Experimental Studying and Optimization of Cutting Parameters in CNC Turning of AA7076 Aluminum Alloy

By

Berhanu Lemmesa Alemu

A Thesis Submitted to

The department of Mechanical Design and Manufacturing Engineering

School of Mechanical Chemical and Materials Engineering

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in
Manufacturing Engineering

Office of Graduate Studies

Adama Science and Technology University

October, 2021

Adama, Ethiopia

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Under the Supervision and Guidance of

Dr. Guteta Kabeta Woyessa

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DECLARATION

I hereby declare that this Master Thesis entitled “**Experimental Studying and Optimization of Cutting Parameters in CNC Turning of AA7076 Aluminum Alloy**” is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation

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Candidate	Signature	Date

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we, the advisors of this thesis, hereby certify that we have read the revised version of the thesis entitled "**Experimental Studying and Optimization of Cutting Parameters in CNC Turning of AA7076 Aluminum Alloy**" prepared under our guidance by **Berhanu Lemmesa** submitted in partial fulfillment of the requirements for the degree of Mater's of Science in **Manufacturing Engineering.** Therefore, we recommend the submission of revised version of the thesis to the department following the applicable procedures.

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Co-advisor	Signature	Date

APPROVAL SHEET

We, the advisors of the thesis entitled "**Experimental Studying and Optimization of Cutting Parameters in CNC Turning of AA7076 Aluminum Alloy**" and developed by **Berhanu Lemmesa**, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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We, the undersigned, members of the Board of Examiners of the thesis by **Berhanu Lemmesa** have read and evaluated the thesis entitled "**Experimental Studying and Optimization of Cutting Parameters in CNC Turning of AA7076 Aluminum Alloy**" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in **Manufacturing Engineering.**

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ACRONYMS AND ABBREVIATIONS

CNC:	Computer Numerical Control
HSS:	High Speed Steel
ANOVA:	Analysis of variance
BUE:	Built Up Edge
DOE:	Design of experiment
DOF:	Degree of freedom
FEM:	Finite Element method
HPC:	High pressure coolant
NDM:	Near Dry Machining
MQL:	Minimum quantity lubrication
MRR:	Material removal rate
OA:	Orthogonal array
MMC:	Metal matrix composites
Ra:	Surface roughness
PVD:	Physical vapor deposition
PCD:	Polycrystalline diamond
rpm:	Revolution per minute

ABSTRACT

The important measure of quality in machining is surface roughness and it is usually difficult to obtain low surface roughness during turning of aluminum alloys due to their high ductility property. This study is mainly focused on optimization of cutting parameters (feed rate, depth of cut and spindle speed) for good surface finish and higher material removal rate during computer numerical control (CNC) turning of AA7076. The experiments were performed by using uncoated carbide insert and new cutting insert was used for each test. Taguchi L9 was selected for design of experiment. Taguchi analysis of signal-to-noise ratio and analysis of mean were used to optimize cutting parameters. Analysis of variance (ANOVA) was used to determine the influence of cutting parameters on surface roughness and material removal rate. The chips were characterized based on the ISO chip classification and the influence of cutting parameters on chip thickness and width was also analyzed. The optimum cutting parameter combination obtained was high spindle speed (1600 rpm), medium depth of cut (1 mm), and low feed rate (0.08 mm/rev). The minimum surface roughness and optimum material removal rate obtained at optimum condition were 0.9875 micrometer and 15682.83 mm3/min respectively. From ANOVA all cutting parameters were found to affect surface roughness and material removal rate significantly. Feed rate weight percentage of 46.03%, depth of cut of 29.18% and spindle speed 20.52% found to have significant influence on the surface roughness while depth of cut weight percentage 54.734%, spindle speed 19.164% and feed rate 17.473% found to have significant influence on material removal rate. From analysis of chip morphology generally snarled tubular, snarled ribbon, washer type helical, and arc type chips were observed and chip thickness was found to increase with both feed rate and depth of cut.

***Key words**: CNC turning, Taguchi, Surface roughness, Material removal rate, ANOVA*

CHAPTER ONE

1. INTRODUCTION

1.1. Background

The term machinability is used for grading of work material with respect to the machining characteristics. Soren et al. [1] have defined machinability as the ease with which metal can be machined which includes all those properties which are relevant to the machining process, such as, tool wear, cutting force, chip morphology, and the surface quality of the final product. Generally machinability can be defined as the ability of the work material to be machined or the response of material to machining.

