polishing and were readily available from the tool crib in a variety of sizes. The gray/brown grit of scotch-brite was selected based on samples sent from a distributor of 3M abrasives, Acklands Grainger.

Initially one of the desirables of the polishing tool is that the material removal is less than 0.001" from the diameter of the part. The ODs of the test pieces were tested using a micrometer capable of reading to the $1/10^{\text{th}}$ of a thousandth of an inch (e.g. 0.0001"). Each of the Taguchi tests was examined and the average change in diameter over 3 separate readings can be seen in Table 4-7 below.

Table 4-7: Changes in Diameter After Spring Loaded NC Tool Polishing

Experiment #\Measurement	1	2	3	Average
1	0.0005	0.0004	0.0003	0.0004
2	0.0009	0.0003	0.0002	0.00046667
3	-0.0005	0.0004	0.0001	1.4803E-16
4	0.0001	0.0002	0.0003	0.0002
5	0.0003	0.0004	0.0004	0.00036667
6	0.0006	0.0014	0.0007	0.0009
7	-0.0005	-0.0005	-0.0004	-0.0004667
8	-0.0004	-0.0004	-0.0004	-0.0004
9	0.0006	0.0009	0.0009	0.0008

Table 4-7 shows decreased outer diameter sizes as positive values, this is because any operation that removes material would instinctively cause a reduction in the diameter. Measurements that were found to be of an increased diameter (negative values) could be explained simply by the fact that the machining operation may not have exactly the same material removal over the entire part. The locations measure pre-polishing were not the exact positions measured post polishing and may have had slightly smaller diameters. Also the accuracy of the micrometer used is only ± 0.0002 despite the fact that it can read to ± 0.0001 some of the negative values could be influenced by errors in the measuring tools. Any vibrations or external noise during the machining operation could explain the very small larger diameter polished regions.

The other requirement of the polishing tool, the one that was the focus of this particular Taguchi experiment, was that after removing the light tool marks, the surface roughness be less than $63 \mu\text{in RMS}$. The surface roughness in micro inches (μin) before and after polishing operations was recorded and the change (delta) was calculated and averaged based on 3 roughness readings. The surface roughness readings were taken using a Mahr perthometer model number PGK 120. The perthometer operates by sending a stylus over the surface of the work piece and recording the changes in height. For the test pieces each of the three surface roughness measurements were taken over a sample length of $0.224''$. Each measurement was from a different region in the test section in order to obtain a more accurate idea of the actual surface roughness over the entire

diameter. After the readings were taken the perthometer then plotted the variation in surface roughness (as seen below) and calculated the average surface roughness over the section.

Figure 4.1: Perthometer Roughness Plot

The above plot shows the surface roughness in μin on the y-axis over the length (x-axis). The results of the roughness tests can be seen in Table 4-8 below.

Table 4-8: Spring Loaded Tool Surface Roughnesses

Experiment #	μin	μin	μin
1	49	51.4	51.8
2	66	63.5	58.8
3	59.2	59.8	57.2
4	53.1	53.5	47.9
5	50.5	50.2	51.4
6	56.1	60	58.2
7	53.8	56.8	58.4
8	29.06	31.28	32.09
9	66.2	68.5	66

Table 4-9: Changes in Roughness and Signal to Noise Data

Experiment	Delta 1	Delta 2	Delta 3	Mean (μin)	Std. Deviation	Signal To Noise
1	8.6	11	11.4	10.33333333	1.514375559	16.68013695
2	25.6	23.1	18.4	22.36666667	3.655589328	15.73287729
3	7.566666667	8.166666667	5.566666667	7.1	1.361371857	14.34563161
4	1.466666667	1.866666667	-3.733333333	-0.133333333	3.12409987	-27.39572344
5	10.1	9.8	11	10.3	0.6244998	24.34609842
6	4.466666667	8.366666667	6.566666667	6.466666667	1.95192213	10.40435975
7	2.166666667	5.166666667	6.766666667	4.7	2.335237318	6.075336713
8	-21.22333333	-19.00333333	-18.19333333	-19.47333333	1.568725597	21.8778663
9	25.8	28.1	25.6	26.5	1.389244399	25.60934439

In Table 4-9 the delta values are obtained by subtracting the original un-polished surface roughness from the polished value obtained from each experiment. It should be noted that while these initial test measurements were performed using the Mahr perthometer, for all of the subsequent surface roughness tests, the Brown and Sharp Surfcom surface roughness tester at Ryerson University was used. Due to the functionality (and age) of the surface roughness tester at Ryerson the test sections measured were 0.2” in length during which span 5 measurements of 0.03” are taken and averaged. The Brown and Sharp Surfcom was set up to take measurements this way to ensure that the surface roughness was measured with no interference from part waviness. Once again multiple test sections were taken per sample.

The changes in surface roughness are positive for an increased roughness after the polishing operation and negative for a decreased roughness after the operation. While it may seem detrimental to have an increase in surface roughness after using a polishing tool, it should be noted that the polishing tool is being used to remove material, albeit a small amount ($< 0.001''$) and some settings may not be optimal. It should also be noted that the ultimate goal of this test was not necessarily the best surface finish but rather to have any marks removed and a finish, which is below 63 RMS; which for most of the tests the surface finish is. A finer finish than 63 μin may require a greater amount of time which is needless and may take longer costing more money.

The standard deviation was calculated using the formula:

$$s = \sqrt{\left(\frac{1}{n-1}\right) \sum_{i=1}^n y_i^2 - \bar{y}^2} \quad (4.1)$$

Where n is the number of samples (in this case 3 per experiment), and y is the change in the surface roughness (delta).

For the purposes of a Taguchi analysis a Type I nominal the best scenario was used. This is because of the presence of both positive and negative readings; a smaller the better scenario cannot have negative numbers [53]. The signal to noise ratios (S/N) that are seen in Table 4-9 were calculated with the formula:

$$S / N = 10 \log \left(\frac{\bar{y}^2}{s^2} \right) \quad (4.2)$$

Where signal to noise is measured in dB.

From the S/N values an analysis of means (ANOM) was performed in order to determine which of the test parameters would be optimal. In this test the goal is to obtain a 63 µin surface finish, not necessarily the lowest possible which would take much longer polishing times than necessary. The optimal parameters are the parameters with the highest S/N ratio. This means that these settings would have the least amount of noise interference so the results produced would be the most uniform and repeatable. The ANOM results were tabulated and plotted and can be seen below.

Table 4-10: Spring Loaded NC Tool ANOM 1

Factor	ANOM (S/N)
A1	15.58621528
A2	2.451578242
A3	17.85418247
B1	-1.546749928
B2	20.65228067
B3	16.78644525
C1	16.32078766
C2	4.648832746
C3	14.92235558
D1	22.21185992
D2	10.73752458
D3	2.942591486

Figure 4.2: Spring Loaded NC Tool ANOM Plot 1

From the ANOM data the factors with the highest S/N ratios are A_3 , B_2 , C_1 , D_1 . This corresponds to a spindle speed of 280 RPM, a polishing force with a spring deflection of 0.050", a 0.006"/rev feed rate and maroon scotch-brite grit. These results make intuitive sense because the faster the spindle speed and the slower the feed rate, combined with the finest scotch-brite grit, should be the settings that give the best finish.

The next step in the Taguchi analysis was to perform an analysis of variance (ANOVA). The ANOVA was used to determine which of the factors had the most effect on the variance of the data. In order to perform the ANOVA analysis first the average S/N ratio was calculated. The result of that calculation is $\overline{S/N} = 11.963992dB$. Next the sum of squares treatments (or sum of squares for each factor) was determined; this was done using the formula:

$$SS_a = \frac{1}{N} \sum_{i=1}^N S/N_{xi} \quad (4.3)$$

Essentially, the sum of squares for each factor is the average of all of the ANOM values for that factor. The individual sums of squares are shown below.

Table 4-11: Spring Loaded NC Sum of Squares Treatments 1

Factor	Sum of Squares
SS _A	414.9025822
SS _B	843.8476884
SS _C	243.7354153
SS _D	563.7260594
SS _{total} (SS _T)	2078.175737

The sum of squares total seen in Table 4-11 above is as the name suggests the total sum of all of the individual values found above it in the table.

The next step in the analysis was to determine the percentage contribution of each factor on the variance. This was done by dividing the sum of squares treatment value by total sum of squares value and then multiplying by 100. The percent contributions can be seen in Table 4-12.

