Optimizing the Economic Efficiency by Micro-drill Life Improvement during Deep-hole Drilling in the 212-Valve Manufacturing Process

by

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Abstract

The micro-drilling process by robodrills in the production of valves at Waters Corporation is the bottleneck caused by the short drill life. This thesis analyzed the chip formation and removal during the process to improve the tool life. The effects of the tool materials, geometry and peck drilling procedures were investigated. Based on these studies, a new micro drill bit, TY130, was selected from the commercial market and the test results for drilling 0.2794 mm holes in the workpiece made of 316-stainless steel showed that it lasted for 120 holes, 5 times longer than the currently used drill bit. An experimental study on various peck drilling procedures demonstrated the advantage of the quadratic pecking procedure, further increasing the tool life by 2 times. Upon the implementation of the new drill bit and the quadratic pecking procedure, the 212-Valve production lead time is estimated to be reduced by 11% and the EDM process will not be starved since the bottleneck process has been improved.

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Chapter 1

Introduction

1.1 Motivation

Waters Corporation is a leading manufacturer of high performance liquid chromatography (HPLC) systems, mass spectroscopy and associated products such as chromatography columns, chemical reagents and valves sample extraction instruments and chemical reagents. The current manufacturing for valves— a critical sub-assembly of HPLC systems— is carried out in a separate manufacturing cell called the valve cell that manufactures 28 different types of valves. Among all valves, the 212-Valve is the one which the Waters pays the most attention. This is because of the 212-Valve's large annual demand volume as well as its latest design which helps win over the competitors.

The 212-Valve production system involves 15 steps, and those steps are shown in Fig. 1 in order of operations: (1) turning, (2) milling, (3) robodrilling, (4) cleaning, (5) primary de-burring, (6) cleaning, (7) wire electrical discharge machining, (8) cleaning, (9) de-burring, (10) cleaning, (11) lapping, (12) passivation, (13) vacuum cycling nucleation cleaning, (14) critical clean and (15) packaging.

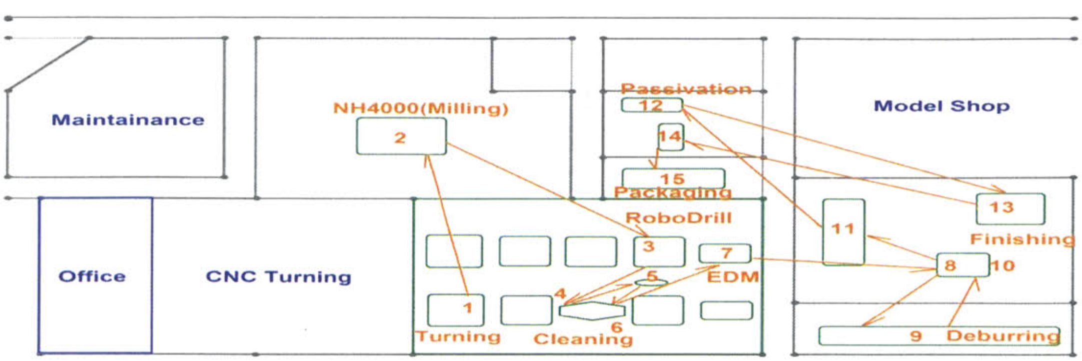


Figure 1.1: 212-Valve manufacturing cell layout and process flow

The production system is seen to have the problem of inefficient material flow. This is in part due to the broken micro drill and excess scrap associated with that discontinuous process; the imbalanced manufacturing line causes inventory build-up. Also, due to the highly diversified nature of the production line, this discontinuity causes numerous complications in the scheduling of orders. With higher expected demand in future, the problem is likely to compound itself, because it will result in much higher waste and scrap rate, not to mention backlog and excessive work in process (WIP) inventory, and a much longer average lead time on all parts.

1.2 Objective

The primary objective of this project was to implement manufacturing process and system improvements in the valve cell of Waters Corporation at their Milford, MA facility. In order to achieve these improvements, the project was divided into three main areas: process improvement, efficient inventory management and lead time reduction. Each team member is in charge of one area and delegates responsibility to other team members in his/her area based on expertise. This author was in charge of increasing micro drill life cycle for effective process improvement, Snegdha Gupta [1] was responsible for implementing efficient line balancing for sizeable inventory reduction and Bingxin Yao [2] was responsible for establishing an optimum push-pull system for significant lead time reduction. More specifically this translates to three main objectives:

- Improve micro-drill performance in deep-hole drilling by increasing the drill life
- Determine the optimal push-pull interface for lead time reduction and proper inventory management
- Develop a balanced line to significantly reduce WIP and make therefore make the system more lean

1.3 Problem Statement

Robodrilling process is determined to the bottleneck of the whole 212-Valve production system. And the micro-hole, 0.2794mm, drilling process is the bottleneck of the Robodrilling process, which is because that the micro drill bits could break at the forth part before the replacement approaches. This is a problem with significant magnitude that Waters suffers most. For the past two+ years, the company has been spending its time and many resources on investigating the root causes of its operation and where there is room for improvement in this specific drilling process.

Over the course of the two years of troubleshooting its micro drilling processes, Waters elected to change drill bits more than once to see if that had anything to do with the inconstant results it was getting. To change brands and administrative process alone is a large undertaking for a company, let alone the impact it may have on the factory floor. An important factor for Waters was that it maintains a steady production rate while undergoing this internal analysis. In order to achieve the desired rate, it was crucial to use every drill to its maximum durability capacity – ideally, find a threshold for where it knows the "breaking point" of the drill, and using said drill until it gets as close to that threshold as possible without going past the breaking point.

Selecting the proper tool and cutting conditions are the most important factors when attempting to optimize the economic efficiency of this drilling process. The term of economic efficiency is defined as producing same amount of valves with same or better quality, all the while lowering overall production cost and reducing cycle time – two critical elements of any manufacturing operation. With the better tool life performance, the number of tools used can be reduced significantly and the "down time" during production is limited. In the meantime, the micro-drill that lasts longer can improve the product's quality rate as well as create the opportunities to longer turnover cycle, therefore reduce the cycle time.

In this thesis, background information about micro drilling process and micro drill bits is introduced in Chapter 2 as well as the results from previously done work. Chapter 3 analyzes the micro drill bit material, geometries and cutting conditions. The designed experiments and test results are discussed in Chapter 4. Chapter 5 shows the effect of the robodrilling improvements on the system. The final recommendation and conclusions are described in Chapter 6 and Chapter 7.

Chapter 2

Technical Background

The goal of this project was to optimize the economic efficiency of the whole 212-Valve system processes by improving the micro drilling process performed on a robodrill machine equipped with a 24,000 rpm max spindle. The economic efficiency of this process is measured by both cycle time and overall cost based on similar or better quality level. In the current process, the conventional micro drill from Japan Union Tool produces approximately 26 holes before replacement. Due to this tool life, the current process requires the company to change the micro drill bit every two machine runs during production. This causes frequent stoppage in production, which creates issues on many levels; namely, it interrupts the material flow and it creates a great deal of waste. Chapter 2 provides the technical background information on the micro drilling process and the basics of the micro drill bit. This chapter will also explore several recommendations of improvement. These recommendations were generated from similar processes that were based on a combination of research and literature review.

2.1 Introduction to Micro-drilling

Drilling is one of the most fundamental machining technologies categorized as "material removal" process. It is an operation in which the drill bit rotates with an axial displacement. The most common and widely used drilling process is making holes, which counts as 75% on all mechanical parts worldwide [3]. With the increasing development of drilling technology and the booming market need for super precision applications, micro-hole drilling is becoming extremely popular and prominent in a variety of industries. This is particularly apparent in certain precision industries, such as chemistry, aerospace, watch, modern medical devices and computer industries. Some examples of applications include liquid injection nozzles Waters Corporation servers at, watch components, electronic printed circuit boards (PCB) and micro sensor in transportation.

The growing competition in applications of micro parts motivates the development of micro features, even improving some technologies like the micro-hole drilling application. Except for mechanical micro drilling, other alternative drilling processes are electrical discharge machining (EDM), laser micromachining, electrochemical micromachining and some others. The mechanical micro-drilling process is still the most preferred choice by manufacturers when analyzing from a cost standpoint, considering suitable workpiece material and its properties and minimizing surface finish work. Short processing time is also a big advantage of mechanical micro-drilling relative to other nontraditional processes mentioned above.

2.2 Basics of Micro-Dill Bits

A drill bit with a diameter of less than 3.175 mm is defined as micro drill [3]. Micro-drill bits are used in a variety of operations from maintenance to high volume precision hole-making. Selecting the right micro-drill is critical to any micro drilling process. Therefore, it is important to take all possible variables into consideration to obtain satisfactory tool performance, such as tool material, coating and geometries including diameter, flute length and point angle.

2.2.1 Tool Materials

According to the theoretical derivation and experimental proof, chips of small size formed during the hole-drilling process cause high stress on the cutting edge of the drill tip and ultimately lead to fatigue and subsequent breakage. As a result, choosing the right material for micro-drill is crucial for micro drilling. An ideal material must have the required hardness and wears resistance at elevated temperatures. Some of the more common commercially available tool materials include, high speed steel (HSS), solid carbide, cermet, and polycrystalline diamond (PCD). Among these, HSS and carbide are most widely used in the micro-drilling industry because of its favorable price to quality ratio.

2.2.1.1 High Speed Steel

HSS is the preferred choice by many manufacturers when considering good tool life as well as minimal cost. In addition to the basic composition of iron (Fe) and carbon (C), HSS alloy often includes other elements, including chromium (Cr), tungsten (W), molybdenum (Mo), vanadium (V) and cobalt (Co). In order to achieve different mechanical properties, the amount of these materials are usually controlled and combined in set amounts. This can increase the hardness of the material which will allow the drill to last longer at elevated temperatures. The development of high speed steel has a long history. The many different types of HSS are assigned names by American Iron and Steel Institute (AISI). M1, M2 and M7 are mainly used for cutting material like carbon steel, aluminum and brass. The added cobalt in M35 and M42 creates better thermal properties than regular HSS, thus making it a better option for cutting harder material.

2.2.1.2 Carbide

Carbide is usually the best choice for a drill material. It is first sintered from random coarse carbide grains in a Co matrix with optional element Mo or Cr added, then ground to be finer and lapped into final geometry. It has a better hardness level and heat resistance when compared with HSS. Ultra fine-grained (0.2 μm to 0.8 μm) high strength carbide with W and Cr added allows for producing a harder, shaper cutting edges, and can help prevent drill breakage due to less than ideal consequences such as interrupted cuts, spindle vibration and chip packing. Brittleness and the possibility of chipping are increased with the use of carbide, but can be significantly reduced when the proper tool and cutting parameters are used.

MA Ford manufacturing company Drilling Production Manager, Joe Krueger pointed out that the high wear resistance of carbide allows for micro-drill speeds of up to three times that of high speed steel, with added life expectancy by two times as well [4]. The high rigidity of carbide also helps maintain hole position and size.

While different compositions of carbide are available, ISO and ANSI have yet to create a standardized method of distinguishing between types. Drill performance can vary greatly from company to company based on their different technologies.

2.2.2 Coating treatment

Coating treatment is achieved by adding a thin (0.002mm to 0.015mm) layer of harder material to the surface of the tool. This thin layer can improve surface properties such as hardness, lubricity, and heat resistance. The common materials used in coating commercial tools are TiN, TiCN and AlTiN. They are applied in mono/multi-layer or gradient structure using different technologies. One method for depositing a chosen coating is called medium-temperature chemical vapor deposition (MTCVD). MTVCD is one of the best ways to provide better wear and heat resistance when machining a high ductile material such as stainless steel. The benefits of current coating technology are undisputable when applied to macro machining, however, this technology is still a great challenge in micro machining due to the size of tools and somewhat unpredictable uniformity and surface smoothness of the various coating available. While the coating thickness can be as little as 0.002mm, even this small amount can affect drilling performance by increasing the dimension of the drill tip and reducing the sharpness of the cutting edge. As Heinemann tested in his experiments, a drill coated with a standard arc-evaporation process, while inexpensive, produces an unacceptable surface finish [4]. While an advanced coating technology with a thickness of less than 0.0015mm is currently possible, an experienced Waters engineer stated that tool life gains are not beneficial at cost-performance ratio.

2.2.3 Geometries of micro-drill

Geometries of micro-drill are the same as those of macro drill, which include drill diameter, flute length, point angle, helix angle, number of flutes, shank diameter as shown in Fig. 2.1.

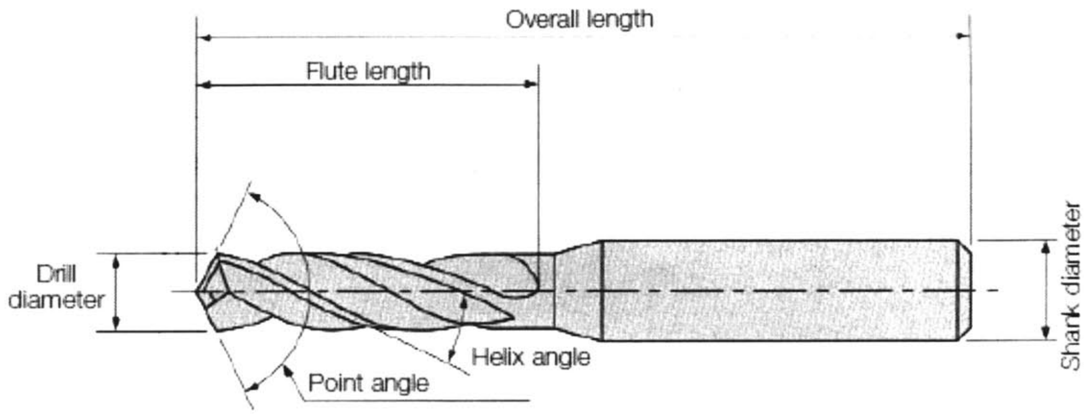


Figure 2.1: Micro-drill geometry glossary [3]

Choosing a drill diameter comes first when selecting a tool. Drills will tend to cut oversize rather than undersize and this factor should be taken into consideration. Drill diameters begin as small as 0.025mm and increase in 0.005mm increments. Generally, any diameter larger than 3.175mm is no longer considered to be a micro drill. Flute length is another key factor that is determined by the depth of hole being drilled. It is optimal to use the shortest flute length possible, while still allowing adequate chip removal. Stiffness is a measurement of rigidity and flute length is one of most important determining factors. High rigidity allows the drilling process to be more stable with increased tool life. Point angle is one of the determinants of tool sharpness. It has an effect on thrust force and torque, along the cutting edge, which ultimately decides the size of the chips. According to tool makers, a small angle of 90° is mostly used for soft materials and a larger angle greater than 130° is best for performance in hard materials. Also, the flatter the point angle is the smaller the chip size will be, with all other parameters being equal. Helix angle is another factor determining tool life and performance. It is not unlike the cutting angle in a simple horizontal cutting process. Helix angle is affected by number of flutes, flute clearance (web thickness) and flute style. The typical helix angle of commercial micro-drills is 30°.