During machining of ductile materials (such as aluminum), large chip-tool contact area is formed which increase cutting forces, machining power, and heat generation and results in formation of long and continuous chips. But, due to lower shear strength of aluminum alloys even with increased chip-tool contact areas, aluminum alloys are relatively easy to machine [2]. Aluminum and aluminum alloys have many outstanding properties that lead to a wide range of applications in different industries like aerospace and automobile. Some of these properties include good corrosion and oxidation resistance, high electrical and thermal conductivities, low density, high reflectivity, high ductility and reasonably high strength, and relatively low cost [2-3]. Aluminum alloys are alloys in which aluminum is alloyed with other metals. The typical alloying elements include copper, silicon, zinc, magnesium, manganese and thin. Series seven aluminum alloys are one of high strength aluminum alloys in which the principal alloying element is zinc, but it may also include other elements such as copper, chromium, magnesium, and zirconium.

Aluminum is lightweight, durable, malleable and corrosion-resistant metal. Aluminum has low melting temperature (660 ^{0}C) than other engineering materials. This metal is widely used for components in the aerospace, transportation and construction industries due to its outstanding properties like good corrosion and oxidation resistance, high electrical and thermal conductivities, low density, high reflectivity, high ductility and reasonably high strength, and relatively low cost [4]. The following table shows the summary of the properties of aluminum.

Table 1.1 Summary of properties of aluminum [1-4].

Chemical symbol	Al
Atomic number	13
Atomic weight	26.9815
Crystalline structure	FCC (Face centered cubic)
Density	2.7 g/cm^3
Melting point	660 ^{0}C
Minimum Yield strength	240 MPa
Maximum Tensile strength	290 MPa
Insulator or conductor	Good conductor
Boiling point	2480 ^{0}C
Modulus of elasticity	72.4 GPa
Cutting modulus	27.5 GPa
Poison’s ratio	0.31
Average specific heat (0-100°C)	$917Jkg^{-1}$ K^{-1}
Thermal conductivity (20-100°C)	238 $Wm^{-1}K^{-1}$
Coefficient of thermal expansion (0-100°C)	23.5x $10^{-6}K^{-1}$
Electrical resistivity (20°C)	$2.67x10^{-8}$ Ω.m
Atomic radius	0.143 nm

Aluminum in its pure form has low mechanical strength. Due to low strength of pure aluminum, it cannot be used for high strength applications where strength of the component is essential. So it needs to be alloyed to increase its strength [5].

1.2. Machining Process

Machining of metals is one of the oldest and very important manufacturing process in which materials are removed from the workpiece to produce the required final shape or product.

Machining is known as secondary manufacturing process as it is a process used to provide the final shape and size for parts created by primary manufacturing processes like casting, forming and etc. Machining process divides into two i.e. conventional machining and non-conventional machining. Conventional machining is a machining in which physical cutting tool is always required for cutting to be performed. For example in machining by lath machine lathe or single point cutting tool is required. On the other, there may not be a physical tool present in a non-conventional machining process. For example in laser machines, laser beams carry out the task of cutting.

1.2.1. Turning Process

Lathe machining is one of the most widely used conventional machining process which used to remove materials from cylindrical workpiece by using single point cutting tool and lathe machine tool. A lathe machine operates on the principle of a rotating work-piece and a fixed cutting tool. The cutting tool is feed into the work-piece, which rotates about its own axis, causing the work-piece to be formed to the desired shape. The following are some of main operations that can be performed on lathe machine.

- Cylindrical and conical jobs (Turning), and chamfering.
- Flat surface cutting (facing).
- Grooving (with sharp corners, rounded corners, beveled, face grooving).
- Drilling, boring, reaming, counter sink and counter boring operations.
- Parting, spinning/rotating.
- Milling, slotting and grinding by special attachments.
- Spring winding, knurling and thread cutting (external and internal).

Turning is the process of bringing a work piece to a circular form from one diameter to another diameter by removing a layer of metal in a lathe by using single point cutting tool [6]. There are two motions in turning operation i.e. primary motion and secondary motion. The primary motion of cutting in turning is the rotation of the workpiece and the secondary motion of cutting is the feed motion. Fig. 1.1 shows the basic parameters involved in turning operation.