Table 4-12: Spring Loaded NC Tool Percentage Contributions 1

Factor	%Contribution
A	19.9647496
B	40.60521318
C	11.72833514
D	27.12600524

Because this was experiment with no replication the next step was to determine how significant each term actually is on the mean. In order to do this any factors that contribute less than 10% are normally pooled as the error. In this case factor C was pooled as the error as it is the closest. This means that the sum of squares of the error is SS_E = 243.735. By using the formula:

$$F = \frac{MS_{Treatment}}{MS_{Error}} \quad (4.4)$$

The “F” ratio can be found to determine whether a factor is in fact significant on altering the variance in the data. In this formula MS stands for Mean Square, or more

simply, the sum of squares of that factor are divided by the total number of remaining factors; similarly, the mean square of the error is the pooled terms divided by the number of pooled terms (in this case this value is simply SS_C). These formulae are shown below.

$$MS_{Treatment} = \frac{SS_{Treatments_Not_Pooled}}{N_{Treatments_Not_Pooled}} \quad (4.5)$$

$$MS_{Error} = \frac{\sum SS_E}{N_{Factors_Pooled}} \quad (4.6)$$

The results of these calculations give the following results.

Table 4-13: Spring Loaded NC Tool F Ratios 1

Factor	F Ratio
SSA	0.567422098
SSB	1.154048797
SSD	0.770953561

Because $F > 1$ for SS_B only, there are no factors that show a strong significance in affecting the variance of the part when using the feed rate as the error term. Because the other 2 factors are less than 1, they cannot be considered as having a significant impact on the variance.

After performing the Taguchi analysis the optimized solution was re-tested on a piece of material to determine the effects on an actual production part. The part was turned using the same spindle speed and feed rate as the actual production part in order to produce a surface finish (prior to polishing) that mimics an actual production part. In addition to using similar machining parameters, similar tooling was used as well. The carbide insert used in the machining of the test piece was the same as the insert used on production parts. This insert was a Sandvik DNMG 331-MF-525; named according to ANSI standards. The DNMG among other things indicates that the insert is a diamond shape with a hole and chip breakers on both sides [54]. The 331-MF numbering indicates that the insert is a 3/8" size, 3/16" thick and has a nose radius of 1/64", the MF indicates

that the insert has a negative rake angle and is used for finishing [54]. The final numbering 525 is the hardness of the insert [54].

Based on the test piece with the production parameters and optimal polishing settings the initial diameter and surface roughness were 1.4795" and 90.6 μin . The polished diameter and surface roughness were 1.4793" and 90.1 μin . This means that the material removal was 0.0002" and that the improvement in roughness of the production part would be approximately 0.5 μin . It should be noted that for this test the material prior to polishing did not contain any tool marks, material abuse or mismatches. Not only did these results not perform as well as is required (the very low improvements in surface finish are not practical for production use) but they were not indicative of the actual production parts because early prototype production parts did contain tool marks due to sources such as an eccentric loading condition.

A second test was run with the intent of producing some tool marks that are less than 0.001" deep to simulate how the polishing tool will react to an actual part. This test was performed using the same tooling and parameters as the previous test; however, prior to polishing a spring cut of 0.0005" was taken with a feed rate of 0.020"/rev in order to produce a light thread cutting to simulate the tool marks. The problem that arises with spring cuts is that the surface finish is often ruined. In the case of the spring cut test the average surface roughness prior to polishing rose as high as 182 μin giving an uncharacteristically rough finish.

Due to the poor results from the scotch-brite testing further tests were run using different abrasives in order to determine the possibility of using a different abrasive. Many tests were run using emery cloth abrasives. All of the tests were conducted by first turning the test piece with the production parameters that way the results obtained will mimic a polishing pass on a production part. Similarly to the results above the surface roughness readings of the pre-test samples were generally in the region of 90-92 $\mu\text{in Ra}$. The best results that could be obtained without changing the turning parameters on the initial machining were done using a 120-grit emery cloth. These results were found after numerous test runs. The spring deflection on the tool was set to 0.050" which was originally determined via the Taguchi experimentation. The feed rate was set to 0.040" per revolution and 3 passes were performed, then the feed rate was decreased to 0.020"

per revolution for the final 2 passes. It should be noted that the emery cloth was rinsed in between passes in order to remove any metal buildup. This test yielded an average polished surface roughness of 84.26 $\mu\text{in Ra}$, an improvement of 7.14 $\mu\text{in Ra}$ and an average decrease in diameter by 0.001”.

After further tests it was determined that due to the low spindle speed the spring loaded tool has a minimal effect on the surface roughness and that in order to achieve the desired 63 $\mu\text{in RMS}$ finish some modifications to the actual production process may have to be made (discussed further in future chapters).

Another test was conducted using the same insert as all of the tests above, as well as the same spindle speed. The difference between this test and the others was that the feed rate for the turning operation was reduced from 0.006” per revolution to 0.002” per revolution. From this test the average surface finish prior to polishing was 29.1 $\mu\text{in Ra}$. The spring deflection and spindle speed and grit of emery cloth were un-changed. Again 3 passes at 0.040” per revolution and 1 at 0.02” per revolution were performed. This led to an average surface finish of 21.57 $\mu\text{in Ra}$ an improvement of 7.53 $\mu\text{in Ra}$. This test led to a decrease in the diameter of 0.0031”. 2 additional passes were then taken with all of the parameters remaining the same but the emery grit changed to 240, this led to an average surface finish of 18.1 $\mu\text{in Ra}$, an improvement from the original of 11 μin . The additional passes had a negligible effect on the diameter of the part from the previous polishing operations. The results of this test indicate that if the machining parameters were altered and a depth of cut approximately 0.003” more shallow were taken, the spring loaded tool would be able to remove the tool marks, that were on the order of 0.0005” due to the loading condition, and the remaining piece would have the desired finish and dimensions.

One further test was performed based on the initial Taguchi optimal settings; in order to speed the process up even further. None of the cutting or polishing parameters was changed for this test, only the abrasive used. The emery cloth abrasive was switched for a mesh abrasive. The idea behind using a mesh abrasive is that the metallic dust produced from the polishing operation will accumulate in the spaces between the meshing rather than on the surface of the emery cloth; and hence, the abrasive will not have to be rinsed or changed after every pass. The two grits of mesh used were 150 and

220 (commercially available). After completing the machining operations the average part diameter was found to be 2.3362" with an average surface roughness of 22.67 μin . Upon completion of the polishing operation the diameter was found to be 2.3348" (a decrease of 0.0014) with an average surface roughness of 18.87 μin (an improvement of 3.8 μin). The mesh abrasive was found to operate as intended as no rinsing was performed during the polishing operation. These results prove even better than the similar test performed with the emery cloth although there was less material removal meaning tool marks may still be present.

The spring-loaded tool was later tested on an actual part. The machinist backed the depth of cut off by 0.050" in order to allow extra material in case the spring-loaded tool did not perform well. The initial surface roughness was 113.5 μin Ra (rougher than expected) caused due to a spring cut as an attempt to blend a mismatch. The NC program created by programmers within the industry used a 0.03"/rev feed, based on conclusions that the feed rate would have to be changed to achieve the polishing goals. A max spindle speed of 250 RPM was set to limit forces that could damage the part. Due to the coarse nature of the part, a 60 grit emery cloth was used first for two passes, after which time the feed rate was reduced to 0.021"/rev for all subsequent passes. The first pass was with the 60 grit emery cloth, followed by 2 passes with 180 grit and 2 passes with 240 grit emery cloths. This gives a total of 7 passes, which is more than initially calculated (1 extra pass); however, in normal cases the starting surface roughness will be much better than 113.5 Ra. The final results of this test was a material removal of less than 0.001" and a final surface roughness of 56.8 μin Ra, meaning that this tool is acceptable for use on production parts and was added to the set sheet.

In order to be complete, further Taguchi testing using the spring loaded tool on 300M steel was performed. The initial testing mentioned above was performed with the intent of obtaining a 63 μin Ra surface finish. In the future it may be required to use the spring loaded tool to obtain even better surface finishes. These further tests were performed with the sole intent to determine the optimal conditions to obtain the lowest possible surface finish (in one tool pass). Again the machining was done using the insert and cutting conditions mentioned above (in order to get a realistic starting point) and the factors for Taguchi are listed below.

Table 4-14: Spring Loaded NC Tool Factors on Steel

Factors	Level 1	Level 2	Level 3
Spindle Speed	115	210	280
Spring Force	0.030"	0.050"	0.100"
Feed Rate	0.006"/rev	0.008"/rev	0.01"/rev
Grit	120	180	240

In this test rather than performing a nominal the best scenario, a larger the better scenario (based on the difference between polished and un-polished) was used, this means the greatest change in roughness from starting to polished is desired. In the larger the better scenario the signal to noise ratio is found using the formula:

$$S/N = -10 \log \left(\frac{1}{N} \sum_{i=1}^n \frac{1}{y_i^2} \right) \quad (4.7)$$

Where y represents the change in the roughness between polished and un-polished. The rest of the Taguchi analysis is performed in a manner as prescribed above. From this Taguchi test the ANOM results were as follows.