2.3 Problems of micro-drilling

The current available micro-drills on the market can machine deep holes with depth-to-diameter ratios of larger than 5. The interior of the hole is satisfactory with smooth surface and great concentricity. However, micro-drilling faces several problems such as tool breakage, tool wear and the appearance of burrs. Short drill life is the critical issue Waters Corporation is suffering from when drilling micro deep holes on stainless steel material. The history of micro drilling is limited, and the limited research results available have revealed that most reasons are related to chip formation. Therefore, in this section of the thesis, mechanics of chip formation, tool breakage and how previous work has been done to improve micro drill performance will be discussed.

2.3.1 Mechanics of chip formation

Studies on chip formation had been started on macro scale machining since early 1940, and several experimental results have revealed that chips are produced by shearing. When the shear strain is excessive, the deformation of workpiece material will move from elastic region to the plastic region, causing breaking material apart and producing the chip. This was examined to be true for both macro machining and micro machining by monitoring the cutting process. The experimental results also showed that the shear strain is largely affected by shear angle or rake angle. In the drilling process, rake angle can be computed from point angle and helix angle. The small helix angle as well as small point angle would generate the large rake angle, which causes the increase in friction force at the tool-chip interface and causes the chip to become thicker [5].

In addition to the different angles, chip size is dependent on the depth of cut as well. The deeper the hole being drilled, the more material is removed. With constant volume of flute, the length of chip will be increased as drilling the process goes on. Heat is another factor that affects the chip shape. Previous studies indicated that 90% of thermal energy created by drilling work is carried on the chips and temperature distributed at the higher value when closer to the tool-tip interface. With the wide margin between chip temperature and room temperature, chips are intent to be broken into pieces when the margin grows larger.

Typically, there are four basic kinds of chips produced in cutting process: continuous, built-up-edge, segmented and discontinuous. Continuous chips are usually formed when drilling the ductile material at high speed performance. Discontinuous chips on the other hand are mostly formed with brittle material at extreme performance with large depth of cut and lack of efficient cutting fluid supply. Built-up-edge chips are commonly observed in all of the cutting processes. Small amounts of workpiece material are removed by large shear strain gradually adheres or packs into the cutting edge and built up as the time goes. Segmented chips are usually produced on the low thermal conductivity material.

2.3.2 Failure modes of tool breakage

As the drilling is a kind of material removal process, chip removal is the one factor that needs to be considered. Especially during the deep micro hole drilling process, chips are not easy to be removed and sometimes become jammed inside the flute, which generates extra stress and heat on the drill which leads to a shortened drill bit life.

The tool failure mechanisms caused by chips can be summarized into three major factors: mechanical effect, thermal effect and adhesion [3]. These are illustrated in Figs 2.2 through 2.4. Mechanical effect is the most common source of micro drill bit breakage. Drill bit sliding from hole's round interior and cutting against hard particles of workpiece can cause the abrasive wear; therefore, one or more grains of tools would be weakened at their grain boundaries leading to premature failure.

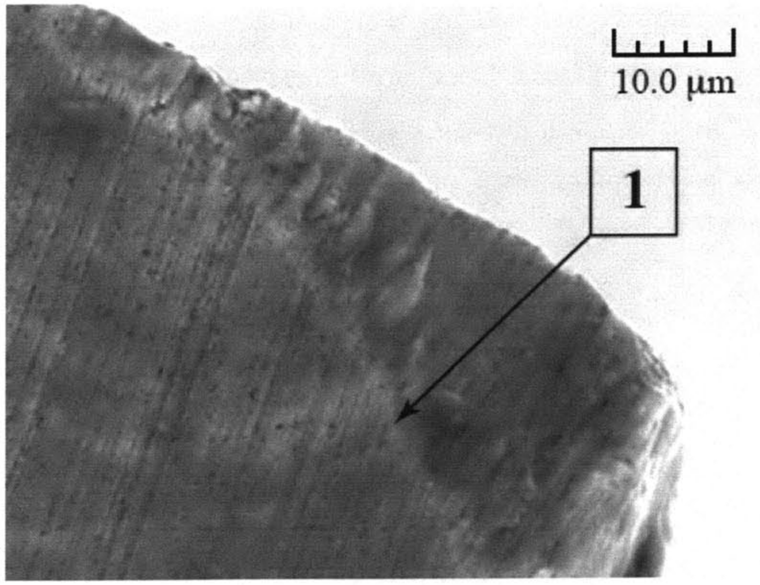


Figure 2.2: Abrasion with progressive wear from center to edge (label "1") [3]

The second source is thermal effect. With the heat generated from a chip jammed inside the hole, the drill bit cutting edge can be softened at high temperature, deformed and switched from elastic region to plastic region and therefore results in tool damage. Based on the research results, both high speed steel (HSS) drill bits and carbide drill bits are susceptible to thermal damage. Diffusion is another consequence of thermal damage, because of which, atoms from the drill bit and workpiece mutually move across their surface margin causing degrading their properties so as to break the drill bit [3].

A built-up-edge (BUE) is defined as an accumulation of workpiece material on the cutting edge of the bit is a major source of tool breakage. The chip is likely to adhere to the drill bit and changes the tool geometry, which reduces the radius of cutting edge and sharpness. The built-up-edge also leaves a lower amount of space for the chip generated in the next step. This can worsen the chip removal process and increase the friction between drill bit and workpiece. The jammed chip often generates more stress and heat that can cause to the drill bit to break much easier.

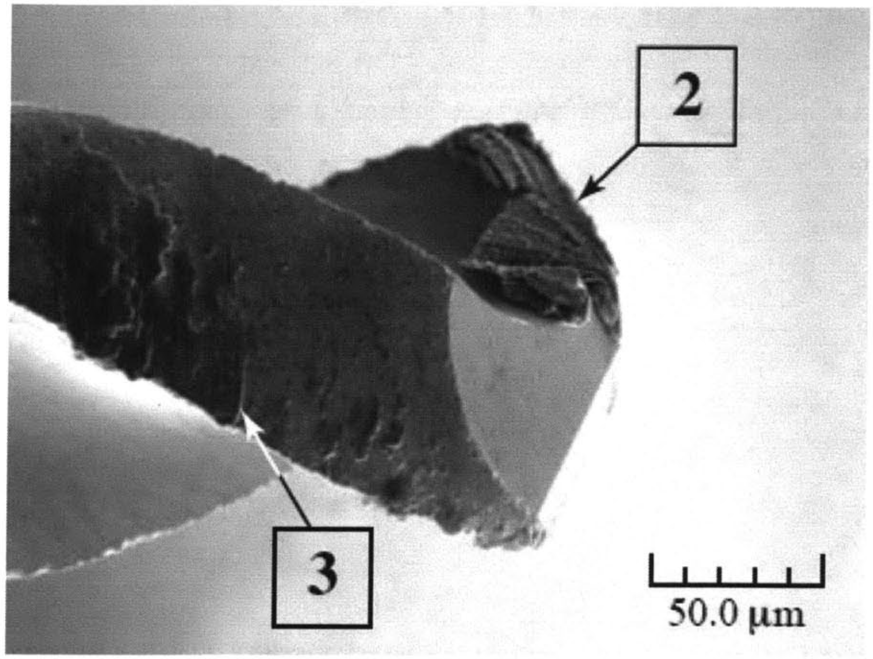


Figure 2.3: Built-up-edge at cutting lip (label "2") and side (label "3") [3]

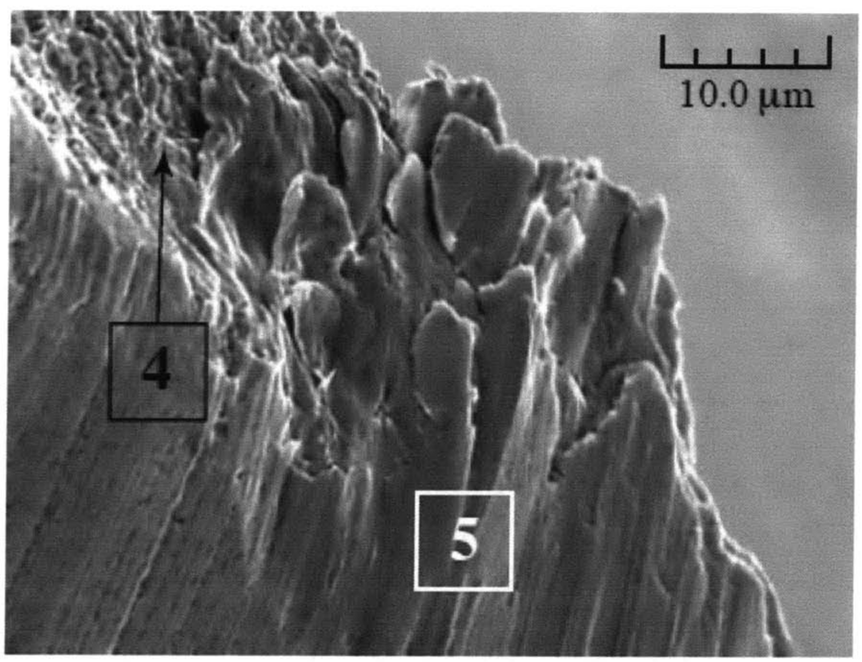


Figure 2.4: Adhesion wear (label"4") due to built-up-edge on a micro tool (label"5") [3]

2.4 Previous works of solving tool breakage problems

Researchers and tool makers worldwide have started investigations on the breakage of micro drills and have concluded several positive results from an academic point of view [3]. The factors being analyzed are, chip formation, tool point angle, starting hole, cutting conditions including spindle speed and feed rate, coolant, and peck drilling.

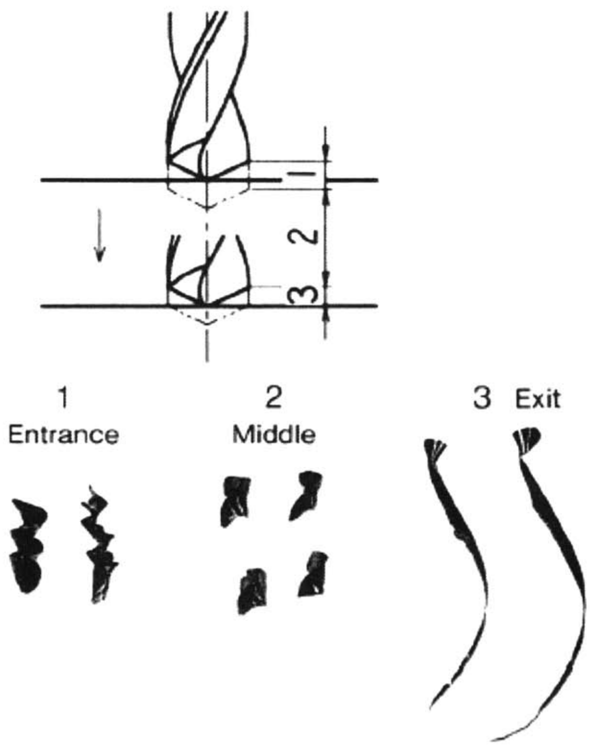


Figure 2.5: Chip form at each stage of the drilling process [6]

Chips are mostly formed to be continuous chip type as the drill bit enters quickly to remove the material from the workpiece since the great thrust force causes the workpiece material to become deformed plastically. With the cutting zone located deeper and deeper within the workpiece, the thermal load on the tool is increased significantly. As the torque changes in relation with the depth of the hole and in difficulties the chip removed from hole, the chip formed at each stage of micro-drilling process are different in shape. As it is shown in Fig. 2.5, the chip is medium at the entrance, shorter in the middle and longer approaching to the exit. A tool maker, Jianling Tech, pointed out that long curly chips tend to adhere to the space in the flute, which prevent the coolant from going through to reduce the temperature and lubricate the drill tip [6]. Chips that are too short are easily clumped together and then pack inside the drill's flutes, which generates more stress and heat to shorten tool life. Ted Xu at Jianling disclosed a tip that size of short chip is the major factor they consider when they provide recommendations on feed rate. By adjusting to a well-chosen chip removal rate, the micro drill can last longer in deep-hole drilling performance.

As to any deep hole drilling process, it is believed that the first few turns are critical since the drill bit bears eccentric force. Any roughness or irregular shape on the workpiece surface would cause the lateral sliding, resulting in deviation and bending force in perpendicular direction of the tool axis that causes the tool breakage. In order to achieve better performance, spot drilling is highly recommended. Spot drilling gives the micro drill a chance to establish more contact area with the workpiece, thus helping the drill to engage in the desired location more precisely and efficiently during the initial stage. Once the entire drill tip gets engaged inside the hole, the drills margins and cutting edge corners guide the drill to move forwards, which assures the hole's straightness and reduces the friction against the wall of the hole [7].

Based on the analysis of two cutting edges contact area and friction force, Mitsubishi concluded that the starting drill (pilot drill) point angle should be smaller than or equal to the micro drill point angle to reduce the unwanted forces created during the initial drilling steps so as to make the drilling process run smoothly [8]. Konig and Hoff [9] pointed out that by reducing the drill's point angle, the thrust force generated in the drilling process can be lowered and the location error can be avoided. Similarly, Heinemann ran several experiments based on different configuration of starting hole with micro drill point angle 130° and observed that in the case of configuration B (120°) and configuration C (130°), the smaller difference in point angle between pilot drill and micro drill has the better force concentration and control of engagement. The comparison is also analyzed by using average tool life testing, whose results are summarized and plotted in Fig. 2.6 [4].