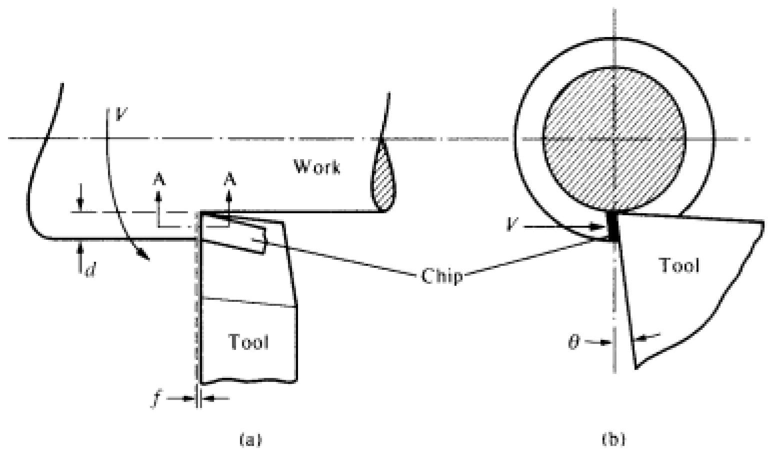


Fig. 1.1. Single point turning operation. (a) Plan view. (b) Side view. [7]

1.2.2. Cutting Parameters

Cutting parameters are a process parameters which greatly influence the machining process and the machining responses. The main machining responses are surface roughness, tool wear, material removal rate, chip formation and cutting forces. Xu et al. [8] found that chip formation and cutting force are highly influenced by feed and cutting speed.

The main cutting parameters involved in turning operation are cutting speed, feed rate and depth of cut.

1. Cutting Speed

In turning operation cutting speed (V_C) is the velocity of the tool relative to the workpiece measured in feet per minute or meter per minute. In equation it can be given as:

$$V_C = \frac{\pi D N}{1000} \tag{1.1}$$

Where, V_C is the cutting speed (m/min), D is the diameter of workpiece (mm) and N is the spindle speed (rpm). According to Eqn. 1.1, the cutting speed is directly proportional to the workpiece diameter and spindle speed.

2. Feed Rate/ Feed

Feed rate (f) can be defined as the relative motion of tool in one revolution of workpiece. It is expressed in millimeter per revolution

3. Depth of Cut

Depth of cut (d) is the total amount of metal removed per pass of the cutting tool. It is expressed in mm. mathematically, it is half of the difference of initial and final workpiece diameter.

$$d = \frac{D_0 - Di}{2} \quad (1.2)$$

Where, d is depth of cut in mm, D_o is initial diameter in mm, and D_i is final diameter in mm.

1.2.3. Surface roughness

Surface roughness is an important measure of product quality. It depends on many parameters such as cutting parameters, machine tool, cutting tool and work holding devices and it greatly influences the production cost and so the machine tool productivity. Average surface roughness (Ra), 10-point average (R10) and root mean square (Rz) are some of the principles which used to measure surface roughness. Unlike surface roughness, surface finish used to indicate smoothness of a surface. Surface roughness and surface finish are inversely proportional. When surface finish is good, its surface roughness will be decreased. Creating high-quality products and achieving high productivity is needed from manufacturing industries to gain market share from today's industry competition [9]. Surface roughness is an important factor in evaluating machining productivity as it has a significant effect on mechanical properties, such as wear resistance and fatigue strength of the machined product [10]. Cutting parameters such as cutting speed, feed rate and depth of cut greatly influence the surface roughness of machined product.

1.3. Research Motivation

A lot of researchers have been researching on experimental investigation of machining process of aluminum alloys to improve machinability of aluminum alloys mainly due to the increasing usage of aluminum alloys in different industries. AA7076 is one of high strength aluminum alloys which widely used in the manufacturing of nuts. Beside its use and high strength property its machinability property has not been studied. Surface roughness directly influence the mechanical performance of any mechanical component and usually obtaining minimum surface roughness during machining of aluminum alloys is difficult due to high ductility of the alloys. So, studying the machinability of this alloy will increase the application area of the alloy and paves the way for further study on the area. Thus, the motivation for this work is mainly due to the above said reasons.