Table 4-15: Spring Loaded NC ANOM Results 2 (Steel)

Factor/Level	Mean S/N
A1	1.006467635
A2	6.076871607
A3	7.120896369
B1	1.834780653
B2	4.641345069
B3	7.728109888
C1	2.196040126
C2	4.285716713
C3	7.722478772
D1	2.464480381
D2	1.951376088
D3	9.788379142

Where once again A is spindle speed, B is polishing force, C is feed rate and D is the grit of abrasive. The ANOM plot is as follows.

ANOM - Spring Loaded Tool On Steel With Emery Cloth

Figure 4.3: Spring Loaded NC Tool ANOM Plot 2 (Steel)

Once again an ANOVA analysis and was performed as well as the subsequent percentage contributions and F ratios; those results are listed below.

Table 4-16: Spring Loaded NC Tool ANOVA 2 (Steel)

S/N_Bar	4.734745204
SSA	64.18522288
SSB	52.13625035
SSC	46.7196058
SSD	115.3213859
SST	278.362465

Table 4-17: Spring Loaded NC Tool Percent Contributions (Steel)

Factor	% Contribution
A	23.05814575
B	18.72962662
C	16.78373045
D	41.42849718

Table 4-18: Spring Loaded NC Tool F Ratios 2 (Steel)

A	0.457946379
B	0.371979811
D	0.822790803

As can be inferred from Table 4-18 the feed rate was pooled as the error term. In this case the percentage contribution of the feed rate is larger than 10%, it is however, still the lowest contributing factor.

The results of the Taguchi analysis for obtaining the best possible steel surface finish indicate that the fastest spindle speed, the most polishing force, the fastest feed rate and the finest emery grit will yield the best finish for 1 pass. The fastest spindle speed and finest grit parameters are identical to what was obtained in the previous test. The fact that this test shows that an increase in force will yield a better finish may be explained due to the fact that the initial test was focused on obtaining a 63 μin finish, not necessarily the lowest surface roughness.

As touched upon initially manufacturing engineers desired a polishing tool that would remove minimal amounts of material from a production part, with that in mind the idea of a multi-objective Taguchi optimization was born. The purpose of the multi-objective Taguchi optimization was to minimize the material removal while at the same time maximizing the surface roughness improvement. The first step in the optimization was to determine the results of a Taguchi test whose sole purpose was to minimize the amount of material being removed from the surface. The results for initial and polished diameters can be found in Appendix C: Test Data. From this data the changes in diameter from the un-polished to the polished condition were used to calculate the signal to noise ratio, similar to the above calculations except a smaller the better scenario was used. The signal to noise ratio for a smaller the better scenario is as follows:

$$S/N = -10\log\left(\frac{1}{N}\sum_1^n y^2\right) \quad (4.8)$$

The signal to noise ratios were found to be as follows:

Table 4-19: Material Removal S/N Ratio (Steel)

Experiment	Signal To Noise Ratio
1	63.0759
2	72.2185
3	n/a
4	67.9588
5	67.9588
6	83.0103
7	n/a
8	70.4576
9	71.8709

In the table above values that read as “n/a” are due to a non-measurable change in the data, this makes it impossible to calculate a signal to noise ratio. From the signal to noise ratio’s obtained the ANOM was once again calculated to determine the optimal settings based on material removal alone, the results were as follows:

Table 4-20: ANOM For Material Removal (Steel)

Factor/Level	Mean
A1	67.64721257
A2	72.97596677
A3	71.16422067
B1	65.51736891
B2	70.21162086
B3	77.4405832
C1	72.18127084
C2	70.68271803
C3	67.95880017
D1	67.63520142
D2	77.61439373
D3	69.20818754

The calculations that lead to the above results assume that the signal to noise ratios are additive. Based on these results it would appear that in order to minimize the amount of material removed a medium spindle speed, with the most polishing force, slowest feed rate and a medium grit emery cloth would have to be used. The results do not correspond with what one would intuitively imagine the optimal results would be.

Such a high signal to noise ratio would indicate that the results are affected very little by un-controlled disturbances and that the accuracy of measuring tools plays a key role in the results.

In order to examine what the results of a multi-objective Taguchi test would be, similar to studies performed in the above chapters a weighted function was used. The formula used was as follows:

$$\eta_{opt} = \omega_1\eta_1 + \omega_2\eta_2 \quad (4.9)$$

Where η_{opt} is the optimized signal to noise value, ω represents the weighting fraction for each of the individual signal to noise ratios and η represents the signal to noise ratio of either the minimized material removal (2) or the maximized change in roughness (1). Based on discussions with engineers it was determined that a 0.7 weight would be given to the surface roughness as this is the most important aspect of polishing. A 0.3 weight was given to the material removal as it is possible to determine how much an offset must be used for a given tool on a given part it will however, take some experimentation. The results of the optimization were found by using the results obtained in earlier chapters. η_1 are the signal to noise ratios taken directly from the results found when using the spring loaded NC tool on steel. η_2 are the signal to noise ratios found in Table Table 4-19. η_{OPT} are the results of using the weighting function. These results were used in another ANOM calculation whose results can be found in Table 4-22 below:

Table 4-21: Multi-Objective Signal To Noise Calculation

EXP	η_1	η_2	η_{OPT}
1	-6.7025	63.0759	14.23102
2	-2.3193	72.2185	20.04204
3	12.0412	0	8.42884
4	7.7815	67.9588	25.83469
5	6.7009	67.9588	25.07827
6	3.7482	83.0103	27.52683
7	4.4253	0	3.09771
8	9.5424	70.4576	27.81696
9	7.395	71.8709	26.73777

Table 4-22: ANOM Multi-Objective Optimization

Factor/Level	Mean
A1	14.23396667
A2	26.14659667
A3	19.21748
B1	14.38780667
B2	24.31242333
B3	20.89781333
C1	23.19160333
C2	24.20483333
C3	12.20160667
D1	22.01568667
D2	16.88886
D3	20.69349667

The multi-objective Taguchi experimentation indicates that the optimal parameters when considering material removal as well as surface finish are to use a medium spindle speed, medium polishing force, medium feed rate and the coarsest grit of abrasive. These results are obviously swayed considerably by the large signal to noise ratio's of the material removal optimization.

The spring loaded NC tool was further tested at Ryerson University, on the polishing of Aluminum 7175-T74 (a common grade of aluminum for landing gear manufacturing). While the spring loaded NC tool was designed and tested with a specific part in mind, future aluminum parts may be developed where the spring loaded tool could be applied. In this case a Taguchi test similar to the ones above was performed. The abrasive used was emery cloth from the start rather than scotch-brite, based on the results above. For this test the initial cutting tool and parameters were the same as those above. In the case of this Taguchi experiment rather than simply obtaining and maintaining a 63 Ra surface finish (as in the case of the first test) the goal was to obtain the best possible surface finish, as a result a larger the better scenario was used on the differences between the polished surfaces and the initially cut surface finishes.

The results from the Taguchi test can be seen in the Table 4-23 below.

Table 4-23: Spring Loaded NC Tool Aluminum Taguchi Test Results

Value	Avg, Change (μin)	Std. Deviation	S/N Ratio
Exp 1	5.3333	3.055050463	10.09657034
Exp 2	15	8.717797887	18.23545468
Exp 3	14.3333	2.081665999	22.9256783
Exp 4	2	0	6.020599913
Exp 5	11	1.154700538	20.72002661
Exp 6	9.25	2.88751346	18.35781466
Exp 7	13	4.573474245	21.0357188
Exp 8	9.3333	1.154700538	19.25366382
Exp 9	32.6666	1.527525232	30.26344577

Based on these results the analysis of means (ANOM) and analysis of variance (ANOVA) was performed. The ANOM results and plot can be seen directly below.

Table 4-24: Spring Loaded NC Tool Aluminum Taguchi ANOM

Factor/Level	Mean
A1	17.0859011
A2	15.03281373
A3	23.51760946
B1	12.38429635
B2	19.40304837
B3	23.84897958
C1	15.90268294
C2	18.17316679
C3	21.56047457
D1	20.36001424
D2	19.20966271
D3	16.06664734

Figure 4.4: Spring Loaded NC Tool Aluminum ANOM Plot

Table 4-25: Spring Loaded NC Tool Aluminum ANOVA Calculations (Aluminum)

S/N_Bar	18.54544143
SSA	117.5737989
SSB	200.4681457
SSC	48.63955709
SSD	29.63485358
SST	396.3163553

With the ANOM and ANOVA completed the percentage contributions and F-Ratios could be determined.