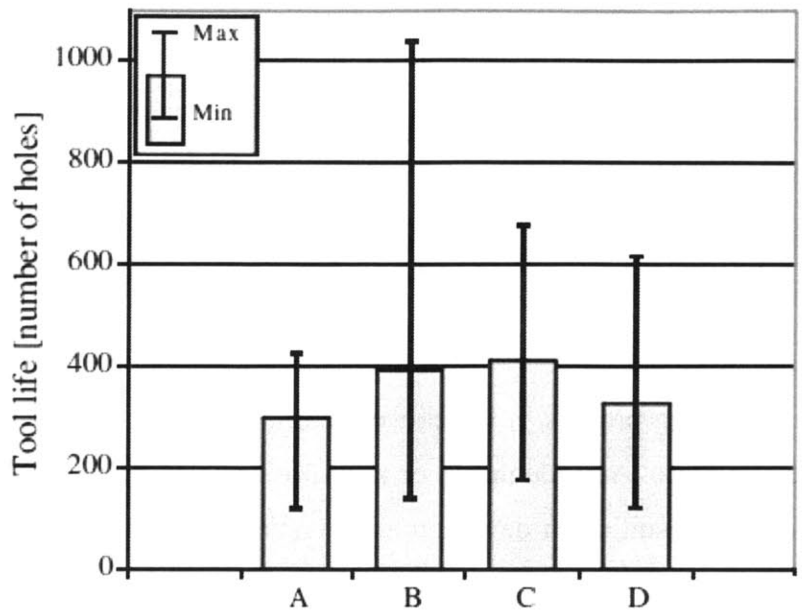


Figure 2.6: Average tool life of twist drills for starting drill configurations A to D, A: 90° starting hole, B: 120° starting hole, C: 130° starting hole, D: 150° starting hole [4]

With respect to the cutting conditions, spindle speed and feed rate are two major factors that need to be explored carefully in order to balance the machining productivity and the yield quality. The material removal rate can be obtained by multiplying spindle speed, feed rate by area of drill cross section. The faster the material removal rate is, the less amount of time each hole-drilling process will take. On the other hand, aggressive drilling pushes harder on the drill tip at every stage, and this leads to a number of negative consequences, including a broken tool. The 29th machinery handbook [3] recommends using a CNC machine capable of spindle speeds of 25,000 rpm or higher. The exact value can be calculated by using Eq. 2.1. This will be further discussed in Chapter 3.

$$N = \frac{V}{\pi \times D} \tag{2.1}$$

where N is the spindle speed (rpm), V is the cutting speed (fpm or m/min) and D is the drill diameter, respectively

As to feed rate, researchers and some of those in the tool making industry do not necessarily share the same opinion on this particular matter. Machinery handbook uses the following equation to convert chip load of a cutting edge to feed rate of the micro drill. Chip load value is determined by empirical values.

$$f = C_L \times n \tag{2.2}$$

where f is the feed rate of drill bit (mm/min), C_L is the chip load of a cutting edge (mm/tooth) and n is the number of cutting flutes (# teeth/rev), respectively

With the difference in workpiece material properties, tool properties and the drilling process, tool makers usually have their own recommendations - this will be discussed in Chapter 3.

Coolant helps lubricate the heat generated drilling process and remove the chip. However, in the micro-drilling process, coolant cannot always flow into the drilled micro hole effectively. Researchers have studied on the selection of cutting fluid, flow rate, and angle between nozzle and micro drill and found a variety of conclusions. A cutting fluid with low viscosity, high thermal diffusivity, and good lubricity is required to obtain an optimal micro-drilling performance. Different brands will have their own proprietary technologies which make their products outstanding. The drop size depends on the supplied air pressure and volume of oil for atomization [3]. In normal cases, the higher air pressure and higher coolant flow rate, the more uniform and smaller the drop size will be. As small droplet can dissipate the heat more efficiently, this prevents the drill bit from being softened by high temperature. An appropriate angle between nozzle and micro drill can be computed from the Eq. 2.3 [3] and be final determined by minor adjustment.

$$\frac{P}{V^{1/3}} = \left[\frac{24}{\pi} \times \frac{(1 - K \times cos^2\theta)^{3/2}}{2 - 3 \times cos\theta + cos^3\theta}\right]^{1/3} \tag{2.3}$$

where P is the projected droplet diameter (mm), V is the droplet volume (mm3), θ is the contact angle (°) and K is 0 for θ between 90° and 180°, 1 for θ between 0° and 90°, respectively

Micro drills are usually slender with low rigidity, and because of this, their length-to-diameter ratio is very high. Even under the consequence of the starting holes drilled for better engagement with all other aforementioned benefits, a tool failure phenomenon is still happening during the direct drilling suffered by many companies, including Waters Corporation. To reduce this problem while maintaining productivity, peck drilling is widely employed for a more effective micro drilling process. It is the operation that periodically retracts and re-inserts the drill bit that is illustrated in Fig. 2.7. This process removes a lower amount of chip, but more frequently. Benes pointed out that chip removal during drilling can be very difficult, especially for micro deep holes in ductile workpiece material [10]. Peck drilling helps prevent the flute from getting jammed by accumulation of chip generated during the process. Besides, these periodic interruptions during the drilling process allows the drill to be cooled down as well as getting become re-lubricated so as to remove the heat more effectively when cutting fluid is restricted provided and therefore to extend the drill life.

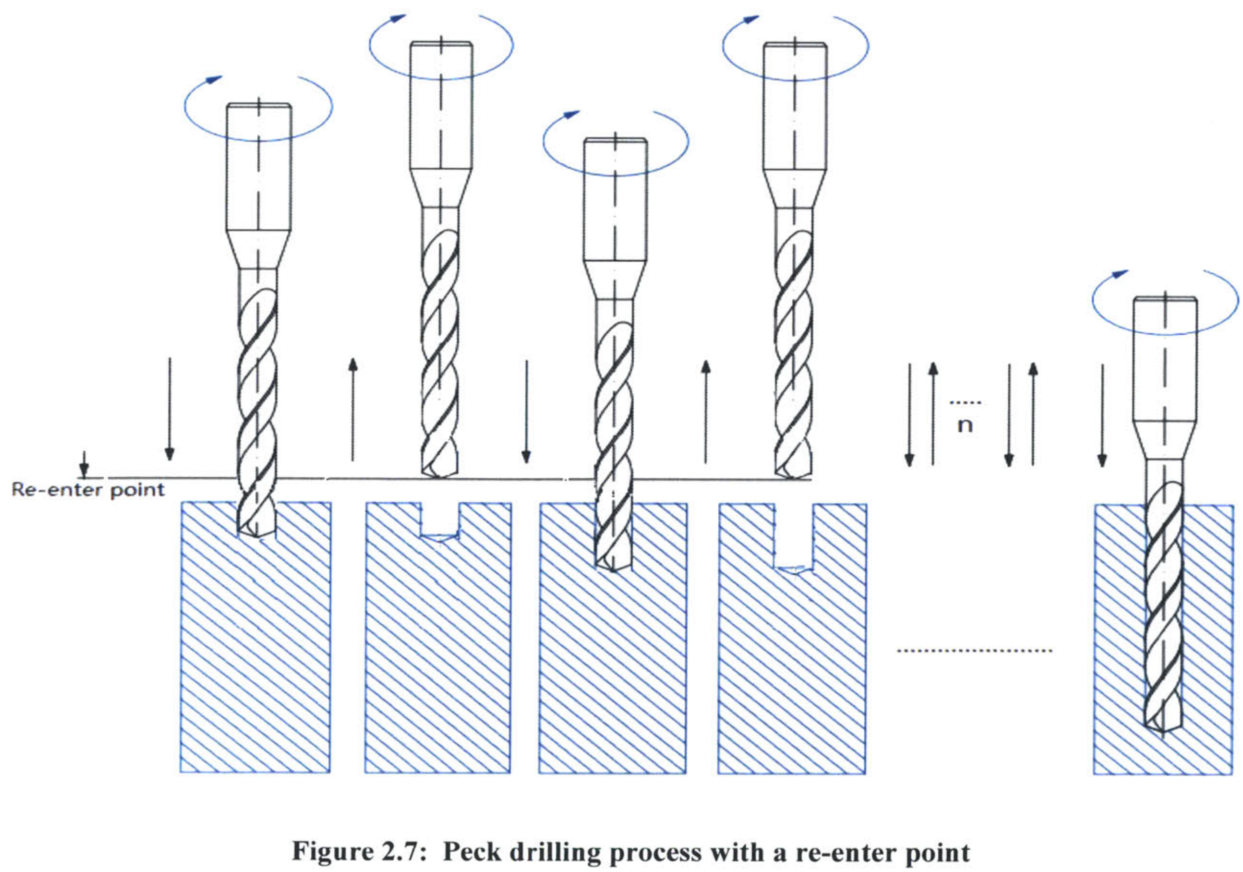


Figure 2.7: Peck drilling process with a re-enter point

Bagci and Ozcelik [11] experimentally observed that temperature at the drill tip was reduced as peck drilling implemented measured by standard thermocouples inserted through the coolant hole. Kim et al. [12] proposed a method to monitor the thrust force during micro-deep-hole drilling process by using dynamometer, PMAC controller and computer monitoring system. The amplitude of the high-pass filtered signal was analyzed to prove that the drill got worn as drilling depth became deeper. The thrust force plot in Fig. 2.8 indicated that the worn drill breaks after the sharp increase in thrust force over a period of machining time. In their studies, peck drilling is recommended to reduce the thrust force by frequent retracting the micro drill bits.

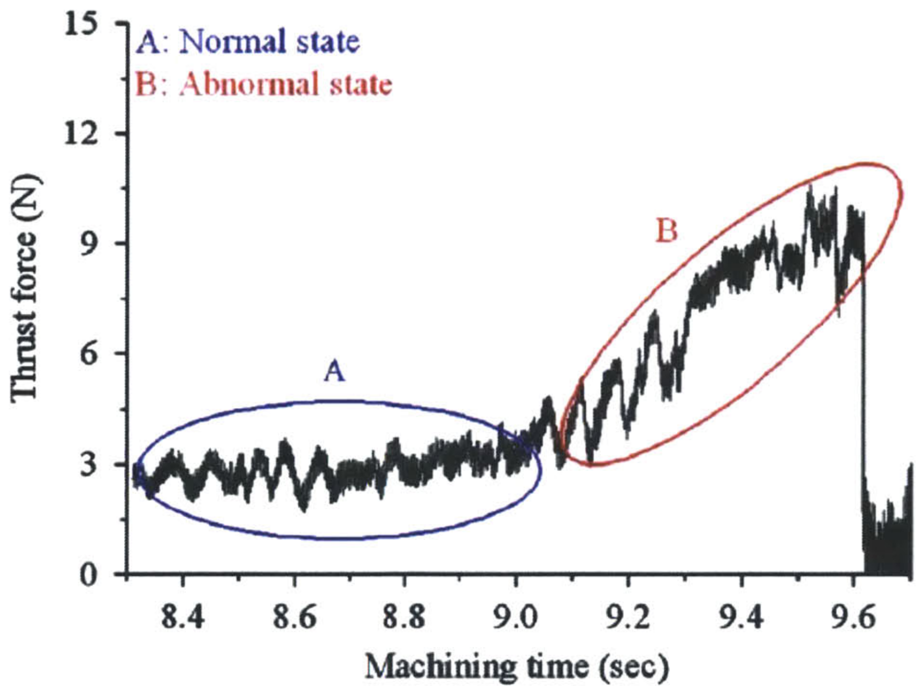


Figure 2.8: Variation in thrust force according to the machining time prior to drill breakage [12]

Chapter 3

Analysis of Variables

The evaluation of the current drilling process indicates that the changing of the conventional micro-drill every 4 parts (24 holes) is not good for productivity. A new drill that can produce more holes under the better cutting conditions is urgent to be found in order to increase performance. Based on background studies and previously tested results performed by Waters' engineers, this chapter's emphasis is on the analysis of both the specifications of the tool itself as well as the cutting conditions. Especially tool material, tool geometries and peck drilling procedures.

3.1 Micro-Drill

3.1.1 Material analysis

To better understand the drilling process, the workpiece that will be drilled on should be studied first. The workpiece material is 316-stainless steel which is annealed and has a hardness value between 135-185 BHN. This material belongs to a hard material class and has very high ductility. The heat resistance is relatively good, while published data shows that when the temperature is elevated up to more than 500°C, several grains can transform to a very brittle phase called sigma [3] and become depleted in Cr and some other elements, leading the material to lose its corrosion and thermal resistance. Thus, chips would adhere to the carbide drill much easier and eventually drilling performance would be affected.

Therefore, an ideal micro drill must have higher hardness and be capable to withstand an elevated temperature under very high speed cutting conditions. Waters Engineers had completed several analyses on micro drilling process and eventually switched from a micro-drill with material of HSS to a carbide drill since their studies showed carbide achieving the better performance between the two. To have the better sense of material when selecting drill, ESD test was conducted to measure the material of the current carbide drill. Fig. 3.1 by a scanning electron microscope (SEM) shown in Fig. 3.2 at Waters identifies the element compositions of current conventional drill that have C, Co and W added. Tungsten has high value in hardness which improves the hardness of drill. Cobalt binder provides the drill with better wear resistance and toughness, which allows the drill perform well under the high speed condition and still remains durable. However, the weight percentage of Co that counts 0.41% is relatively low. This creates the doubt whether cobalt added really helps or not. HSS's classification and experimental results demonstrate that M42 that has highest Co percentage of 8% performs much better than M35 that has 5% Co. Thus, another question raised is if more cobalt can be added to the carbide so as to increase wear resistance of the drill and result in a better performance. Market research on published material data from several carbide making companies found out that weight percentage of cobalt can be up to 2% in tungsten carbide.