1.4. Statement of Problem

In the recent years the application of aluminum alloys in manufacturing industries has been increasing significantly due to the outstanding properties of aluminum alloys like corrosion resistance, high electrical and thermal conductivity and relatively low cost. Due to this growing demand the machining of aluminum alloy has been growing significantly. The major challenge in any modern manufacturing industry is increasing productivity in the competitive market by manufacturing a quality product that meets the customer demand. Productivity in machining means manufacturing of good quality product at lower cost in a lesser time. The important measure of quality in machining is surface roughness which mainly affected by cutting parameters (spindle speed, feed rate and depth of cut). Material removal rate is one of the measure of productivity during machining and it also depends on cutting parameters. Generally increasing feed rate, depth of cut and cutting speed increases material removal rate which increases production rate but also increase risk of deterioration of surface quality and increase of tool wear. Due to high ductility of aluminum alloys achieving good surface finish is usually difficult.

Thus, during machining of aluminum alloys, optimizing cutting parameters for good surface finish, high material removal rate and low tool wear rate is compulsory to achieve high productivity and meet the growing customer demand for quality product in this competitive market. During aluminum alloy machining determining optimum parameters at which best surface finish is obtained greatly improves the productivity of the machining process as achieving good surface finish is the major problem during aluminum machining.

Generally, studying the machinability of AA7076 and optimizing cutting parameters for good surface finish and optimum material removal rate increases the productivity and economy of the machining process.

1.5. Research Questions

At the end of this research work the following question will be answered:

I. What are the difficulties in machining of aluminum alloys particularly in CNC turning of AA7076 and how to minimize them?

II. What is the optimum cutting condition in the turning of AA7076 aluminum alloy and what are the most significant cutting parameters?

III. What does the chip morphology of AA7076 aluminum alloy look like and how cutting factors affect the chip thickness during turning?

IV. What are the values of surface roughness and material removal rate at the optimum condition?

1.6. Objectives of the Study

1.6.1. General Objective

The general objective of this research is to study the machinability of aluminum alloy AA7076 and optimization of cutting parameters for optimum surface finish and material removal rate.

1.6.2. Specific Objectives

The following are the specific objectives of the research:

I. To study the machinability of AA7076 aluminum alloy.

II. Optimizing cutting parameters for good surface finish and identifying the most influential parameter on surface roughness and material removal rate during CNC turning of aluminum alloy AA7076 by using DOE.

III. To determine the surface roughness and material removal rate at optimum cutting parameter.

IV. To analyze chip morphology during CNC turning of aluminum alloy AA7076.

1.7. Significance of the Study

Profitability is the ultimate goal of any manufacturing industry and it directly relates to quality of product to be manufactured and the total cost of machining. Turning is one of widely used machining process due to its wide application as cylindrical components. So, it is important to study and optimize the effect of cutting parameters such as feed rate, depth of cut and spindle speed on surface roughness and material removal rate. Surface roughness is an important measure of product quality and it directly influences the mechanical performance of any mechanical component. Therefore, one of the significance of studying the machinability of AA7076 and optimizing cutting parameters for minimum surface roughness is that it can increase the profitability of the machining process by increasing the quality of final product and reducing the total machining cost. Therefore, it is highly significant for metal manufacturing industries particularly for local industries like Akaki Basic Metals Industry. The other significance of the study is for researchers who want to further explore about the machinability of AA7076 aluminum alloy.

1.8. Scope and Limitation of Study

The scope of the study mainly focused on studying the machinability of AA7076 and optimization of cutting parameters (feed rate, depth of cut and spindle speed) for good surface finish. In this study the most significant cutting parameter that affect the surface roughness were identified. The chip morphology was also analyzed.

The limitation of the study is that the effect of cutting force, machine vibration, tool geometry and tool material on surface roughness and material removal rate were not studied. This was due to the difficulty of considering all factors simultaneously and unavailability of equipment to measure cutting force and vibration frequencies.

1.9. Structure of the Thesis

This thesis organized from five chapters as follows:

- ✓ Chapter one presents introduction about the thesis which includes introduction to aluminum alloys and machining process parameters, problem of statement and motivation for the study, significance and objectives of the study, and finally scope and limitation of the study are included.
- ✓ Chapter two presents a review of research works on machinability of aluminum alloys. The chapter discusses the viewpoints of several researchers on machining of different types of aluminum alloys.
- ✓ Chapter three discusses about the methodology of the thesis which includes equipment used, experimental procedure, workpiece and tool material, design of experiment, and measurement of response parameters.
- ✓ Chapter four presents result and discussion of the major findings of the experimental work. It discusses the effect of cutting parameters (feed rate, depth of cut and spindle speed) on surface roughness and material removal rate. It also discusses about the chip morphology during turning of AA7076.
- ✓ Chapter five presents conclusion of the overall study and recommendation for future research work.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Introduction