Table 4-26: Spring Loaded NC Tool Aluminum Percent Contributions

Factor	% Contribution
A	29.66665324
B	50.58285964
C	12.27291189
D	7.47757522

From Table 4-26 the effect of the emery cloth grit (factor D) is less than 10% so it is pooled as the error term in order to calculate the F-ratios.

Table 4-27: Spring Loaded NC Tool Aluminum F-Ratios

Factor	F-Ratio
A	1.322472075
B	2.254869088
C	0.547098559

The results of this Taguchi test indicate that the fastest spindle speed, the most spring force, the highest feed rate and the coarsest grit will yield the best surface finish on an aluminum part (for one pass). These results are interesting because they yield similar optimum conditions to using the spring loaded tool on steel with emery as the abrasive. In both cases (steel and aluminum) the higher the spindle speeds, spring force and feed rate gave the best solutions. In the case of aluminum, however, it was found that the coarsest grit, not the finest would yield the best finish.

4.3 Dynangle Tool Parameter Optimization

The Dynangle tool was tested at Ryerson University; again to avoid delays in manufacturing production. The air supply for the Dynangle came from a central airline at Ryerson University that is regulated to supply air between 90-110 PSI, within the operating range of the tool. Taguchi tests were again performed to determine the optimal parameters for use. Owing to the fact that the tool was originally intended as a generic tool the Taguchi tests were performed on both aluminum (2024-T351) and steel (300M). In the case of the Dynangle testing the aluminum used was not the same 7175-T74 grade for the reasons mentioned earlier.

The first Taguchi test performed on the Dynangle tool was using the 300M steel. For both of the Taguchi tests the same insert and tooling parameters were used, as listed earlier to prepare the surfaces for polishing.

Again a larger the better scenario was used to compare the polished roughness and un-polished surface roughness. For the Dynangle tool the grit of the abrasive used was not considered to be a factor owing to the fact that the vast majority of polishing

operations using the pneumatic tool are all performed with the same type of maroon ¾” scotch-brite belt. Because there is one less factor a $L_4(2^3)$ orthogonal array was used for testing. As the name would indicate this means that 4 tests, with 3 factors and 2 levels per factor is the nature of the test. The corresponding orthogonal array appears as follows.

Table 4-28: $L_4(2^3)$ Orthogonal Array

Experiment	Level of A	Level of B	Level of C
1	1	1	1
2	1	2	2
3	2	1	2
4	2	2	1

The factors that were used and the corresponding levels are as seen in Table 4-29 below.

Table 4-29: Dynangle Tool Taguchi Factors (300M)

Factors	Level 1	Level 2
Spindle Speed	108	260
Polishing Force	0.200"	0.400"
Feed Rate	0.020"/rev	0.040"/rev

In the case of the Dynangle tool the polishing force is not applied via a spring. The Dynangle pneumatic tool is passively compliant by nature. The tension on the scotch-brite belt is how the polishing force is adjusted. The deflection in the belt was measured from the instant the belt made contact with the work piece.

The results of the test as well as the ANOM results are listed below.

Table 4-30: Results of Dynangle on 300M Testing

Value	Mean (μ in)	Std. Deviation	S/N Ratio
Exp 1	30.33333333	2	29.60053289
Exp 2	35.00000003	0.577350572	30.87902698
Exp 3	2.6666666633	2.516611479	4.875546236
Exp 4	29.25	1.5	29.29711401

In this case A is the spindle speed, B the polishing force and C the feed rate. As was the case in several of the Taguchi tests above a larger the better scenario was used when calculating the signal to noise ratio, once again equation 4.7 was used. The ANOM was calculated in the same manner as prescribed above and the results are listed as follows.

Table 4-31: ANOM Results for Dynangle Tool on 300M

Factor/Level	Mean S/N
A1	30.23977993
A2	12.21078389
B1	12.36249333
B2	30.08807049
C1	29.44882345
C2	13.00174037

Figure 4.5: ANOM Plot for Dynangle Tool on 300M

After performing the Taguchi tests the material removal was approximately 0.001”-0.002” per polishing pass.

The results of the Taguchi test indicate that the optimal conditions for running the Dynangle tool on 300M steel involves the slowest spindle speed, the highest polishing force and the slowest feed rate. The fact that the slowest spindle speed gives the best finish is explained due to the fact that the normal direction for the lathe spindle is counter-clockwise (facing the chuck) and the normal direction of rotation for the Dynangle is from top to bottom; this means that the lathe’s rotation actually decreases the relative polishing speed. These results comply with the earlier ones that found the higher the relative rotational speeds the better the polishing results were.

The Taguchi test was run once again, this time on the aluminum 2024-T351 piece in order to determine the optimum parameters on aluminum. Once again a larger the better scenario was used on the changes in surface roughness from polished to unpolished. The results of the aluminum test results are as follows.

Table 4-32: Taguchi Test Results for Dynangle Tool on Aluminum

Value	Mean (μ in)	Std. Deviation	S/N Ratio
Experiment 1	40.75	4.39698653	29.51628915
Experiment 2	33.75	4.69041576	27.22669473
Experiment 3	50.666667	1.732037644	34.0840209
Experiment 4	45.3333337	3.51187813	34.32464272

Once again the same formulae were used as in the previous tests and the ANOM was calculated from the data obtained. The ANOM results are as follows.

Table 4-33: ANOM Results for Dynangle Tool on Aluminum

Factor/Level	Mean S/N
A1	28.37149194
A2	34.20433181
B1	31.80015503
B2	30.77566872
C1	31.92046593
C2	30.65535782

The resulting plot from the ANOM values can be seen below.

Figure 4.6: ANOM Plot for Dynangle Tool on Aluminum

Using an $L_4(2^3)$ array to perform Taguchi testing has one limitation that a larger test does not have. Due to the nature of the orthogonal array it is not possible to perform any ANOVA calculations as all of the sum of squares will be the same; this means that it is not possible to determine which factors will be able to affect the variance should fine tuning be required.

The results of the Taguchi test on the aluminum indicate the exact opposite of the results from the test on the steel parts. The aluminum shows that the fastest spindle speed (and hence lowest relative velocity) the lowest force and the highest feed rate should be used. It must be noted however that the differences seen in the ANOM regarding the feed rate and polishing force are very low and as a result the difference between using these values and the ones obtained in the test with steel would be small. It should also be noted that from the ANOM plot on the test with steel the differences in force and feed rate between the optimal and non-optimal settings would have a much more noticeable impact than a difference seen on aluminum.

The observed amount of material removal seen in the test with aluminum was found on average to be 0.001" or less.

Upon completion of Taguchi testing the Dynangle tool was tested on the same production parts as the spring loaded NC tool. If one recalls the spring loaded tool was created with a radial leading edge to match the part profile. As it turns out the radial profiles were not a source of noticeable tool marks or areas of high surface roughness; as such the Dynangle tool was run using the same profile as the spring loaded tool, only the starting and ending points were closer together (avoiding the radial run-outs). The results of the Dynangle tool were excellent with 1 pass decreasing the roughness from an initial value of 89 Ra to an acceptable 51 Ra. The Dynangle tool was run on existing G-code (with modified starting and ending points) which gave a feed rate of 0.120" per revolution at a spindle speed of 100 RPM, the polishing force used was a 0.100" deflection in the belt. The reason for the quick feed rate and lower polishing force was to avoid potentially scrapping the part as the part that was used for testing was produced without backing the tool off (to final dimension). The amount of material removed was 0.0015" which is within the +0,-0.003" tolerance on the given part. As a result of the performance of the Dynangle tool it was adopted to polish the entire batch of that particular part and has been added to the set sheet to be used on all future batches.

4.4 Formed Emery Head Parameter Optimization

The actual manufacturing of the formed emery head tool was outsourced by in order to avoid creating possible delays in production. Serious issues caused by the outsourced manufacturer caused problems with testing this tool. The outsourced manufacturer made an error in the creation of the metal spindle that extends through the polyurethane; this error was solved before the tool was delivered, even though the solution was not to follow the original engineering drawings and re-create the part. Upon receiving the formed head it was found that the polyurethane was machined to have an incorrect radius on the edges (which match the part profile) despite the correct one being listed on the engineering drawing. After correcting the edge radius when testing the tool

it was found that the top surface of the tool was actually slightly concave in nature as opposed to being completely horizontal (as specified). The concavity meant that a small portion of the innermost diameter was not being polished (the un-polished portion was not used for surface roughness measurements during testing). This means that despite any early promise this tool may show the polyurethane head must be re-manufactured to the specifications given before it could be used on production parts.