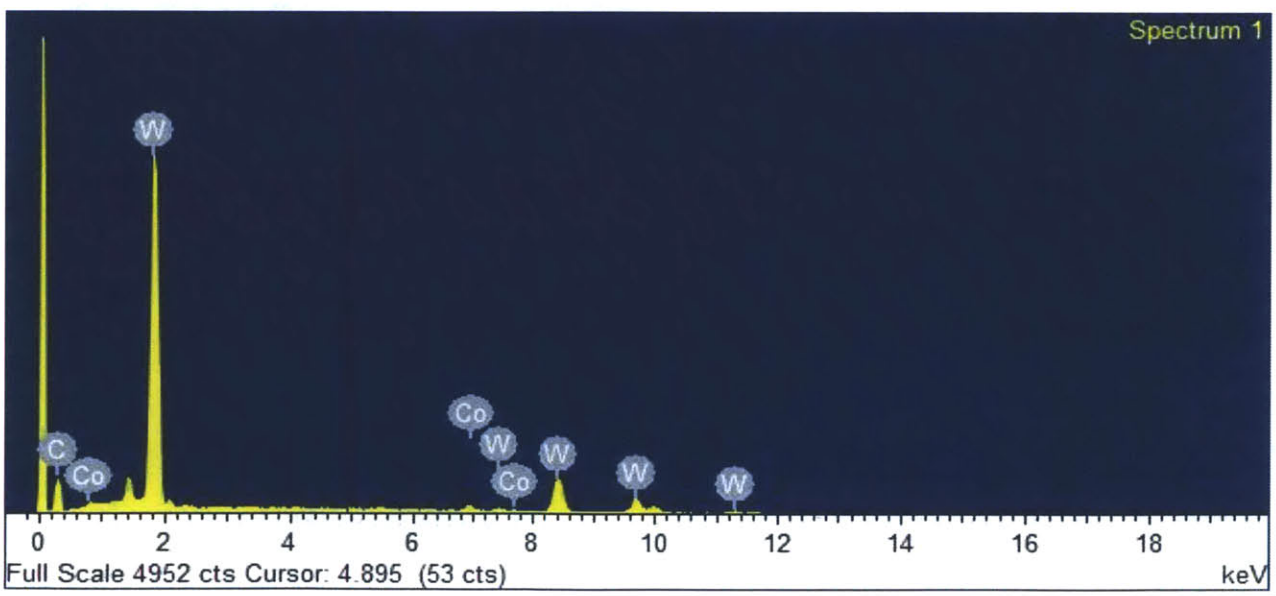


Figure 3.1: Material analysis of the conventional drill bits

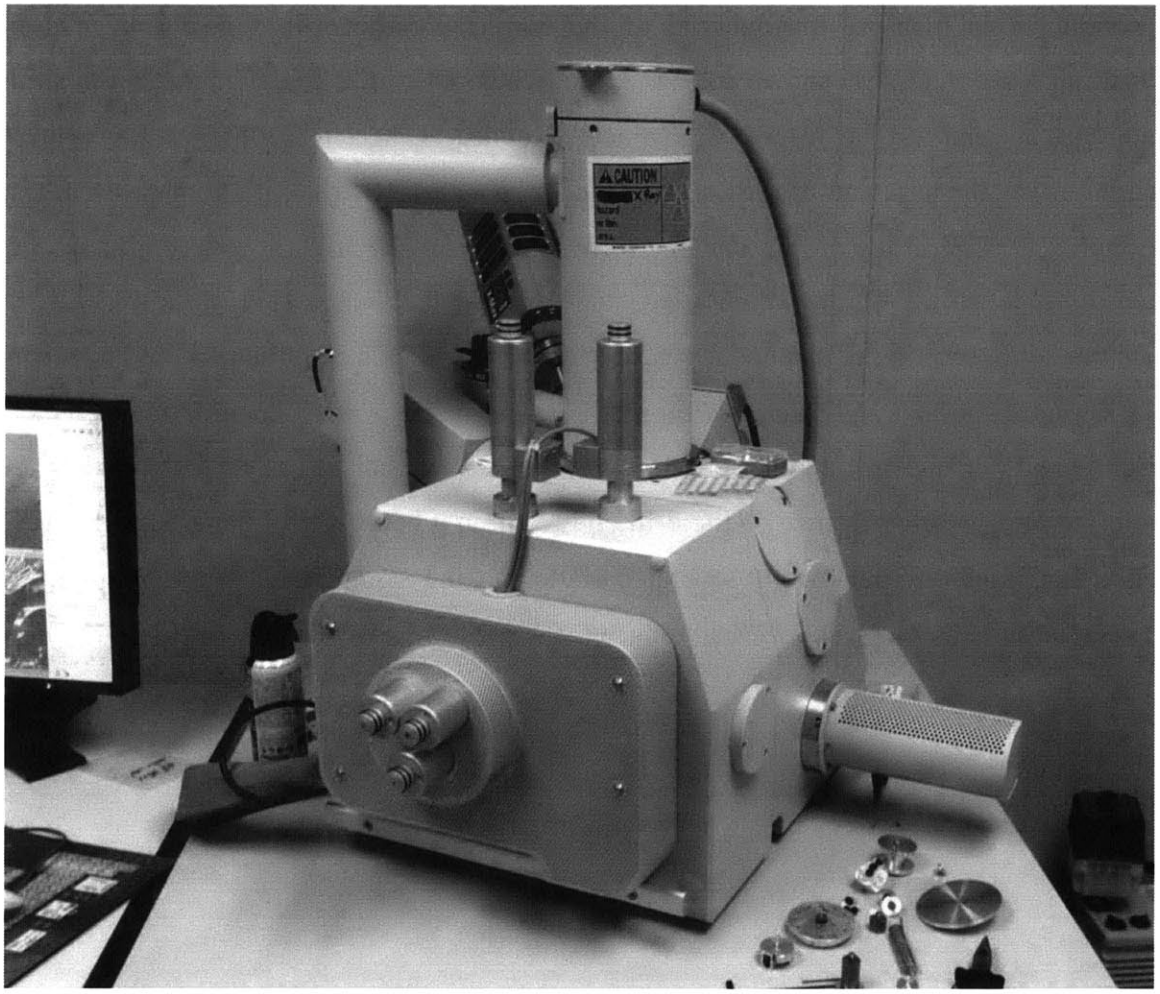


Figure 3.2: Scanning electronic microscope

Figure 3.3 shows a shear plan on the broken interface of drill bits and illustrates the failure to be characterized as brittle fracture. By increasing the hardness of drill bits, it can help resist higher shear strain before drills finally become fractured. Comparing the hardness of different elements that could be added into micro carbide drill, Cr is the best result, which has an even higher hardness than tungsten. Besides, its high melting point provides the high heat resistance that would also help drill perform better. By taken these two factors (percentage of cobalt and optional chromium) into consideration, several kinds of tungsten carbide material were compared and AF1 from Japan Sumitomo was chosen to be the best material among all of them to make the micro carbide drill.

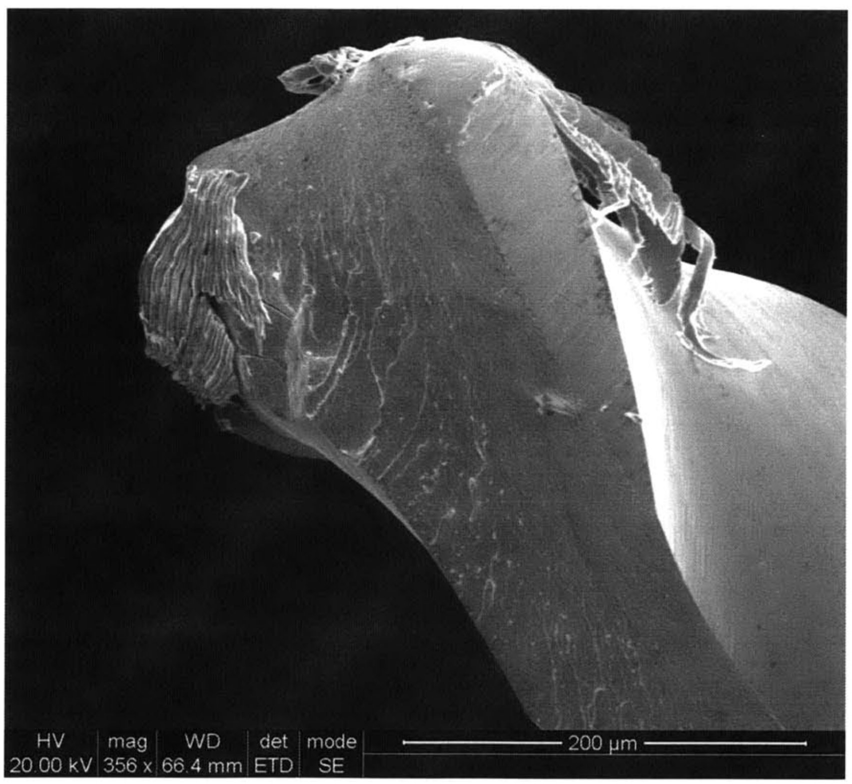


Figure 3.3: Drill breakage analysis – Brittle fracture

3.1.2 Analyses of Drill Geometries

The diameter of hole is designed to be 0.2794 mm (0.011 in). Experience has shown the presence of oversize, which makes diameter of the drilled hole is slightly larger than the drill diameter. Taking this effect into consideration and to leave tolerance for next step work, the drill diameter should be chosen smaller than the diameter of hole in size, but the closer, the better. Diameter 0.27mm drill will need more material remove during the surface finish process. In this case, the dimension of new drill should be 0.275 mm in diameter same as the conventional drill.

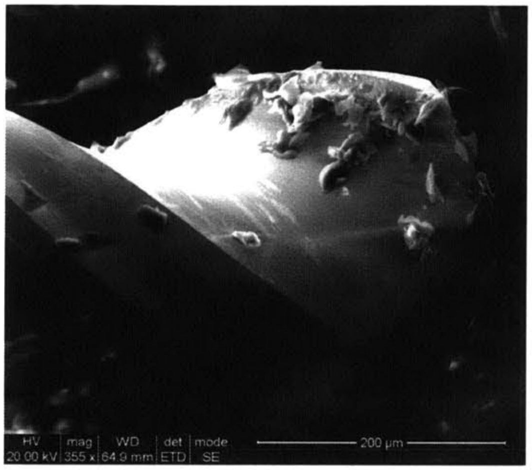
According to the design at Waters, micro deep hole exists inside the two other small holes, which required the flute length to be minimal 4.48mm to achieve the drilling 0.2794mm (0.011in) hole. The standard micro-drill does not have the right flute length to achieve the hole-making process. Therefore, either choosing extended micro-drill available in the market with 4.8mm or 5.2mm in flute length or customizing the drill to a designed length will work. Stiffness that affects the drilling performance and tool life is proportional to tool diameter^4 and flute length^{-2}. To achieve the high stiffness, the flute length should be as short as possible. The ideal case will be just above the requirement value, which is 4.5mm. The difference in stiffness between 4.5mm and 4.8 mm can be computed by Eq. 3.1:

$$\Delta E = \frac{(L_2)^{-2} - (L_1)^{-2}}{(L_1)^{-2}} \tag{3.1}$$

where ΔE is the difference in stiffness, L_1 is the original flute length (mm) and L_2 is the proposed flute length (mm), respectively

As the result, the 0.3mm change in flute length will lead to an increase in torsional stiffness E of 13.8%, which will also increase the drill life. However, according to the time constrain and minimum order requirement, drilling micro deep hole with customized drill bits is not achievable but leaves the more analysis for the future work. Therefore, in this case, the flute length is decided to remain 4.8mm.

Most commercial micro-drills with diameter between 0.250mm to 0.30mm have 130° as point angle based on existing micro tool making technology. Since the starting drill the company uses has 120° for point angle, sharpening the micro-drill a little bit could help the micro-drill tip match the starting drill leading to a better engagement at initial drilling. Drill reconditioning is feasible by using current grinding technology with a special designed fixture and several kinds of commercial drills that have this feature are available on the market. Therefore, point is recommended to be sharpened a little to a certain degree within the range of 120°-130° as the point angle.



(a) **(b)**

Figure 3.4: Chip jamming and Chip adhesion

Chip jamming and chip adhesion are two of the critical reasons for causing micro-drill breakage. Figure 3.4 (a) and (b) show chip jamming and chip adhesion under current cutting conditions. Small chips started packed in the cutting edge and occupied space inside the flute. As drilling process goes on, heat accumulation caused the drill to be soft. Therefore, long continuous chips at elevated temperature were more likely to adhere to the flute. When more and more chips were produced and stocked in the flute, it naturally leaves less clearance for other chips to be removed, so it increases several kinds of force, such as drag force and friction force. Heat generated from additional friction force would also raise the temperature to an even higher value, which further softens the drill and makes chip adhesion even easier. So the conditions become worse and worse in drilling performance. Therefore, enlarging the space in the flute, especially the first one, which can accommodate more chips, will help generate the longer tool life. The variable spiral technology is developed by adjusting twist speed and feed rate when making the drill. It can be applied to make the flutes near drill tip wider and deeper. In this case, the helix angle will also be reduced and therefore smooth the cutting process.

Summary

Based on the aforementioned analysis and recommendations on drill diameter, flute length, point angle with additional sharpening process and variable spiral technology, one micro drill that meets all requirements is finally selected from 30 micro drill candidates commercially available A set of micro drills were ordered and prepared for the experimental studies.

3.2 Cutting Conditions

3.2.1 Peck drilling

Peck drilling has been studied and used by the company for micro hole drilling to maintain the drill bit for a longer time. The machine has its built in program which can generate the constant peck value over the course of the drilling process. While, research and previous test results found out the chip removals in the initial peck and final peck are different, reducing the values in pecking as the drill gets deeper is one method to achieve the better drilling performance. Four major factors that affect the peck drilling performance are re-enter point position, initial peck value, final peck value (or number of pecks) and sequence type of peck values.

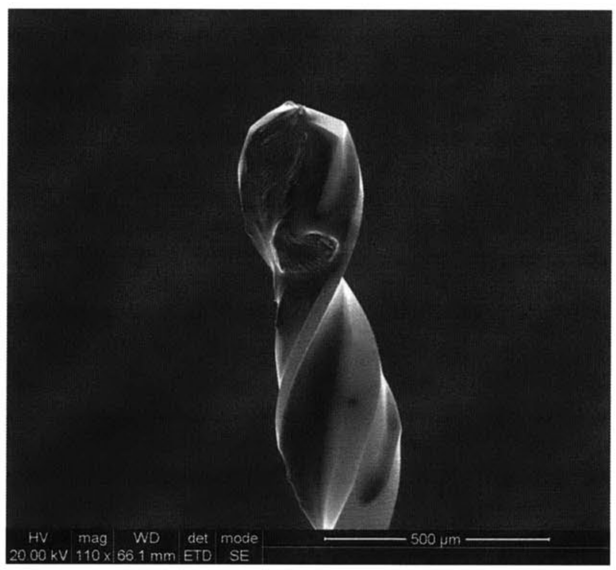


Figure 3.5: Drill bit without retract completely out of hole

In macro-scale machining, drill bits are usually retracted by only a certain small distance above from the previous drilling depth. This could help reduce heat generation by sliding against the hole wall. The less distance the drill travels, the less time each hole making process would consume, which helps keep the production rate steady to some extent. However, coping from macro machining practice doesn't work well on micro drilling process, especially for this particular case. Cutting fluid barely gets into the hole without help from drill insert. Thermal energy will be accumulated at the drill bit tip in the shorter time than macro-scale case, in which, temperature will soon rise and become higher than melting point, causing chip adhesion easily. Figure 3.5 shows a drill bit after several holes being produced by not retracting the drill bit out of the hole. The severe adhesion of chips caused drill tip geometry to be dull with less web volume and reduced the chip removal rate. These changes increase vibration of drill as well as wear rate. It was observed that the micro drill was broken after few more holes were produced. Completely retract the micro dill out of the hole can delay the chip adhesion or even prevent it. Coolant can penetrate directly to the drill tip, remove the chip that may be welding to the drill bit and leaves some droplets of coolant inside the flute getting into the hole to remove heat of workpiece on the contact point and lubricate the drilling process when drill is inserting back. The re-enter point was decided to be positioned to be 0.762mm (0.03in) above the hole's top surface with previous analysis and several comparison done by Waters.