Due to the increasing demand of aluminum alloy in machine components there is a great need for producing high quality machined components at reduced cost and to the required surface finish. Cost and surface finish mainly depends on the cutting process parameters employed during machining. The most important cutting process parameters are cutting speed, feed rate, and depth of cut. Optimizing these process parameters reduce the total production cost and increase the surface finish of the final product. These cutting parameters also greatly influence cutting force, heat generation, tool life, tool wear, and surface integrity during machining. So, it needs to be optimized. Many researchers have investigated the effect of cutting parameters (cutting speed, feed rate, depth of cut) on surface roughness, chip morphology, tool life, and production time during machining of different aluminum alloys. To understand machining process it is essential to be familiar with the chip formation process. Machining of aluminum alloys usually generates long and stringy chips which results in poor surface finishing and augment cutting forces. But in relation to other metals machining of aluminum alloys is relatively easy as the shear strength of aluminum alloy is relatively low [2].

This chapter covers a review of factors governing the machining of aluminum alloys. These are cutting factors used during machining and the machining responses obtained. The main cutting factors during machining are the cutting parameters (cutting speed, feed rate and depth of cut), coolant, and cutting tools. The main machining responses are surface roughness, tool wear and cutting forces. Generally in this chapter the following main points will be covered:

- Forces and power generated when machining of aluminum alloys
- Recommended cutting tool and tool wear when machining of aluminum alloys
- Recommended cutting fluid when machining aluminum alloy
- Chip formation when machining aluminum alloy

In each sub topics, the viewpoints of several researchers are presented and discussed in detail.

2.2. Forces and Power Generated during Machining of Aluminum Alloys

During machining process, cutting force is the most important response parameter which directly affects the cutting process. Tool breakage, tool-wear and workpiece deflection are mainly developed due to cutting force produced during the machining process. During turning process the force is acting on the tool material, and can be resolved into feed force (F_f), radial force (Fr), and cutting force (F_c). These force components acting on the tool material are shown in Fig. 2.1

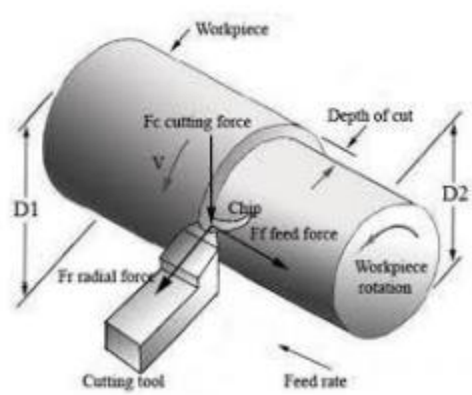


Fig. 2.1. Schematic representation of cutting force during turning [11].

Due to lower mechanical strength of aluminum alloys, cutting forces in the machining of aluminum alloys are usually low compared to those of ferrous alloys. Cutting parameters greatly influence cutting force during machining. During aluminum machining increasing the cutting speed normally reduces the machining forces [12], [13]. S Ohdar et al. [14] have experimentally investigated the effect of cutting parameters (feeding rate, cutting velocity and cutting depth) on cutting force during turning of Al-SiC alloy using HSS cutting tool. They found that feed and depth of cut greatly influence cutting force than cutting speed. Researcher at [15] also found that cutting force is greatly influenced by feed rate and depth of cut than cutting speed.

Rao et al. [16] have studied the effect of cutting parameters on cutting force during turning of aluminium alloy-AA6063 using physical vapour deposition coated and uncoated carbide tools. The ANOVA result showed that the depth of cut influenced (79%) more on cutting force compared to speed (8%) and feed (5%). Agustina et al. [17] have performed experimental analysis on the effect of cutting parameters on cutting force during dry turning processes of aluminium alloy (UNS A97075). After analysis by design of experiment, it was observed that feed rate is the most influential parameter on cutting force followed by depth of cut and spindle speed respectively. Larbi et al. [18] have studied the effect of cutting parameters such as speed, feed and rake angle on the main cutting force by simulating an orthogonal cutting operation on a testing apparatus based on a split Hopkinson pressure bar on 6060 Aluminum, 2024 Aluminum, 35 NCD 16 Steel and TAl6V4 Titanium. The result showed that, for all materials the cutting force decreased with the increase in cutting speed.