One possible solution to avoid issues with suppliers is to purchase castable liquid polyurethane and to use an exact mold of the desired feature (with allowance given for the emery paper). The castable polyurethane is inexpensive and additives are available to produce any desired hardness on the durometer scale.

Initially the Formed Emery Head was tested using industry facilities due to the lack of proper equipment at Ryerson to prepare the test samples, based on the material obtained. A Taguchi test was attempted on the industrial lathe however the necessary tests could not be completed as the pneumatic die grinder did not have the appropriate amount of strength to drive the head. A Taguchi test was performed on the formed head as a static tool, with the work piece rotating. After the test pieces were created and the static tests were completed, testing was carried out at Ryerson University once again to avoid delaying industrial production.

Before any of the Taguchi tests were completed the Formed Emery Head showed promise as the emery paper used easily withstood the polishing forces and remained in tact (a concern of methods engineers). Another concern that was laid to rest was the fear that the polishing forces would be so great that the triangular section on the spindle (holding the polyurethane in place) would begin trenching into the polyurethane. The triangular extrusion on the spindle performed its task perfectly with no trenching evident.

After taking a roughness measurement from one of the static samples a pneumatic drill was found and used to see if the rotating head could perform better. It must be noted that the pneumatic drill is not suitable for use as it would not fit down the bore of an actual part, nor could it be mounted on a boring bar. The purpose of the drill was only to determine the feasibility of a rotating formed emery head. The pneumatic drill produced even greater results than the static head and shows quite a bit of promise if a similar torque pneumatic tool that can be mounted to a boring bar could be found. Failing that

the reduction of weight of the formed emery head could be possible by replacing the steel components with aluminum, this would however, significantly increase the cost of the tool.

The results obtained on the production lathe and the pneumatic drill were taken to Ryerson University to perform Taguchi testing on the Formed Emery Head tool.

The first Taguchi testing done at Ryerson was to complete the static testing analysis. By using the Formed Head statically the tool can be mounted on a conventional boring bar and the issues of finding a new pneumatic tool or re-designing for light weight are laid to rest. Once again an $L_4(2^3)$ orthogonal array was used. The three factors that were examined were the spindle speed of the lathe, the force of the spring and the dwell time of the tool at the bottom of the bore, the levels used can be found in Table 4-34 below.

Table 4-34: Formed Emery Head Static Taguchi Test Factors (Hy-Tuf)

Factor	Level 1	Level 2
Spindle Speed (RPM)	312	765
Force (inches)	0.1	0.2
Dwell Time (s)	10	20

The results of the Taguchi testing can be seen in Table 4-35 below.

Table 4-35: Static Formed Emery Head Results (Hy-Tuf)

Experiment	Mean (μ in)	STD. DEV	S/N
1	29.98	7.909930467	28.82489078
2	6.57	7.274384281	7.437859905
3	36.665	29.08131703	26.71064348
4	9.616666667	19.6738405	17.96047283

From the results found in Table 4-35 above the ANOM was calculated and plotted and can be found below.

Table 4-36: ANOM for Static Formed Emery Head Test (Hy-Tuf)

Factor/Level	Mean S/N
A1	18.13137534
A2	22.33555815
B1	27.76776713
B2	12.69916637
C1	23.39268181
C2	17.07425169

Figure 4.7: ANOM Plot for Static Formed Emery Head Test (Hy-Tuf)

Based on the results from the ANOM the using the Formed Emery Head tool statically yielded the best results when the fastest spindle speed is used, the lowest spring force and the shortest dwell time.

After completing the static testing on the Formed Emery Head tool, the Formed Emery Head was mounted into the pneumatic drill which was fixed to the tool post of the lathe and a rotary test was performed. The manual lathe at Ryerson University is not capable of the all of the same spindle speeds as the production manual lathes within the aerospace industry, also based on advice from the machinist the polishing dwell times

were slightly changed for this test. The levels of each of the factors examined in the rotary Taguchi test can be seen in Table 4-37 below.

Table 4-37: Formed Emery Head Rotary Taguchi Factors (Hy-Tuf)

Factor	Level 1	Level 2
Spindle	350	625
Force	0.15	0.2
Dwell	10	20

It should be noted that for this experiment the lathe spindle was run in reverse, this is due to the direction that the pneumatic drill rotates. By reversing the direction on the lathe the relative speeds between the part and the polishing tool increases.

The results from the rotary Taguchi experiment can be seen in Table 4-38 below.

Table 4-38: Formed Emery Head Rotary Test Results (Hy-Tuf)

Experiment	Mean (μin)	STD. DEV	S/N
Exp 1	51.96	26.30532266	32.36087236
Exp 2	6	6.130524719	6.062246572
Exp 3	50.65	11.55782563	33.4309911
Exp 4	41.06	5.449770637	32.09304056

Based on the results obtained in Table 4-38 above the ANOM calculations were performed and a plot was generated, the results can be seen below.

Table 4-39: ANOM Results for Formed Emery Head Rotary Test (Hy-Tuf)

Factor/Level	Mean S/N
A1	13.14931289
A2	32.76201583
B1	32.89593173
B2	13.01539699
C1	32.22695646
C2	13.68437226

Figure 4.8: ANOM Plot for Rotary Test of Formed Emery Head (Hy-Tuf)

Based on the test results obtained for the Formed Emery Head tool, regardless of whether the tool is mounted in a pneumatic drill or stationary the best results occur with the fastest relative speed, the lowest polishing force and the shortest dwell time. The fastest spindle speed result comes as no surprise as having the highest relative speed between part and polisher is common between most of the tests. In the case of the rotary test using the lowest force also comes as no surprise as it was found that applying excessive force would actually cause the rotational speed of the pneumatic tool to slow down (and hence reduce the relative speed between polishing tool and part).

A few things must be noted about the testing performed on the Formed Emery Head tool. Firstly it was not possible to gauge the material removal with the equipment available. It was not possible to use a Vernier caliper or micrometer to measure the material removal at the bottom of the bore. The dimensions of the test pieces meant that using a Vernier caliper to directly measure the depth was not possible because the extension would rest on the fillet bottom edge rather than the bottom face. Due to the large diameter of the bore and the hole present in the center of the test pieces it was not

possible to use a depth micrometer to measure the before and after depths to determine material removal.

One other thing that must be noted in the testing of the Formed Emery tool was that in order to determine the surface roughness of the test pieces a wax impression had to be made before and after each test and it was the wax impression that was measured for surface roughness. Due to the geometry of the test pieces (and actual pieces) it was not possible to place a stylus on the bottom of the bore and that is why the wax impressions had to be made. A photograph of one of the wax impressions taken can be seen in the figure below.

Figure 4.9: Wax Impression

The wax impression that is shown is one taken from an actual production part. The curvature just beyond the mismatch is due to the bottom profile of the part. The build up of wax on right of the drawing is where the hole in the center of the bore is situated and the wax began to run into the hole prior to curing.

5. Process Optimization

When comparing potential solutions, the time involved to produce the part is critical. In many respects time is money and in some situations it is not worthwhile to spend a great deal of time in producing a non-critical feature. At other times, such as in the production of critical parts it is acceptable to have an increase in production time to ensure quality and accuracy. This chapter compares the time it takes to produce a part with the manufacturing techniques described above. In order to determine which methods of manufacturing were appropriate in each situation a modified Program Evaluation Review Technique (PERT) chart was produced in each case. A PERT chart is a graphical method that generally uses arrows to indicate tasks that take time, while the circles (in these cases ovals) represent events [55]. The PERT chart is used to determine the “Critical Path” or which scenario is the longest route to complete the task [55]. For the purposes of this research the tasks and activities have been combined into one ellipse and the arrows are used to indicate the flow of operations. The modified PERT chart was then used to determine based on time which method of manufacturing was superior, the time being later used to determine cost. PERT charts were only created to compare methods that could suitable replace each other, in other words to compare apples to apples.

In constructing the PERT chart the times indicated inside the ellipses are a total of the queue, move, set-up and actual machining times for each operation. For many of the operations the process planners have already determined the times associated; for the new or modified operations the non-machining times (such as queue and move times) were based on the values used in existing process plans.

Operations in existing process plans that occur after the manufacturing stages such as part washing and painting were excluded, as they have no effect on the times involved in manufacturing.