Initial peck is a key factor, because it demonstrates the effectiveness of the drill's engagement and the peck value would affect the cutting force as well as chip removal. If the initial peck value is too small, the engagement of the drill will not perform well because there will be too small of a contact area between the drill and the hole surface area. This potentially leads to location problems for the second peck, as there is a much smaller surface area location for the drill to re-engage. On the other hand, when the initial drill entry is too large, the chips generated are too great, leading to blockage in the flute along with increased heat on the drill. Too large of an entry point results in higher thrust which can lead to instability during the drilling process. Therefore, a medium value for the initial peck should be used for the optimal peck procedure. The machinery handbook suggests the first peck value to be 2 $\times$ drill diameter. However, several previous testing results state that the initial peck value should between 0.07mm to 0.21mm to generate the satisfactory outcomes.

Final peck is the most critical determinant of drill life in peck drilling procedure. As it was analyzed, heat accumulation raise the surrounding temperature to maximum in the end of drilling process, which causes the chips from last few pecks easily adhere to the flute. The difficulty of removing chips in the end also increases the chance of chip jamming, which contributes to the tool breakage eventually. Thus, a lower amount of chip can help drill bits perform better (last longer) which leads to a conclusion that the smallest final peck value is desirable to achieve the longest tool life.

The number of pecks (cycles) is another parameter in peck drilling procedure. It closely related to the initial peck value and final peck value. In general, the more pecks would allow the final or initial peck value to be small. On the contrast, the small amount of pecks would generate a fair large final peck value. In some pecking procedure, the number of pecks can be a variable to adjust the final peck based on the equation the peck values are fitted in.

Machinery handbook provides Eq. 3.2 as the guideline for drilling high depth-to-diameter ratio hole.

$$\frac{P}{D} = \frac{1}{9} \times (-1.5R + 19.5) \tag{3.2}$$

where P is the incremental pecking depth (mm), D is the drill diameter (mm) and R is the drill aspect ratio, which equals to hole depth / drill diameter, respectively

R value will be changed as the hole becomes deeper with drilling process going on. Therefore, P to D ratio is changed simultaneously. With the recommended initial peck value as the value of 2xdiameter, Table 3.1 was made with all the peck values calculated. To meet the depth of hole, the final peck value is adjusted.

Table 3.1: Pecking cycle, drill diameter = 0.275mm, hole depth = 2.667mm

Pecking cycle #	Hole depth (mm)	Aspect ratio, R	P/D	Pecking depth, P (mm)
1	0			0.55
2	0.55	2	1.833	0.504
3	1.054	3.833	1.528	0.420
4	1.474	5.361	1.273	0.350
5	1.824	6.634	1.061	0.292
6	2.116	7.695	0.884	0.243
7	2.359	8.579	0.737	0.203
8	2.562			0.105
	2.667			

Final peck value of 0.105 mm and 8 pecks seem aggressive in micro-drilling of deep hole. A quick study with 3 duplicated experiments was conducted to verify the theoretical suggestion. The results of 2, 3, 3 successful holes are significantly lower than any tested results by other procedures. This discrepancy abandoned the idea of choosing 2xdiameter as the initial peck value to do experiment studies. Instead, the initial peck value will be considered between 0.07 mm to 0.21 mm as previous work recommends.

The simplest equation to fit the decreasing peck values is linear equation with two variables: slope, a, and intercept, b, as shown:

$$PV = -a \times (n-1) + b \tag{3.3}$$

where PV is the peck value (mm) and n is the n^{th} peck, respectively

The peck values in linear relationship belong to arithmetic sequence. The number of pecks can be obtained by dividing the hole depth by the average of the initial peck value and final peck value as Eq. 3.4 shows. From Eqs. 3.5 and 3.6, a can be computed as the difference between neighbor peck in sequence and b can be computed as equal to the initial peck value, respectively. Therefore, this simple math makes the linear equation easy to be programmed into the machine, which makes it widely used by machine operators.

$$N = \frac{L}{\frac{(PV_1 + PV_N)}{2}} \tag{3.4}$$

where N is the number of pecks, L is the depth of hole, PV_1 is the initial peck value and PV_N is the final peck value, respectively

$$a = \frac{PV_1 - PV_N}{N-1} \tag{3.5}$$

$$b = PV_1 \tag{3.6}$$

The current peck drilling procedure (LP1) uses a linear equation with the initial peck value of 0.1016 mm (0.004 in) and the final peck value 0.0508 mm (0.002 in). In order to test the effect of final peck value and check if the smaller final peck value generates the better result, an experiment (LP2) was designed by reducing the final peck value based on the current procedure while keeping the same initial peck value.

In order to test the effect of initial peck value, two values were chosen near the one used in the current procedure (LP1). Based on recommendation from the previous results (0.07 mm – 0.21 mm), 0.762 mm and 0.2032 mm were used as the initial peck values for another two designed experiments by considering generating the integer for the number of pecks. Therefore, LP3 (3^{rd} linear procedure) and LP4 (4^{th} linear procedure) were developed by keeping the same final peck value as the current peck procedure.

The parameters of all four linear pecking procedures were listed in Table 3.2.

Table 3.2: Peck drilling parameters summary of four different linear procedures

	Peck drilling parameters			
	LP1	LP2	LP3	LP4
Initial peck (mm)	0.1016	0.1016	0.0762	0.2032
Final peck (mm)	0.0508	0.0254	0.0508	0.0508
Cycles	35	42	42	21

Linear pecking procedure has its detriment. L is not always an integer multiple of the average of the initial and the final peck values. Therefore, Eq. 3.4 would generate a non-integer. Machine program would round it off to the nearest integer and then adjust the final peck value to meet the hole depth. The experimental design in this project does not have this concern since the depth of hole is a multiple of 3, 5 and 7, while in general, if final peck value is adjusted, then the drilling performance would be affect as well. Thus, a new equation involves the initial peck and the number of pecks as variables is desired to be developed.

A quadratic equation can solve this problem. The more important reason is that the quadratic procedure can allow the final peck be much smaller than the linear procedure.

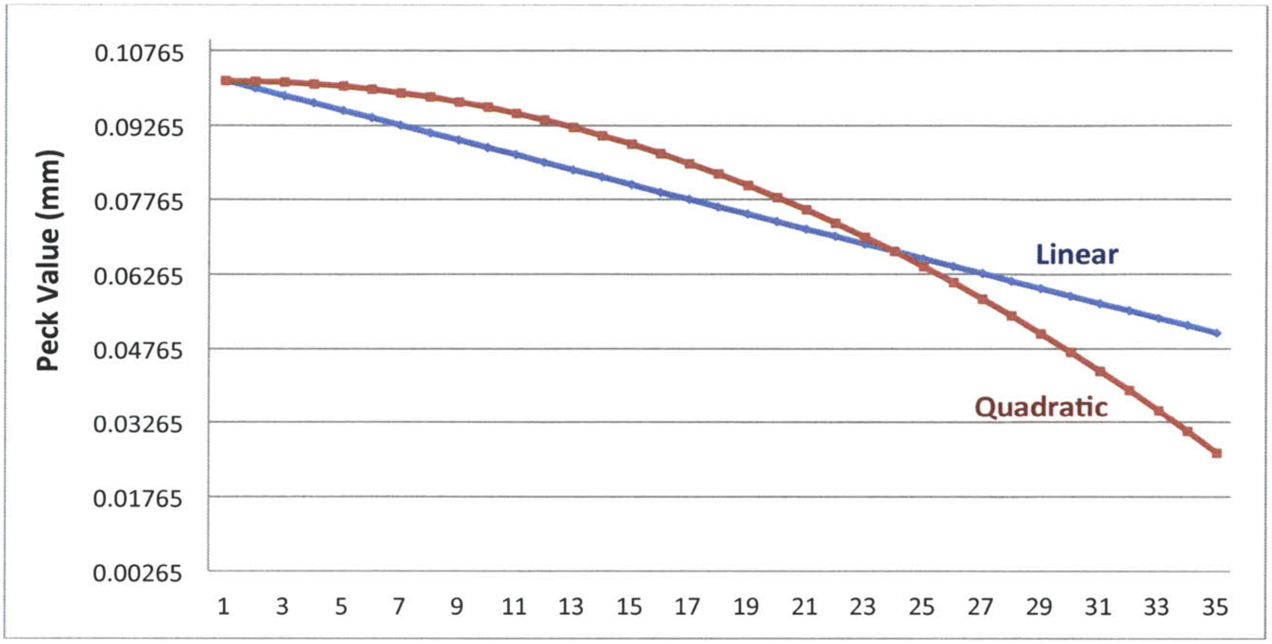


Figure 3.6: Comparison between linear procedure and quadratic procedure

Fig. 3.6 shows the difference between linear procedure and quadratic procedure. By using same initial peck value as well as same number of pecks, the quadratic procedure would allow drilling process to remove much more chips than linear procedure at the beginning when it is efficient for chip removal. In the end, due to the property of quadratic equation, the peck value is decreased significantly to a much smaller value than that in linear procedure. As analysis indicates, the new procedure with quadratic equation can generate the better result.

A quadratic equation was selected by considering the first peck as the maximal value. The symmetry axis was chosen to be at n =1 as for generating largest values at the beginning and smallest values in the end. The designed quadratic equation is shown as.

$$PV = -a \times (n-1)^2 + b \tag{3.7}$$

In quadratic procedure, the initial peck and the number of pecks are independent variables; the final peck is dependent variable. By determining the initial peck value and cycles, the quadratic equation can be obtained through Eqs. 3.8-3.12.

$$L = \sum_{n=1}^{N} -a \times (n-1)^2 + b \tag{3.8}$$

$$L = \sum_{n=1}^{N} -a \times n^2 + 2a \times n - a + b \tag{3.9}$$

$$L = -a \times \frac{n \times (n+1) \times (2n+1)}{6} + 2a \times \frac{n \times (n+1)}{2} - a \times n + b \times n \tag{3.10}$$

Since the b value is equal to the initial peck value, therefore, a and b can be obtained as:

$$a = \frac{PV_1 \times n - L}{\frac{n \times (n+1) \times (2n+1)}{6} - n \times (n+1) + n} \tag{3.11}$$

$$b = PV_1 \tag{3.12}$$

Then, the first quadratic procedure (QP1) can be developed by using the same initial peck value and same number of pecks as the current procedure (LP1). This can test the hypothesis of the smaller final peck value the better and verify the advantage of quadratic procedure over the linear one.

To verify the effect of final peck value within quadratic procedures, the second quadratic procedure (QP2) was developed by using the same initial peck value. The number of pecks (N) is adjusted to get the minimal positive number for the final peck value. In this case, the number of pecks is determined to be 39 and the final peck value is then computed through Eq. 3.11.

Similar to linear procedure design for testing the effect of the initial peck value, the 3rd quadratic procedure and the 4th one were developed by using the initial peck value as ± 0.0127 mm (0.0005 in) from 0.1016 mm (0.004 in). Then the numbers of pecks were both adjusted to generate the smallest final peck value.

In sum, four quadratic pecking procedures were prepared and all the parameters are listed in Table 3.3

Table 3.3: Peck drilling parameters summary of four different quadratic procedures

	Peck drilling parameters			
	QP1	QP2	QP3	QP4
Initial peck (mm)	0.1016	0.1016	0.1143	0.0889
Final peck (mm)	0.026416	0.003302	0.001778	0.00508
Cycles	35	39	35	42

Therefore, 8 different pecking procedures were ready to be tested.

3.2.2 Spindle speed

The cutting speed for micro-drilling is usually above the 25,000rpm. The high spindle speed will give the great surface finish and good production rate. According to the model listed on machinery handbook, the spindle speed for micro-drilling can be computed by Eq. 2.1.

In this case, the micro drill with diameter 0.275mm is used for drilling 316 SST. Table 3.4 suggests the cutting speed (drill speed) of 28 m/min based on workpiece material. Therefore, the recommended spindle speed can be obtained as 32,000 rpm.

Table 3.4: Speeds and Feeds for Micro Milling/Drilling with Uncoated Carbide Tools [3]

Materials	Examples	Vicker micro-hardness	Mill speed (m/min)	Drill speed (m/min)	Chip load (μm/tooth), *D* = drill or mill diameter				
					D < 1.0 mm	*D* < 1.5 mm	*D* < 2.0 mm	*D* < 2.5 mm	*D* < 3.0 mm
Steel	12L14	<120	170	65	38	43	50	57	65
	1010	<265	138	43	33	38	43	51	58
	4063	<208	110	43	33	38	43	51	58
Stainless steel	409, 410,446	<318	75	38	15	15	20	23	25
	304, 316, 316L	<265	68	28	13	15	18	20	23
	17-7 PH	<318	70	45	10	11	15	18	23
Plastics	ABS, PVC thermoplastics		190	150	150	173	198	229	262

Several tool makers have recommended spindle speed value for drilling 316 SST, which are between 25,000rpm to 35,000rpm. Due to the capacity limit of CNC machines at Waters, the maximum spindle speed is lower than any recommended values. Practice shows that the closer to recommendation, the better result will be. Therefore, machines should run at the maximum spindle speed that is 24,000 rpm.

3.2.3 Feed rate

The feed rate is one of other critical determinants that affect tool life and surface finish. The lower the feed rate, the finer the surface will be. However, it takes more time leading to low production rate and also increases the brittleness of drill make it shorter life. Thus, an appropriate feed rate should be determined.

Feed rate of drilling process can be calculated by using Eq. 2.2. The chip load value can be found under the column of "D < 1.0 mm" in Table 3.4. However, this value may not be right for a drill diameter less than 0.5mm. As to the drilling process with diameter of 0.275 mm, the chip load is even harder to be measured. Therefore, simply using the value in Table 3.4 is not suitable for calculating feed rate of this particular micro-drilling process.

Tool makers like Mitsubishi [8] and Jianling [6] recommend that the feed rate should be in the range of 0.00254 mm/rev to 0.0127 mm/rev (0.0001in/rev to 0.0005 in/rev). Based on the previous studies done by Waters' engineers, the optimal feed rate was decided to be 0.00762 mm/rev (0.0003 in/rev). With the time constraint, the feed rate would not be adjusted to run more experiments. Thus, all of the tests would be run at the feed rate of 0.00762 mm/rev (0.0003 in/rev).