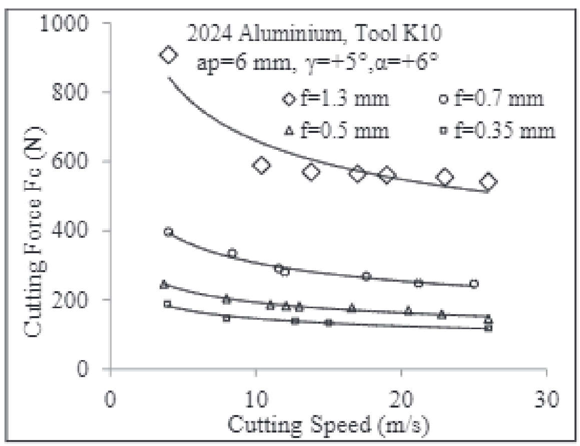


Fig 2.2. Effect of cutting speed and feed on cutting force for 2024 T4 [18]

Tool geometry strongly influences machining forces during machining of aluminum alloys. An increase in the rake angle reduces the machining forces as it can reduces the chip-tool contact area [19]-[20]. Roy et al. [21] have studied cutting forces in dry machining of aluminium using seven different cutting tool materials : coated carbide tools with a top coating of (1) as received, (2) TiC , (3) TiN, (4) Al_2O_3, (5) AlON, (6) TiB2, and (7) diamond—HFCVD (hot filament chemical vapor deposition). The result clearly reveals the inefficiency of TiC, TiN, TiB2, Al_2O_3, and AlON in dry machining of aluminium due to high cutting force as shown in Fig 2.3. High cutting force is the result of the formation of very large amount of metal built-up in both rakes and flank surface.

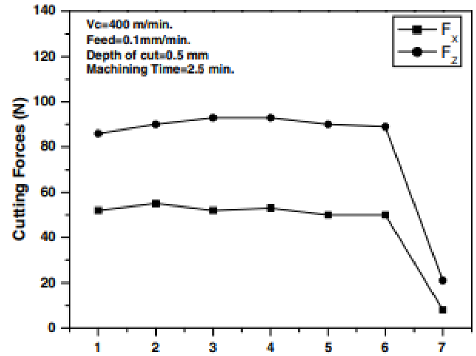


Fig. 2.3. Cutting forces developed by different cutting tools during turning aluminum bar after 2.5 min [21].

Ajay and Vinoth [22] have studied the influence of cutting parameters such as depth of cut (d), feed rate (f) and cutting Speed (s) on cutting force during turning of aluminium 6061 using High Speed Steel (HSS) cutting tool. Experiments were conducted using central composite design. They found that feed rate and depth of cut greatly influence the cutting force and the cutting force increases with the increase of both depth of cut and feed rate.

During machining of metals the cutting power generated depends on the mechanical strength of the metal, the cutting parameters and the type of cutting tool material used. Rao et al. [16] found that machining with PVD coated carbide inserts delivered 10% less power compared to uncoated carbide inserts during turning of aluminium alloy AA6063. Nur et al. [23] have investigated the effect of cutting parameters on power consumption during dry turning of treated Al-11%Si alloy using coated carbide tool at different cutting speed (70, 130 and 250 m/min) and feed (0.05, 0.10 and 0.15 mm). It was found that cutting power increases with increase of depth of cut and decreases with the increase of cutting speed.

2.3. Cutting Fluid or Coolant

Machining is a very important process in manufacturing and has direct effect on the total production cost. Cutting fluids are applied during machining of metals for lubrication and cooling purpose which used to improve production rate. During machining heat is generated due to the friction between chip and cutting tool and friction between chip and workpiece [24].

The main benefits of coolant in machining are:

- Lubrication of tool/chip/workpiece interfaces.
- Cooling the workpiece and the tool.
- Prevent or delay formation of a built-up edge (BUE) on the tool.
- Prevention of corrosion of the workpiece and/or the machine tool.
- Help to evacuate the chips out of the cutting area.

Four main types of cutting fluids used in machining are straight petroleum-based oils, emulsifiable oils, synthetic fluids, and semisynthetic fluids. Synthetic fluids can be used in milling and turning processes for lubrication and cooling purposes.