The PERT charts were fabricated by grouping similar operations; this helps to reduce the size of the PERT chart as well as avoids revealing any proprietary information regarding the part manufacturing. Operations listed as machining include turning, boring and milling operations. Surface preparation stands for operations such as polishing,

deburring, honing, abrasive blasting, peening, grinding and like operations. Outsourced operations are any operations that are either done outside of the plant or operations that are in house but only exist due to following or preceding outsourced operations. For instance any inspections that occur in house prior to an outsourced operation and any subsequent inspection upon its return would be grouped into outsourcing. Other operations such as CMM inspection and non-destructive testing are self-explanatory.

5.1 *Spring Loaded NC vs. Bench Working vs. Dynangle*

The newly designed spring loaded NC tool as well as the Dynangle tool was developed to replace the existing manual polishing done at a bench station. The existing part used is not a straight cylindrical section but rather a tapered part with radial run outs on the ends (as previously stated). The time involved in producing the landing gear with the newly designed tools was determined by first recording the actual machining times required with the new tools.

Based on the production part tests, the actual polishing time required for the spring-loaded NC tool is approximately 30 minutes per landing gear (both legs). As mentioned earlier tests conducted at Ryerson also produced a method of polishing using the spring loaded NC tool that involved slowing down the feed rate in order to accomplish the polishing in less passes, this method is also examined. The Dynangle tool was found to require approximately 2 minutes per leg of machining time. Because the tool is to be used after normal cutting operations it is not necessary to add extra time to switch the part to machine the second leg (it is accounted for already in the machining time). The total additional time required for the Dynangle tool is then approximated as 4 minutes (2 legs).

For the purposes of comparison, a PERT chart was made comparing the new methods of polishing with the bench working solution that is currently in place for this problem, the chart can be seen in the figure below.

Figure 5.1: PERT Chart for OD Tools

From the PERT chart it is evident that the spring-loaded tool and the Dynangle are in fact faster than the traditional method of bench working. By using the spring loaded tool a total of 24 hours are saved, or 1.61% of the current manufacturing time. By opting to use the Dynangle tool a total of 24.433 hours are saved over bench working which equates to saving 1.64% of the current manufacturing time. By examining the PERT chart it is evident that the preliminary process using the Spring Loaded NC tool, where the feed rate is reduced prior to polishing, there is still a time saving over bench working. By using the preliminary process plan with the Spring Loaded NC tool a total of 23.82 hours or 1.60% of the total time. The preliminary process plan using the Spring

Loaded NC tool is not; however, an optimal solution as the newer process saves even more time.

It should be noted that of the 24.5 hours of time to perform bench working operations the majority of that period is queue time and in fact the actual polishing time for bench working is identical to the time required for the spring loaded NC tool (current method).

With the use of the Spring Loaded NC tool on actual production parts G-Code had to be programmed off-line in order to ensure that the followed the part profile. The G-Code used in the testing (and now the implemented code) can be found in Table 5-1 below.

Table 5-1: Spring Loaded NC Tool G-Code

CODE	MEANING
N10 G90 T0000 M41	Outer Diameter Cutting Cycle
N20 G20	Inch Data Input
N30 G00 X43.7530 Z.1000	Positioning (Rapid Traverse)
N40 G20 G90	
N50 G04 U1.00 T0816	Dwell 1ms with Polishing Tool
N60 G00 X15.0000 Z.1000	Positioning (Rapid Traverse)
N70 G92 S250	Max. Surface Speed 250 SFM
N80 G96 M03 S130	Constant Surface Speed 130 SFM Main Spindle Clockwise
N90 G00 X9.2500 Z-6.3750	Positioning (Rapid Traverse)
N100 X1.5500 Z-3.1500	
N110 G01 X1.0300 F0.0300	Linear Interpolation (Feed) with Feed Rate of 0.03"/rev
N120 Z-5.0701	
N130 X1.3510 Z-11.2500	
N140 X2.9045	
N150 G00 X9.2500 Z-6.3750	
N160 X15.0000 Z.1000	
N170 M30	Program End

5.2 Formed Emery Head vs. CNC Lathe

Previously when there has been a need to manually polish features on the bottom of a bore the machinists performed this function manually by attaching a ball of emery paper onto a rod. Since the ban on manual polishing there have been many attempts to

polish the bottom face of a bore; to date the only method that has had any success is to take extra finishing passes with the lathe. Currently in order to eliminate tool marks on the bottom face of the bore the machinists are setting the tool offsets to be 0.005" away from the bottom of the bore. Once the CNC program is complete the machinists remove the chips that have formed in the bore and then re-run the program approximately 0.002" closer than previously. The process is repeated about 3 times in order to ensure that there are no tool marks. This process does not cause the same problems as a traditional spring cut because the cutting is on the bottom face of the bore, not the side walls, so the part itself acts to steady the cutting tool. This process of taking finishing passes is a relatively new process and is still not perfect. After taking a wax impression of the bottom face of a completed part it was evident that a very small mismatch was still present, although not large enough to warrant any rework (eg. within tolerance).

The Formed Emery Head solution was designed to eliminate the extra 3 machining processes as well as any mismatch present. Once again a PERT chart comparing the two processes was created and can be seen in the figure below. It should be noted that because the formed emery head solution was never tested on a production part some estimations had to be made. First off for the purposes of a PERT chart the case where the Formed Emery Head tool is rotating was assumed, as this was the original design intent and proved to be more effective. An average surface roughness from the Taguchi tests was found to be 89.1425 μin , which is similar to the starting roughnesses of the other production parts tested earlier, as a results this was assumed the starting roughness. It was further assumed that a surface finish of 63 μin would be acceptable, as that is often the standard used on production parts. By subtracting the average improvement of 37.4175 μin per pass that was obtained in the Taguchi testing it was found that one pass would be necessary. Since it would make sense that the optimal solution would be able to at least match the average value of the non-optimal tests this value seemed reasonable. The Taguchi tests showed that the optimum dwell time was 10 seconds, so this value was also used. Based on the existing process plan the machining operation preceding the formed emery head requires 3 hours of set-up time. Since there is no need to mount the part in a fixture, then the fixture in the chuck, nor change the chuck, nor re-check indicator run-out etc., a set up time of 1 hour was approximated (in

reality this should be more than enough). The resulting PERT chart can be seen in the figure below.

Figure 5.2: PERT Chart Internal Diameter Solutions

From the PERT chart created it is evident that the Formed Emery Head solution is the faster solution, with a time savings of approximately 0.5 hours per part, or 0.03% of the total time.

5.3 Optimized Process Costs

When comparing which of the manufacturing techniques should be used in a given situation, the costs associated with each process must be considered. At times an increase in cost is acceptable in order to ensure the desired quality of part, or production time. Sometimes, such as when time and quality are less critical it is not beneficial to

have a more expensive operation. In previous works often researchers attempted to develop automated polishing tools that are “optimal” based only on the tooling parameter optimization and not necessarily the whole process.

Costs associated with each manufacturing process include tooling costs such as the cost to produce the tool, abrasive materials needed etc. Other costs include the actual machining costs associated with producing the part. Because these tools can be applied to many different parts it is not possible to know how many parts will be machined during the life of the tool, unlike cutting tools. For these reasons the cost of to produce each tool is listed; however, determining the optimal solution based on cost is done exclusively by the time savings. Using only the time savings is justified by the relatively low price of the automated polishing tools (compared to other methods such as robotic polishing and the cost of a landing gear component). Furthermore all of the abrasives used on the polishing tools are readily available and most are used in other operations in the production/polishing of a landing gear, as such they are bought in large quantities, making the cost per part negligible.

The actual hourly cost associated with machining is proprietary information and is not disclosed, as these costs are used to determine the customer’s costs. For the purposes of apply a cost to perform the analysis the in-house machining costs were assumed to be \$150/hr (USD). One basis for this assumption is that when outsourcing tool manufacturing (such as the tools designed) generally costs are in the neighborhood of \$70/hr (USD) and the assumed sub-contracting cost for outsourcing labour intensive parts used in the aerospace industry is \$90/hr (USD) (discussed later) [56,57]. With these values in mind and the fact that many landing gear parts are very complex and that a large company would have more overhead costs than a small machine shop the \$150/hr (USD) figure was estimated.

For the purposes of estimating times, the previous chapter involved the comparison of in-house polishing techniques using PERT Charts. It should however, be noted again that with the ban on manual polishing techniques in place some of the tool designs listed could also be applied to problem parts that are not currently in-house. As touched upon above, there is a general approximation used in the aerospace industry for

determining the cost of a potential outsourcing. Table 5-2 below illustrates the cost per hour for various levels of labour intensity.