Summary

8 different pecking procedures (4 linear + 4 quadratic) would be tested at the same cutting conditions. The spindle speed of 24,000 rpm and the feed rate of 0.00762 mm/rev were selected.

Chapter 4

Experimental Study and Results

In order to provide the recommendation on choosing a new drill and a new peck drilling procedure, several tests were conducted for verification and comparison. 8 different pecking procedures were proposed based on analysis of each parameter. With 4 duplicate tests for each procedure and 5 tests for old drill life tests, 45 tests in total were required. Due to the time constraint of the project and the availability of machines at Waters, the design of experiments was modified and the experimental logic is summarized in the Fig. 4.1. Three peck drilling procedures with new drill were tested first in order to verify the small variation of drill quality and to confirm the difference between experiments is the result of difference in procedures not due to the drill itself. By using the new design of experiment, 25 tests were completed and the holes drilled by the selected procedures were measured to ensure the quality level.

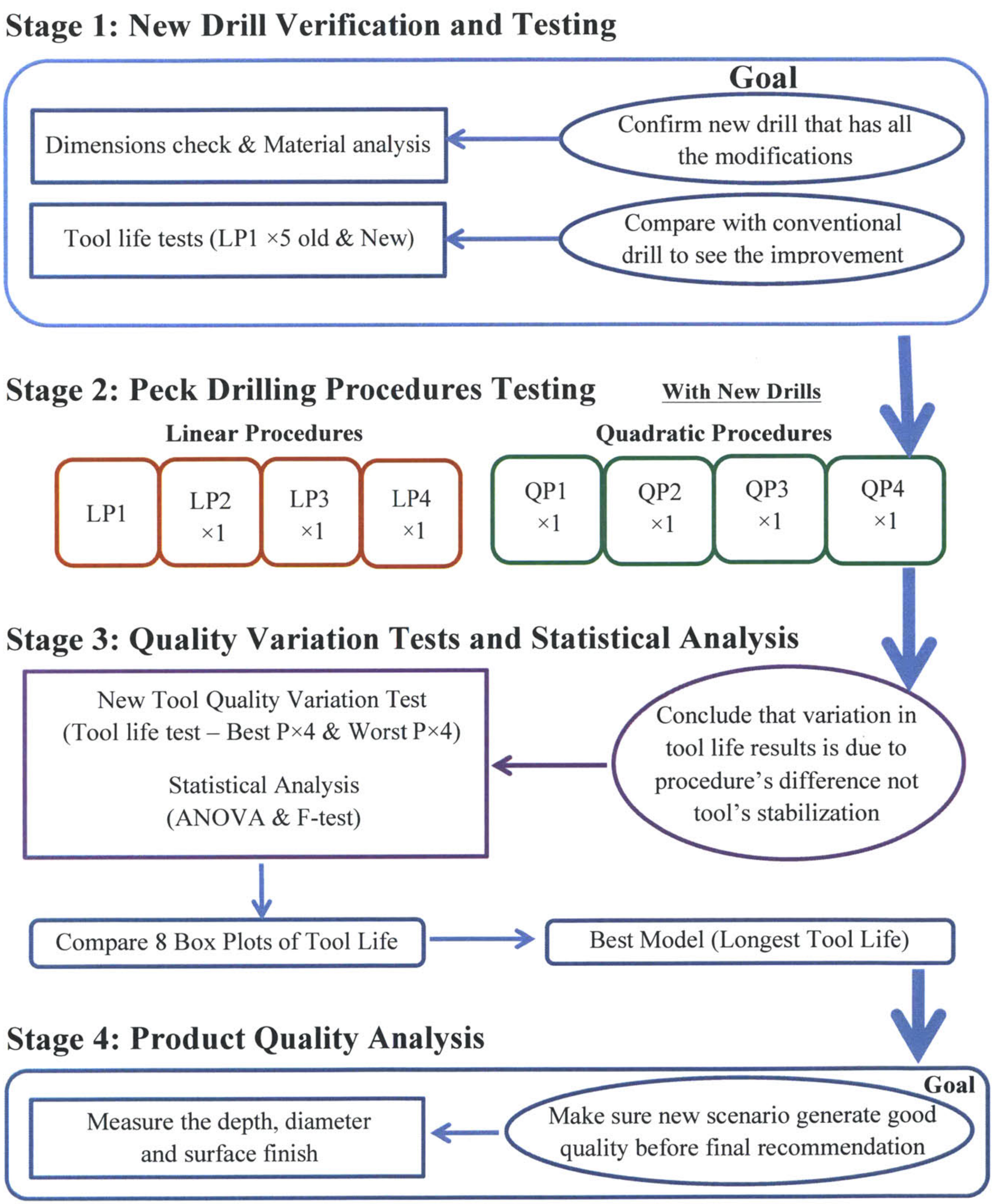


Figure 4.1: Design of experiments

4.1 New Drill Verification and Testing

4.1.1 Material analysis

By using SEM, the material of new drill was analyzed and all the elements are plotted in Fig. 4.2. This verifies the existence of Cr. According to the results of the hardness test, the new drill is around 5% stronger than the conventional drill. The weight percentage of Co was measured to be 1.88%, which is four times of that in conventional drill. The relative high Co would help new drill increase in wear resistance and therefore increase in tool life as well.

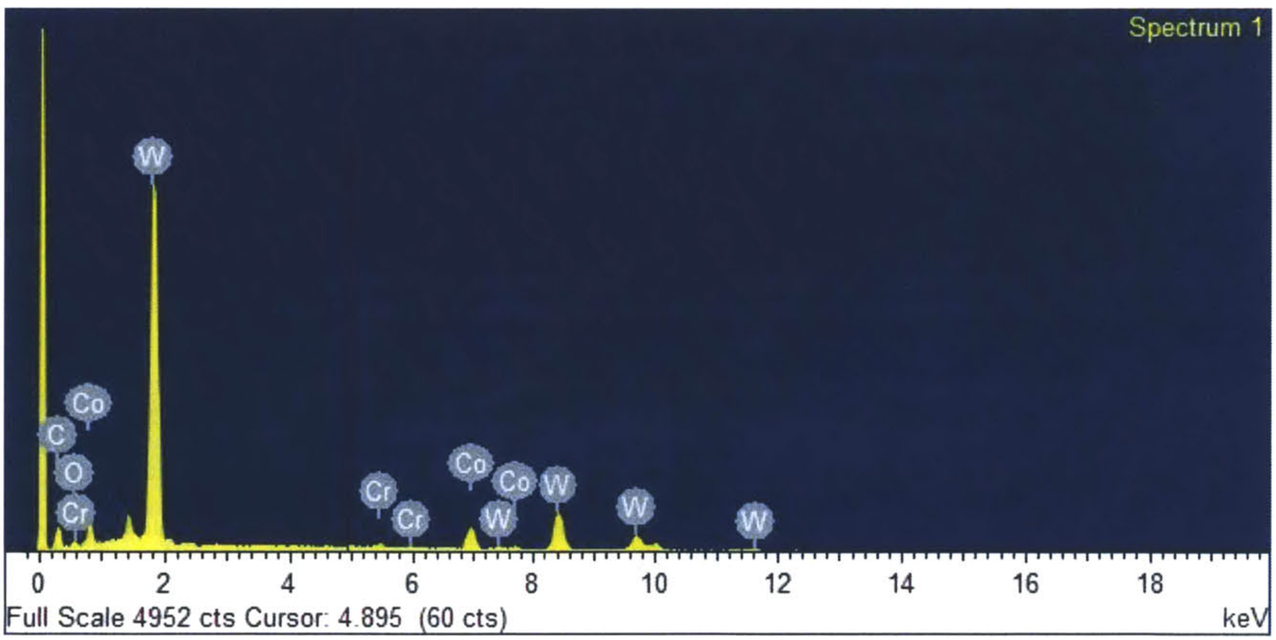


Figure 4.2: Material analysis of new micro drill bits

4.1.2 Dimension measurements

Figure 4.3: Dimension measurements of new micro drill bits

Three drills are randomly selected from a set of 100. The flute length is measured by Zoller as 4.8001mm, 4.8000 mm and 4.8000mm, respectively. Three values in drill diameter are all measured to be exact 0.275mm. Point angles measured by using JSL electronic measurement instrument, Fig. 4.3 are in the range between 124.4° to 124.5°, which verifies the drill reconditioning applied on the new drill.

To verify the variable spiral technology applied on the new drill, a conventional drill and a new drill were inspected under the computer controllable microscope as shown in Figs. 4.4 and 4.5 respectively. By measurement, each flute size of the conventional drill is the same in depth and width. While, in the new drill, the flute close to cutting edge is much wider and deeper than the flute close to the shank. Measurement data also showed that the distance of l_2 on the conventional drill shown in Fig. 4.4 is 10% shorter than the distance of l_2 on the new drill shown in Fig. 4.5. Additional space for chip removal would help chip and temperature flow through the flute more efficiently to reduce the tool wear and chip adhesion happen.

Figure 4.4: Conventional drill bit ($l_2 = l_1$)

Figure 4.5: New drill bit ($l_2 > l_1$)

4.1.3 Drill tool life test comparison

Five new drills and five conventional drills are randomly selected to be tested under the same cutting conditions as run on the real production. 316-stainless steel from carpenter technology was used as testing workpiece material. The workpiece was prepared into the shape like real products shown in Fig. 4.6. Three holes were equally distributed on the bottom side, which allows them to be placed on the designed fixture shown in Fig. 4.7 to ensure the evenness of surface. The micro deep holes were drilled on the top surface. The outer loop has 90 holes and the number of holes is reduced gradually with the decrease in radius. The inner loops have 72, 60, 45 holes, respectively. All the drilling tests were conducted on a Fanuc Robodrilling machining center, shown in Fig. 4.8. The tool life experiments were carried out at spindle speed (cutting speed) of 24,000rpm and feed rate of 0.00762mm/rev (0.0003 in/rev) in the first linear peck drilling procedure (initial peck: 0.1016mm, final peck: 0.0508mm, cycles: 35). The regular microscope was used under various magnifications to capture the images and record the number of holes making by drills before they were broken. The results are summarized in Table 4.1.