Table 5-2: Cost Approximation per Hour Outsourced

Hours of Labour	Cost Per Hour (USD)
<0.6	50.00
0.6-2.5	60.00
2.5-8	70.00
8-23	80.00
23-45	90.00

While the costs above are cheaper than the assumed hourly shop rates, the above costs of outsourcing do not include shipping costs, or any account of the effect on lead times or any potential risk of part damage. The costs above are also generic costs for outsourcing, many of the costs listed in the subsequent chapters are the actual costs associated with an outsourced operation.

One more fact that must be kept in mind when examining the costs is that any machining time saved by eliminating a process, may not be the same as the total time saved above, this is due to the elimination of queuing times. Eliminating queuing times is considered as a non-value added process and must not be counted at the shop hourly rate. Where the elimination of queuing times would save money is in the reduction of lead times, a facet that is not quantified in the production of landing gears.

5.3.1 Spring Loaded NC Tool vs. Dynangle Tool vs. Bench Working

The first cost that must be considered when evaluating the spring loaded tool concept, is the actual cost of the tool itself. With the spring-loaded tool that was designed (found in Appendix A: Tool Designs) the cost to produce the tool was \$468.31 (CAD). When the \$150 per hour shop rate is applied to the results from the PERT chart (Figure 5.1), the spring-loaded tool's current processes ends up costing the same as the bench working solution, the reason being that of the 24 hours saved this is non-value added (queue) time and must not be considered when applying the hourly rate. When examining the first spring-loaded NC Tool "optimized" solution it winds up costing an additional \$27 per part.

The largest cost of producing the Dynangle tool for the NC lathes is the actual cost of the Dynangle. Obtaining a new Dynangle for use on this tool would cost \$1135.00 (CAD), for the purposes of testing a Dynangle was borrowed from the metal finishing department [58]. When the Dynangle Tool is considered a total of 0.433 billable hours are saved, which equates to \$65 (USD) per part produced, over the existing technique.

When the approximate in house manufacturing cost of \$7732.50 (USD) and the actual \$1618.91 (USD) for subcontracted manufacturing are combined the decreased cost of using the Dynangle tool is 0.7% of the total. Again any reductions in overhead are not considered when determining the manufacturing costs of the bench working solution.

5.3.2 Formed Emery Head vs. CNC Lathe

The first cost that must be considered when evaluating the formed emery head technique is the cost of the actual tooling. The cost to produce the formed emery head tool was \$735.47 (CAD). Along with the formed emery head the cost of the steel tubing which acts as a boring bar and the cost of the die grinder must be considered. The steel tube currently being used has a cost of \$50.00 (CAD) for a standard length of 21 ft [59]. Even though the polishing is only using a 72" (just over 6ft) length the cost is still assumed to be \$50.00 as it was cut from a standard length. The die grinder used in the end of the steel tubing has a cost of \$915.00 (CAD) [60].

When the PERT Chart comparing the Formed Emery Head tool to the existing CNC method (Figure 5.2) is examined it is found that using the formed Emery Head would save approximately \$150/piece (USD). It should be noted that the CNC lathe solution is not perfect and some re-work may be required, increasing the costs further; however, the Formed Emery Head solution is also not at a production stage yet.

6.0 Conclusions

6.1 Contributions

The above chapters introduce designs for safe automated CNC polishing of aerospace components and a novel method to optimize the process. The Taguchi method was used to optimize the tooling parameters while PERT charts were used to optimize the overall process, by examining both times involved and costs associated with implementing each method. The time involved adds a new dimension to automated polishing operation, one which has been often overlooked. In manufacturing settings lead times often control make vs. buy decisions so the time involved with a process can be crucial. To date most researchers have not examined the entire manufacturing process in order to develop optimal automated polishing, opting instead to investigate the individual tooling parameters. Multi-objective Taguchi optimization was also examined for polishing purposes, to date researchers have concerned themselves with the finish obtained and have paid little attention to the final dimensions of the polished pieces. In reality many landing gear components have strict tolerances which must be observed. Often when strict tolerances must be observed it is necessary to perform tedious calculations of pre-polishing dimensions in order to ensure that there is no excessive material removal. The multi-objective Taguchi optimization was based on realistic weighting factors as opposed to a trivial average or a fitness function which also averages the results. Even by considering the importance of each factor the multi-objective testing has illustrated that when attempting to optimize functions the individual performance (ie. scale of S/N ratio's) plays an important role in the optimized results. While obvious in setting it sheds light on the fact that many tests are potentially being conducted with optimization driving the process.

This contribution may also be considered investigation into automated bore polishing, a research area that has not been extensively studied to date. To date very few researchers have investigated the possibility of requiring internal free-form features; focusing mainly on the external free-form features that are required in mould polishing. With increasing demand on safety, speed and repeatability internal polishing has become

often overlooked, when in fact internal dimension in many landing gear components such as pistons have tight tolerances and play a crucial role.

6.2 Discussion

With the development of the passive compliance polishing tools the optimized tooling parameters were discerned through the use of the Taguchi method.

The results of the Taguchi testing have shown that with the exception of the Dynangle Tool on the Aluminum it did not matter what the tool or material was the fastest relative polishing speed (as controlled by the spindle speed) yields the best results. Even though this result did not hold true for the Dynangle Tool on the aluminum piece the variation in the ANOM indicates that there was very little variation from the lower to the higher spindle speed.

With the case of the polishing force, most research has suggested that the greater the polishing force the greater the finish. When examining the Spring Loaded NC tool on both steel and aluminum this holds true and is further supported by the fact that the original Scotch-Brite test indicated that to obtain a 63 μ in finish (rather than one even better) the polishing force would have to be reduced in order to avoid over polishing. When testing the effects of the polishing force on the Dynangle tool the steel test showed that yet again the best finish was obtained with the most force; however, when tested on aluminum the lower force gave the best result. Again with very little change in the ANOM from one polishing force to the other there would be only a slight change. The results of the Dynangle Tool on aluminum do however; agree with researchers that feel that the best surface finish is not always obtained with the highest force. In the case of the Formed Emery Head tool the results yet again indicate that the lowest polishing force gives the best results; this however, is more likely due to the fact that when the polishing force is increased often the pneumatic drill slowed down, lowering the relative polishing speed. This result would lead one to believe that the relative velocity therefore has a greater effect on the surface finish than the force, as force is sacrificed for speed in the optimal setting.

While investigating the feed rate it was found that the results varied. In the case of the Spring Loaded NC tool it was found that the fastest feed rate yielded the best results. This is most likely due to the fact that the abrasives were either rinsed (in the case of early tests) or replaced between passes. By using a slow feed rate the material builds up on the polishing surface, inhibiting the polishing process; by switching the abrasives between passes and using a faster feed rate the entire work piece is more uniformly exposed to fresh cutting surfaces. In the case of the Dynangle tool the test on steel showed that the best results were obtained using the slowest feed. This may be due to the fact that the abrasive is rotating, allowing the work piece to be exposed to fresh cutting abrasives continuously, eliminating the need for a fast feed rate. When the Dynangle was tested on the aluminum again the results were opposite, although once again the ANOM indicates that there is little difference in the final results between the two methods.

Based on the results found in the Taguchi testing, for automated polishing it would appear that in general the best results are obtained from using the highest relative polishing speed and highest polishing force. Based on examining the results it would also appear that the selection of abrasive grit and feed rate depend greatly on the material being polished and the nature of the polishing tool.

By using PERT charts to examine a possible method of process planning it was possible to determine the optimal solution not only based on the quality of finish but also on time and cost. By looking at the PERT chart for the OD solutions it is obvious that the initial optimal settings for the Spring Loaded NC tool may have give the best results for one-pass polishing; however, when it came to the time and cost involved it was found that an optimized multi-pass polishing solution yielded the best results.

6.3 *Future Work*

As mentioned previously this work was intended to provide safe optimal polishing tools for CNC production. While the OD solutions have been optimized and put into production the ID Formed Emery Head solution was not able to be tested on production parts. Therefore, it is desired and necessary to re-manufacture the

polyurethane polishing head and conduct further tests. By testing the Formed Emery Head solution on a production part a more precise value for the set time could be used and actual cost savings verified.

Further research would also investigate the effects of CNC milling machine polishing to see if the conclusions drawn about polishing force and feed rate apply for milling type operations.

Other considerations for future work would be to refine the methods in which researchers are performing multi-objective Taguchi optimizations with the idea in mind that S/N scales may not be the same, and hence one process may be driving the results.