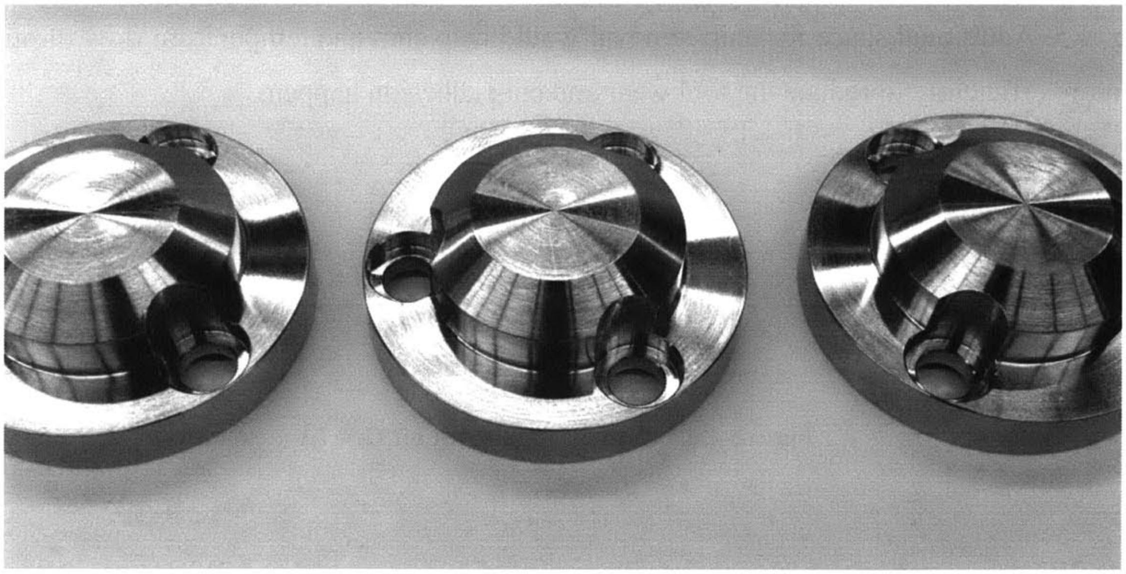


Figure 4.6: 316 stainless steel testing workpiece

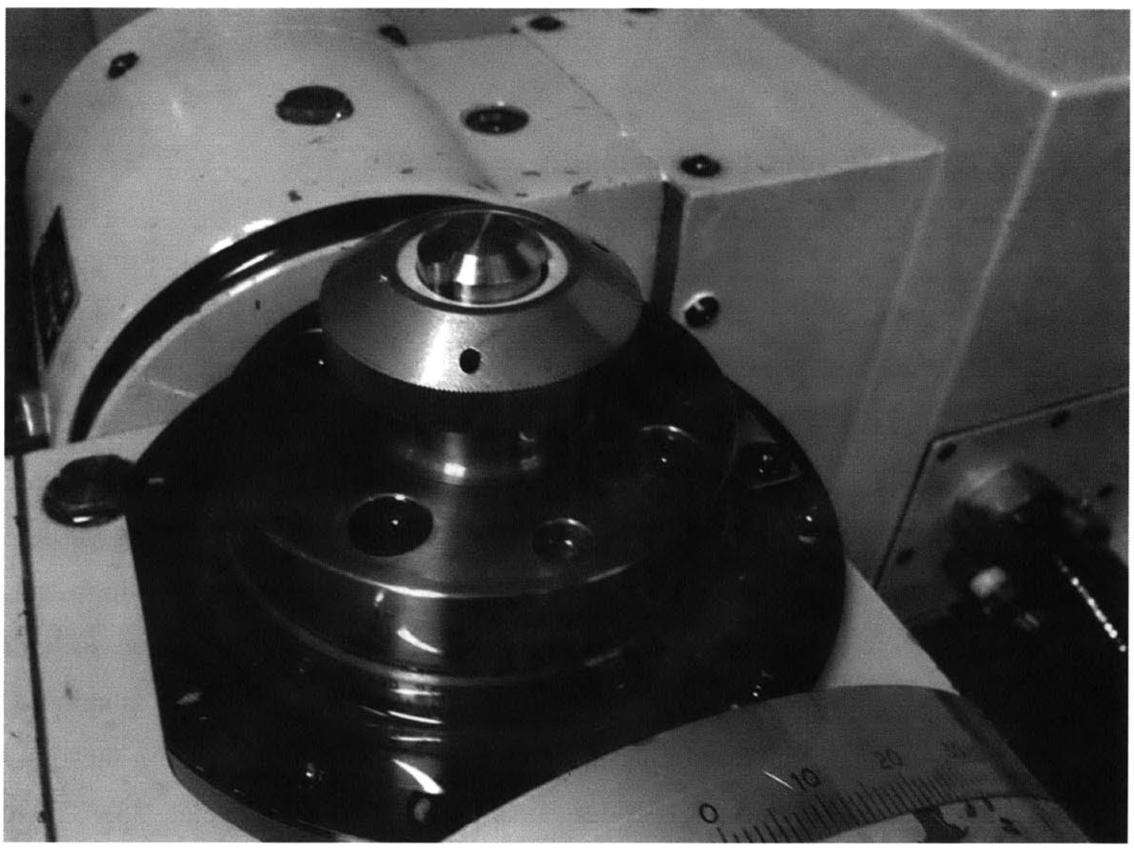


Figure 4.7: Designed fixture

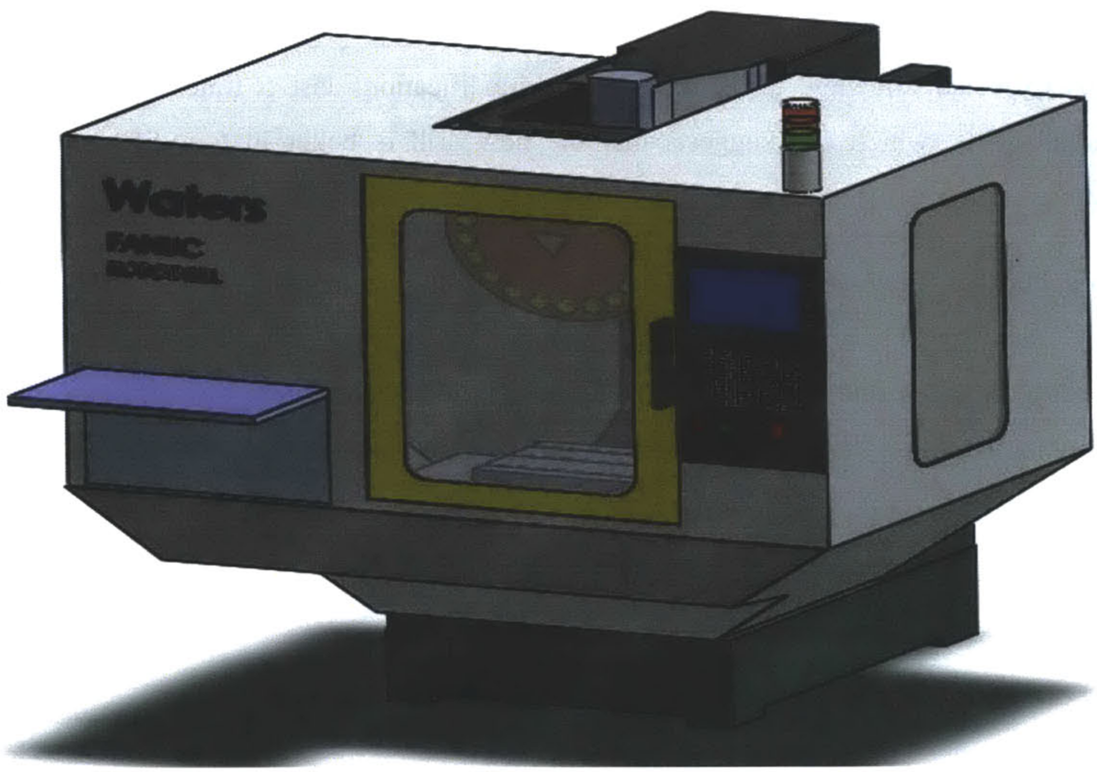


Figure 4.8: Robodrill

Table 4.1: Tool life comparison between conventional drills and new drills

	Tool life (# of holes)	
	Conventional Drills	New Drills
1st test	27	120
2nd test	25	118
3nd test	24	121
4th test	24	119
5th test	26	123

As it was expected, the new drills with all the modifications last 5 times longer than the conventional drills, which can suggests that the new drill is better in tool life and drilling performance.

Difference between new drill bits and conventional drill bits concludes that the additional material element to add hardness and heat resistance, point angle that allows the drill bits to become better engaged and variable spiral that helps remove chip more efficient can improve drill quality in drill life.

4.2 Peck Drilling Procedures Testing

In order to compare the performance of the pecking procedures proposed, each of the remaining seven designed experiments, including three linear peck procedures and four quadratic peck procedures, was conducted once for simplicity. All the experiments were carried out under the same cutting conditions including the same spindle speed, feed rate and other variables associated with coolant. What varied were the peck drilling parameters only. The summary in Table 4.2 shows all eight models with their peck drilling parameters as well as the results generated from tool life tests.

Table 4.2: Summary of all pecking procedures

	Peck drilling parameters							
	LP1	LP2	LP3	LP4	QP1	QP2	QP3	QP4
Initial peck (mm)	0.1016	0.1016	0.0762	0.2032	0.1016	0.1016	0.1143	0.0889
Final peck (mm)	0.0508	0.0254	0.0508	0.0508	0.026416	0.003302	0.001778	0.005080
Cycles	35	42	42	21	35	39	35	42
	Tool life (# of holes)							
	LP1	LP2	LP3	LP4	QP1	QP2	QP3	QP4
1st test	120	150	112	80	147	173	252	184
2nd test	117							
3nd test	121							
4th test	119							
5th test	123							

Figure 4.9: Testing result from 3rd quadratic procedure

By and large, the tool life using linear pecking procedures were worse than those from quadratic procedures. At the same time, by pairwise comparison of the pecking procedures, the experiment results confirmed what had been discussed in Chapter 3 Specifically,

4.2.1 Effect of the final peck value

The comparison between 1st linear procedure and 2nd linear procedure suggests that the smaller amount of chip removal in the end with the same initial peck value can generate a lower amount of heat, which leads to a longer tool life.

The comparison between 1st quadratic procedure and 2nd quadratic procedure also suggests that the smaller amount of chip removal in the end with the same initial peck value can generate a lower amount of heat, which leads to a longer tool life.

More importantly, comparing the 1st linear procedure and 1st quadratic procedure, 1st quadratic procedure generated a better drill life. This is because quadratic procedure allows achieving the smaller final peck value given of the same initial peck value and number of pecks. Again, this can generate a lower amount of heat, which leads to a longer tool life.

Therefore, experimental results confirmed that the smallest final peck value generates the longest drill life.

4.2.2 Effect of the initial peck value

The comparison among the 1st linear procedure, 3rd linear procedure and 4th linear procedure suggests that with the same final peck value, the drill life reaches to its optimal results and then drops down as the initial peck value keeps increasing. This can be explained by a proper initial peck value that can balance the engagement performance and effect of resistance.

Therefore, experimental results confirmed that a moderate (0.0762 mm – 0.2032 mm) peck value can help generate the longest drill life.

In sum, the quadratic procedures would produce better results compared to linear procedures. They have the advantage of quickly achieving smaller peck values in the last few pecks. According to the experimental results, among the 2nd, 3rd and 4th quadratic procedures, quadratic procedure 3 by far obtained the optimal performance in the tool life test as it achieved the smallest final peck value among all.

4.3 New Drill Tool Life Variation Tests and Statistical Analysis

The three measurements in Stage 1 indicated that variation in tool's dimension is very small. In order to generate final recommendation rigorously with fewer amounts of experiments, variation tests of tool life were conducted by additional two sets of four duplicated experiments. One set of experiments was carried using the worst scenario, which is the 4th linear pecking procedure. The other set of experiments was carried using the best scenario, 3rd quadratic pecking procedure. The parameters of these two procedures are listed in Tables 3.2 and 3.3, respectively. Again, the regular microscope was used to help count the number of holes making by drills to record their tool life values. The two sets of results are listed in Table 4.3 as well as the first linear procedure's results.

Table 4.3: Tool life results from three procedures

	Tool life (# of holes)		
	New Drills (1st linear procedure)	New Drills (4th linear procedure)	New Drills (3rd quadratic procedure)
1st test	120	80	252
2nd test	117	84	250
3nd test	121	82	255
4th test	119	87	258
5th test	123	85	251

Results indicate that there exist significant differences in tool lives among three pecking procedures. Hence, it can be concluded that the new drill has pretty good quality in terms of tool life stability under different pecking procedures. Variation in drill performance is for most caused by the difference in pecking procedures, not by variation in drill quality.

Hence, it confirms that it is not necessary using multiple duplicated experiments in testing the performance of pecking procedures and the experimental results obtained from previous section is statistically significant.

Therefore, according to the experimental results in pecking procedure testing, the 3rd quadratic procedure with initial peck value of 0.1143mm, final peck value of 0.001778mm and cycles of 35 turned out to be the best procedure.

4.4 Product quality analysis

4.4.1 Diameters

A “pass” or “not pass” method was used to measure the quality of holes in diameter. 20 holes were randomly picked on each testing workpiece from the third quadratic pecking procedure and 100 holes in total were checked. The 100% pass indicated the product quality rate is satisfactory.

4.4.2 Depth of holes

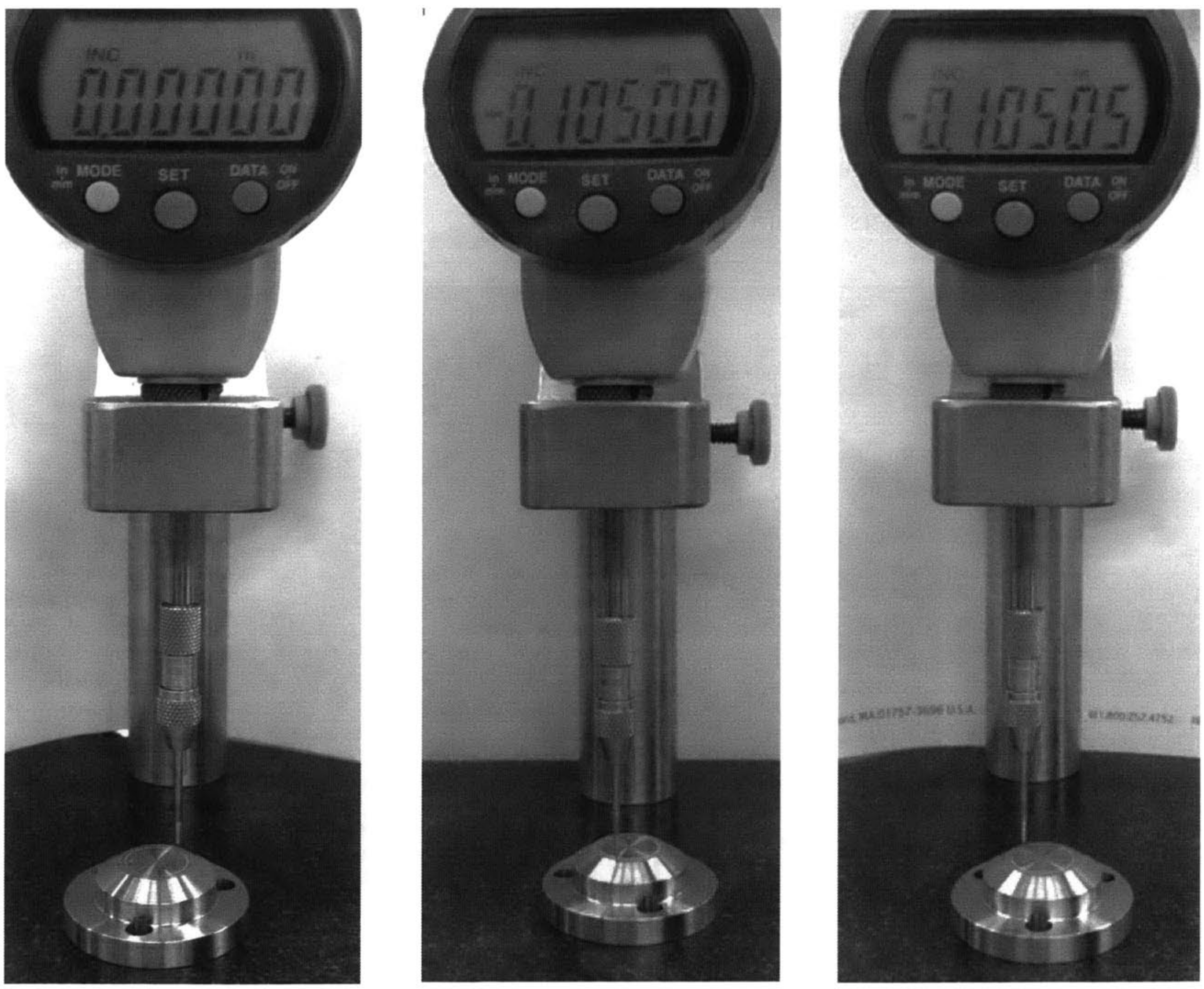


Figure 4.10: Measurements in depth of holes

Depth of hole is the most critical quality term at micro-drilling process step as to 212-Valve. It was measured by advanced electronic gauge as accurate to 5 decimal places. Fig. 4.10 shows the starting point and two measurements with their results.

125 holes (25 holes from each experiment) were measured and results were converted to metric. A process capability was then studied and it generated a very high Cpk value. This means quality of holes in term of depth is perfect controlled.

4.4.3 Surface finish

Surface finish of micro drilling process was inspected by using SEM (Fig. 3.2) shown in Fig. 4.11. Under the 50 μm scale, the surface still seemed to smooth, which was considered to be acceptable quality by Waters' requirement.