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Appendix A: Tool Designs

REV.	DESCRIPTION	BY	DATE	REASON

THIRD ANGLE PROJECTION	IF IN DOUBT - 2ND DO NOT SCALE THIS TAG.	DIMENSIONS IN DASHES UNLESS OTHERWISE SPECIFIED
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REAR VIEW

ISOMETRIC VIEW
(FOR REFERENCE ONLY)

REV.	DESCRIPTION	BY	DATE	REASON

REV.	DESCRIPTION	BY	DATE	REASON

REPORT ALL	1. DIMENSIONS SHOWN 2. DIMENSIONAL TOLERANCES	TO TOL. BASIS SHOWN	UNLESS OTHERWISE SPECIFIED: DIM. IN DASHES TOLERANCES: FRACTIONS DECIMALS ANGLES FINISH
REPORT ALL DIMS & SHARP EDGES UNLESS OTHERWISE SPECIFIED	TO BE SHOWN ON TOL. BASIS WHERE POSSIBLE, OR ETCHED.	UNLESS OTHERWISE SPECIFIED: DIM. IN DASHES TOLERANCES: FRACTIONS DECIMALS ANGLES FINISH	FINISH

Messier-Doty
Machine Group

CJ5753-49-03
Rotary Head

CATIA V5
6U890-28 Drawing

REV.	DESCRIPTION	BY	DATE	REASON

REV.	DESCRIPTION	BY	DATE	REASON

ISOMETRIC VIEW
(REFERENCE ONLY)

(7.880)
NOTE:
TO SHARP CORNER

0	1	5/16" - 18 UNC Hex. Socket Cap	Length 7/8"												
5	1	5/16" - 18 UNC Hex. Socket Cap	Length 5/8"												
4	2	Screw	Not Shown												
3	1	5/16" Spring Washer	Not Shown												
2	1	CC15250-209-03 Flange	Hot Rolled Steel												
1	1	CC15250-209-02 Bracket	Hot Rolled Steel												
1	1	CC15250-209-01 Tool Shank	Hot Rolled Steel												
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CC15250-209 Dynangle Tool Holder	CC15250-209 Dynangle Tool Holder	CC15250-209 Dynangle Tool Holder	CC15250-209 Dynangle Tool Holder

Appendix B: Sample Calculations

$$\begin{aligned}
 s &= \sqrt{\left(\frac{1}{n-1}\right) \sum_{i=1}^n y_i^2 - \bar{y}^2} \\
 &= \sqrt{\left(\frac{1}{3-1}\right) [(28.3^2 - 30.3^2) + (32.3^2 - 30.3^2) + (30.3^2 - 30.3^2)]} \\
 &= 2
 \end{aligned}$$

$$\begin{aligned}
 S/N &= 10 \log \left(\frac{\bar{y}}{s^2} \right) \\
 &= 10 \log \left(\frac{30.3^2}{2^2} \right) \\
 &= 2.3608
 \end{aligned}$$

$$\begin{aligned}
 S/N &= -10 \log \left(\frac{1}{N} \sum_{i=1}^n \frac{1}{y_i^2} \right) \\
 &= -10 \log \left(\frac{1}{3} \left(\frac{1}{28.3^2} + \frac{1}{32.3^2} + \frac{1}{30.3^2} \right) \right) \\
 &= 29.60
 \end{aligned}$$

$$\begin{aligned}
 SS_a &= \frac{1}{N} \sum_{i=1}^N S/N_{xi} \\
 &= \frac{1}{2} (30.239 + 12.21) \\
 &= 21.225
 \end{aligned}$$

$$\begin{aligned}
 MS_{Treatment} &= \frac{SS_{Treatments_Not_Pooled}}{N_{Treatments_Not_Pooled}} \\
 &= \frac{414.9}{3} \\
 &= 138.3
 \end{aligned}$$

$$\begin{aligned}
 MS_{Error} &= \frac{\sum SS_E}{N_{Factors_Pooled}} \\
 &= \frac{243.735}{1} \\
 &= 243.735
 \end{aligned}$$

$$\begin{aligned}
 F &= \frac{MS_{Treatment}}{MS_{Error}} \\
 &= \frac{138.3}{243.735} \\
 &= 0.56741
 \end{aligned}$$

Appendix C: Test Data

Spring Loaded NC Tool

Initial Scotch-Brite Test

Original 1 (μ in)	Original 2 (μ in)	Experiment 8 (μ in)
43.8	52.8	50.95
38.7	53.1	50
38.7	49	49.9

Experiment #	Uin	Uin	Uin
1	49	51.4	51.8
2	66	63.5	58.8
3	59.2	59.8	57.2
4	53.1	53.5	47.9
5	50.5	50.2	51.4
6	56.1	60	58.2
7	53.8	56.8	58.4
8	29.06	31.28	32.09
9	66.2	68.5	66

Emery Cloth on Steel Test

Initial Roughness

Experiment 1	85	87	82
Experiment 2	85	85	83
Experiment 3	85	80	87
Experiment 4	82	87	80
Experiment 5	85	87	82
Experiment 6	85	80	87
Experiment 7	85	80	87
Experiment 8	82	87	80
Experiment 9	85	87	82

Polished Roughness

Experiment 1	85	83	85	83
Experiment 2	87	85	85	85
Experiment 3	80	80	80	
Experiment 4	85	85	83	
Experiment 5	82	82	83	
Experiment 6	85	82	76	
Experiment 7	85	77	80	
Experiment 8	80	80	80	
Experiment 9	83	80	82	

Initial Diameters

Experiment 1	2.305	2.3055
Experiment 2	2.1472	2.1472
Experiment 3	1.9888	1.9886
Experiment 4	1.9889	1.9889
Experiment 5	2.305	2.305
Experiment 6	1.9888	1.9886
Experiment 7	1.9888	1.9886
Experiment 8	1.9889	1.9889
Experiment 9	2.305	2.305

Polished Diameter

Experiment 1	2.3046	2.3045	
Experiment 2	2.1468	2.1471	2.1471
Experiment 3	No Change	No Change	
Experiment 4	1.9885	1.9885	
Experiment 5	2.3046	2.3046	
Experiment 6	1.9887	1.9887	1.9886
Experiment 7	No Change	No Change	No Change
Experiment 8	1.9886	1.9886	
Experiment 9	2.3047	2.3048	

*Emery Cloth on Aluminum Test***Initial Roughness**

Experiment 1	91	95	93	
Experiment 2	80	77	95	
Experiment 3	79	79	85	
Experiment 4	102	80	77	80
Experiment 5	85	80	77	82
Experiment 6	90	82	80	79
Experiment 7	82	77	96	82
Experiment 8	79	79	79	79
Experiment 9	85	77	82	

Polished Roughness

Experiment 1	91	85	87	
Experiment 2	63	65	79	
Experiment 3	65	66	69	
Experiment 4	77	77	77	
Experiment 5	69	69	71	71
Experiment 6	76	71	76	71
Experiment 7	69	74	76	66
Experiment 8	69	71	69	
Experiment 9	47	49	50	

Dynangle Tool

Steel Test

Initial Roughness

Experiment 1	83	82	82	
Experiment 2	80	83	82	
Experiment 3	80	79	79	
Experiment 4	82	82	74	82

Polished Roughness

Experiment 1	54	50	52	
Experiment 2	47	47	46	
Experiment 3	74	77	79	
Experiment 4	49	50	52	52

Aluminum Test

Initial Roughness

Experiment 1	90	88	95	98
Experiment 2	90	88	95	98
Experiment 3	106	107	107	
Experiment 4	106	107	107	

Polished Roughness

Experiment 1	50	57	47	54
Experiment 2	54	57	60	65
Experiment 3	55	55	58	
Experiment 4	65	61	58	

Formed Emery Head Tool

Static Test

Initial Roughness

Exp 1	96.3	75.2	69.4			
Exp 2	59.1	55.9	44.6	40	52	
Exp 3	105.3	120.9	118.3	101.6		
Exp 4	89.8	97.6	102.3	125.6	161.5	161.3

Polished Roughness

Exp 1	59.1	55.9	44.6	40	52
Exp 2	33	49	47	46	
Exp 3	52.9	72.3	77.2	122.3	49.6
Exp 4	117.2	87	128	134.6	100.2

Rotary Test

Initial Roughness

Exp 1	147.9	126	105.5	132.2	111.2
Exp 2	33	49	47	46	
Exp 3	117.2	87	128	134.6	100.2
Exp 4	52.9	72.3	77.2	122.3	49.6

Polished Roughness

Exp 1	62.1	30.9	90.9	87.4	91.7
Exp 2	30	41	36	44	
Exp 3	79	55	63	54	
Exp 4	27	38	39	36	29