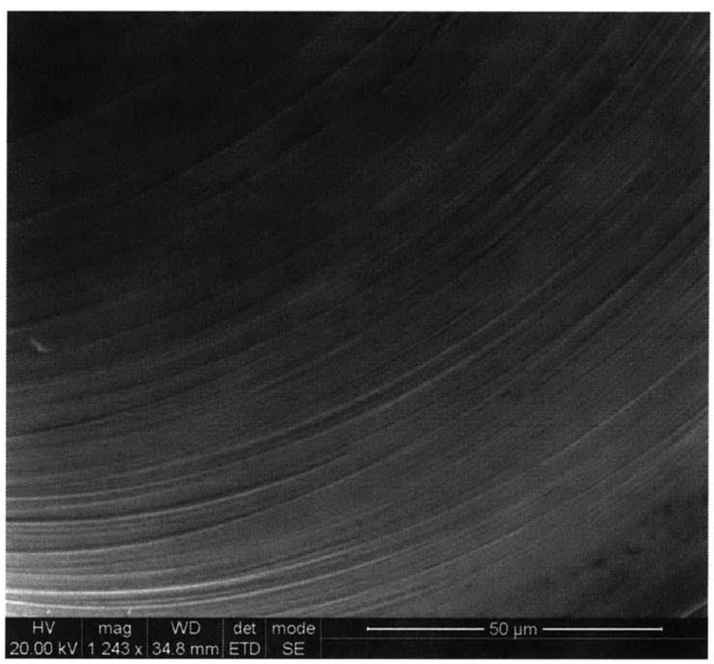


Figure 4.11: Surface finish of the selected hole drilled by 3rd quadratic procedure

Chapter 5

Effects of tool life improvement on the system performance

5.1 Quality improvement

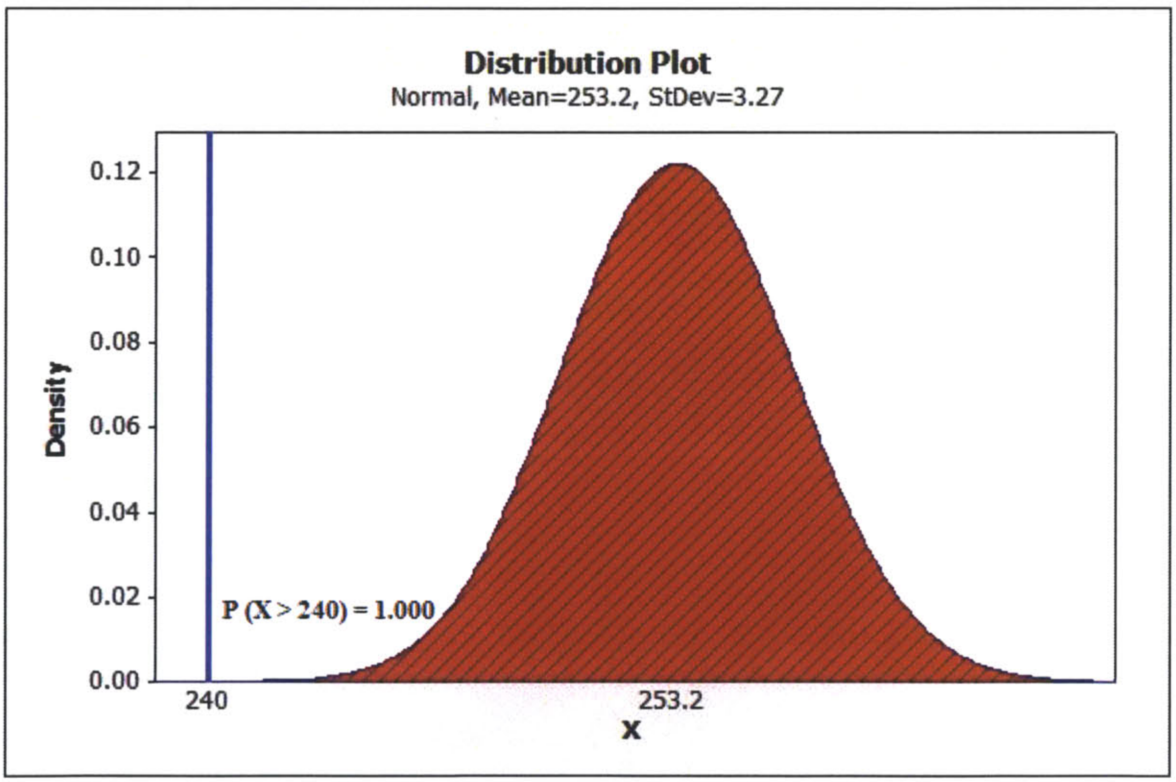


Figure 5.1: Probability distribution with a test data (240 holes)

To see how much the tool life improves by using the new micro drill and pecking procedures introduced, the maximum number of holes (tool quality) produced by individual drills was carefully measured and studied. A sampling normal distribution of tool life was generated as Fig. 5.1 according to the tool life statistics collected in the tool life test using the new drill and 3rd quadratic procedure (optimal combination). The standard deviation of the new tool life was computed to be 3.27. According to the sampling distribution, 99.7% of the tool life tested should fall between the mean value 253.2 ± 3 sigma (standard deviation), which is between 243.39 and 263.01. And approximately 100% of the tool life tested lies between ± 4 sigma (standard deviation) of the mean value that is between 240.12 and 266.28. This suggests that the micro drilling process would generate approximately 100% in quality rate if changing the drill bit after producing every 240 holes or less.

SAP data (Waters internal database) in a 2-year period states that robodrilling step has 1595 scraps out of 38440 produced valves, which generates 95.85% as overall quality rate. Among them, only 72 scraps were not caused by broken conventional micro drill. By the improving the micro drill life, 240 holes (40 parts) can be produced with 100% confidence. Taking other factors into consideration, this would conservatively increase the quality rate of Robodrilling stage from 95.85% to 99.81%.

5.2 Cycle time Reduction

The significant extension in tool life is expected to reduce the cycle time at the robodrilling step and hence improve the entire system performance. In order to see how the tool life improvement affects the cycle time, a time model was introduced for cycle time comparison between the current and proposed procedure.

5.2.1 Time model

The lead time between parts arrival and departure at the robodrilling step was monitored and broken into several segments: machining cycle time, drill changing time, loading & unloading parts time and others such as walking time and waiting time when operator is working on other things. 1.1 is the safety factor to consider other variation. The relation is shown as Eq. 5.1.

$$C_t = T_{Machining} + T_{DrillChanging} + T_{Loading\&Unloading} + T_{Others} \quad (5.1)$$

The time difference between current peck drilling procedure and selected quadratic pecking procedure is calculated to be less than 1s for each hole, which does not consider affecting the machining cycle time. The improved drill life performance can reduce times of changing tools, which costs around 2 min for each time. In this case, improving from changing drill every 4 parts to changing drill every 40 parts would save 18 min in total.

Based on the conventional drill's performance, it sometimes breaks at the forth part, which stops the system until the broken drill and scrap have been replaced. Rotary table that allows 2 parts loaded at the same is decided to use for the purpose of balancing the process flow rate and probability that process is paused due to the broken drill. With improved drill performance, the alternative rotary table (load 4 parts at a time) is recommended to reduce the operator walking time and machine waiting time as well. These time values count 20% of total cycle time based on the average value of ten measurements at the shop.

5.2.2 Cycle time comparisons

100 parts are assumed to be produced by using both the current situation and proposed solution with new drill and new peck procedure. Quality rate is considered, which required the current process to produce 104 parts to meet the requirement while proposed process can only produce the exact 100 parts. The current process needs to change drill bits 49 times (100/2 -1) while only 2 times for proposed process with improved drill life. With a new rotary table implemented, 4 parts can be loaded at the same time without worrying about the broken drill, which can reduce the machining cycle (MC) to from 50 to 25. Therefore, each process time can be computed as shown in Table 5.1.

Table 5.1: Comparison on cycle time between current process and proposed process

	Machining Time 11.5 min/part	Drill Changing Time 3 min/time	Loading Unloading Time 1 min/MC	Others 5 min/MC	Cycle time Per part
Current	1196 min	147 min	50 min	250 min	16.5 min
Proposed	1150 min	6 min	25 min	125 min	13.1 min

As it is stated, cycle time per part is reduced by 3.4 min as the result of the improvement of drill life performance, which counts the 21% reduction.

5.2.3 System lead time reduction

The wire EDM process is found out to be even faster than the robodrilling process, which results in WIP between the two processes to quickly become exhausted. This result would stop the EDM process, and would increase the total lead time of 212-Valve production system. A base stock level of 5 trays for WIP buffer is determined to balance the machining time of two processes in the designed pull based system [2]. With other buffers and inventory management policy implemented, the lead time to produce 100 units of the 212-Valve is estimated to be 33 hours [1]. The robodrilling process is still the bottleneck of the 212-Valve production system, and the improvement of this process discussed in this thesis can help material flow more efficiently. A 21% reduction in the cycle time of the robodrilling process would make EDM wait 2 trays less than that, even without improvement based on the simulation results [2]. The corresponding savings in the overall lead time is calculated to be 3.78 hours [2]. Therefore, a reduction in lead time of 11% can be achieved by using the new drill bits and new pecking procedure. Refer to Bingxin Yao's and Snegdha Gupta's theses [1-2] for detailed analyses.

Chapter 6
Recommendation

6.1 New Micro Drill Bits

As the analysis and experimental results show, the new micro drill bits last 5 times longer than the conventional drills (125 holes vs. 25 holes). The additional cobalt percentage and chromium improves the drill bits hardness and wear resistance. The reconditioned point angle helps achieve the better engagement. The wider and deeper flute near the cutting edge helps remove chip more efficiently. The specification of new micro drill bits is listed as following:

Table 6.1: Specification of new micro drill bits

Material	Tungsten carbide (Japan Sumitomo AF1)
Diameter	0.275 mm
Flute length	4.8 mm
Re-conditioned point angle	124.5°
Variable spiral technology	●

Therefore, the new micro drill bits with all modifications are recommended to replace the conventional drill bits and use on the real production process.

6.2 Quadratic Peck Drilling Procedure

Peck drilling is preferred to be applied when drilling deep holes. Decreasing the peck value as the drill reaches deeper will help limit the amount of heat generated at the end of drilling process and also remove chips more easily. Analysis and experimental results indicate that decreasing the peck value as a quadratic form generates the better tool life performance than decreasing the peck value linearly. This can be explained by the shape of parabola. Quadratic procedure allows drilling much deeper at the beginning compared to the linear procedure when chip is easily to be removed out and heat is not accumulated to a certain level. At the end of drilling process, quadratic procedure will only remove less amount of material when temperature is elevated to extremely high and coolant is impossible to penetrate into the bottom of hole. Three quadratic procedures were compared by adjusting parameters such as initial peck value and number of pecks. Final peck value was calculated by an appropriate equation. It is found out that initial peck should not be aggressive (large than 1 diameter) that causes drill bits hard to engage into the starting hole and become broken easily. Initial peck value near 0.11 mm is the optimal when balancing the drill life and drilling cycle time. The comparison of experiments also concluded that the less chip removal in the end, the better tool life result will be generated. This leads to the third quadratic procedure generate the best results among all the experiments.

Therefore, quadratic peck drilling procedure with 0.1143 mm (0.0045 in) as the initial peck value, 35 as peck cycles and 0.001778 mm (0.00007 in) as the final peck value is recommended to be run on the real production.

6.3 New Rotary Table

As the micro drill life improved, concern on the quality of micro drilling can be eliminated. The more parts machined at the same time, the less machining cycles there are for the operator to manage. The walking time and waiting time, or "down time" as it is referred to in most manufacturing industries [14-17], is significantly reduced as well as other time associated with the current process. The comparison between current process and proposed process in Table 5.1 demonstrates the benefit of new rotary table.

Therefore, a new rotary table that allows 4 parts loaded is recommended.

Chapter 7
Conclusion and Future work

7.1 Conclusion

In this thesis, drill bit parameters and peck drilling procedures were analyzed and modified to improve the drill life performance and therefore optimize the economic efficiency of the drilling process.

Tool material properties were analyzed first. The measurement result states that the conventional carbide drill has a low percentage of cobalt, which has strong characteristics for wear resistance and heat resistance. Thus, high weight percentage of cobalt became the first criteria to select the new drill on the market. Analysis on the drill breakage type shows it belongs to brittle fracture, which can be avoided by improving the hardness of the drill. In order to achieve this, chromium is added because of its superior hardness property. Drill diameter and flute length are two major factors that affect the stiffness of the drill bits used. Choosing the largest diameter and shortest flute length as possible while also considering the presence of oversized cutting and design requirement is the way to maximize the stiffness of any drill. To better engage into the initial hole made by the spotting drill with point angle of 120°, research and analysis suggests reconditioning the point angle by considering the point angle of 130° as the normal case for commercial available high performance micro drill bits. Space inside the flute is another factor being analyzed. Chip adhesion and chip jamming are two common problems for micro drilling. With the larger space to remove heat and chip efficiently, the drill life was predicted to be longer than it used to be using the current process. Considering the effect of all of the independent variables, a qualified drill bit was selected from market search to meet all the requirements and recommendations. Measurement outcomes confirmed all the modifications of new drill bits and their benefits. Testing results show the huge difference in drill life performance between two kinds of drill bits and indicate that the new drill bits are preferred on the real production.

Peck drilling procedure is the only dependent variable being adjusted and tested. Different from the procedure of pecking with constant value, drilling deeper in depth at the beginning while shallower in the end is recommended to use, based on the analysis of chip formation and chip removal. Reducing algorithm can be fitted in either a linear form or a quadratic form, while quadratic procedure can help remove more material than linear procedure based on their equation properties. Experimental results confirmed the advantage of quadratic procedure. Three quadratic procedures with different parameters were tested and compared to provide the optimal result. The initial peck value was determined to be near 0.11mm according to the previous work done by Waters. Final peck valuc was adjusted by number of pecks to reach the minimal positive number. Comparison results concluded that the smaller final peck value, the longer drill life it would be. The optimal quadratic pecking procedure has the initial peck value of 0.1143 mm (0.0045 in), the final peck value of 0.001778 mm (0.00007 in) and 35 pecks in total.

The benefit of the new drill and new pecking procedure was evaluated in chapter 5. Even making the decision of changing drill bits every 40 parts (240 holes), statistical analysis predicted the quality rate of micro drilling would reach to 100% based on the central limit theory of normal distribution. The improvement of drill life also can reduce the cycle time at this step by 20%, which help increase the system efficiency significantly.

7.2 Suggestions for Future Work

Based on the scope of project and time constraint, research in the following areas was not conducted while it is worthwhile to pay attention to these factors to achieve the better results.

Coolant – coolant varies widely based on their composition and density, which each caused different surface energy, thermal diffusivity and lubricity. The viscosity of the coolant is one of the important factors that need to be considered in micro drilling. The low viscosity liquid coolant can flow easily through to the bottom of the deep hole while higher viscosity liquid cannot. Pressure and velocity are another two factors that can be adjusted to check the difference in tool life performance. Besides, micromist nozzle can be used to better penetrate the coolant with micro droplet size into the hole.

Horizontal Drilling Process – Most research results are analyzed and tested by using vertical CNC machining center. The chip moves upwards with the drill, which needs to resist the gravity force. Besides, small amount of chips may stick to the bottom of hole that causes the additional cutting force required. With the development in technology, machine manufacturers such as Mori Seiki, Haas and Kitamura have already released their horizontal machining centers. Drilling holes in horizontal direction can improve chip removal and help cutting liquid penetrate more easily. The drilling performance is predicted to be better but the real benefit compared to vertical drilling is highly expected.

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