The appropriate selection of cutting fluids in machining process depends on many factors such as workpiece material, cutting tool, machining process and cutting speed used. Generally cutting temperature increases with the increase in the cutting speed. By using cutting fluid the build-up edge (BUE) formation during low speed machining of aluminium alloys can be reduced. The oils or emulsions and Semisynthetic fluids can be used for machining of aluminium alloys.

Several lubrication or cooling techniques have been developed in recent years for controlling the temperature in the cutting zone during machining. Some these techniques are:

- Cryogenic cooling.
- Solid coolants/lubricants.
- Flood cooling.
- Minimum quantity lubrication (MQL)/near dry machining (NDM).
- High pressure coolants (HPC) and.
- Internal tool cooling and use of compressed air/gases.

When applied during machining of aluminum alloys cutting fluids reduce surface roughness of machined workpiece, reduce built up edge on cutting tool and facilitate chip removal from tools rake face [21], [24]. Minimum quantity lubrication is a mode of lubrication in which very small lubricant flow (ml/h instead of l/min) is used. The lubricant is mixed with air to form an aerosol and delivered close to the cutting edge. MQL is one of cooling techniques, which is economical and eco-friendly and more efficient than dry machining in generating good surface finish, lesser tool wear and economic machining [25-26]. Cagan et al. [27] investigated the surface roughness and chip morphology of aluminum alloy in dry and minimum quantity lubrication machining. Al7075-T6 aluminum alloy was turned at different cutting speed in dry and minimum quantity lubrication (MQL) conditions. It was found that the surface quality of the Al7075-T6 alloy workpiece was improved when machined in the MQL than in the dry condition. It was also found that longer chip formation occurs in the MQL environment than a dry environment. Kishawy et al. [28] investigated the effect of flood coolant (CM2 coolant), dry cutting, and minimum quantity of lubricant (synthetic phosphate ester BM2000 with pressure) technologies on tool wear, surface roughness and cutting forces during milling of aluminum alloy A356 at different cutting speed and feed rate. It was observed that the better results were obtained under MQL condition.

Generally according to reviewed works in the literature, better surface quality, lower cutting forces, better tool life and chip formation can be achieved when aluminum alloys are machined under lubrication condition. Yoshimura et al. [29] on their study on near dry machining of aluminum alloy, they suggested that aluminum alloys should not be machined dry due to their high ductility. List et al. [30] also suggested the same thing.

2.4. Selection of Cutting Tool

High-speed steels (HSS), straight grade (K) of cemented carbides, and diamond-based tools are the main tools which used for machining aluminum alloys [16]. Coated carbide tools are not suitable for machining of aluminum alloys as they have a chemical interaction with the aluminum matrix which results in a rapid tool failure [20]. Umroh et al. [31] experimentally found that uncoated carbide tool can successfully machine Aluminum 6061 at high speed. On the other hand, Hariharan et al. [32] found that coated carbide tools generate good surface finish than the uncoated carbide tools. Diamond cutting tool highly reduces the adherent layer accumulated on the tool edge during aluminum machining [29]. Toropov et al. [33] recommended K10 grade cemented carbide tool for machining of silicon containing aluminum alloys. Polycrystalline diamond (PCD) tools can withstand the wear mechanism more efficiently than cemented carbide tools, so they are recommended for machining of aluminum alloy that contains very hard particles like ceramic or silicon [34]. Liew et al. [35] performed dry machining experiment for proper selection of cutting tool. Machining of rolled aluminum were carried out at cutting speeds of 336, 426, and 540 m/min, feeds of 0.045, 0.06, and 0.09 mm/rev, and a constant depth of cut of 0.2 mm in dry condition. Five cutting tools WC SPUN grade, WC SPGN grade, WC + PVD (physical vapor deposition) TiN coating, WC + Ti (C, N) + Al_2O_3 PVD multilayer coatings, and PCD (polycrystalline diamond) were utilized for the experiments. The surface roughness produced, total flank wear, and cut chip thicknesses were measured. They found that PCD tool provides better results in all aspects. Ciftci et al. [36] performed turning tests in the Al-2014 alloy matrix composites containing 8 and 16 % vol. SiCp using uncoated and triple-layer coated (TiC, Al_2O_3 and TiCN) carbide (K10) inserts with 5° rake angle and cutting speeds ranging from 20 to 80 m/min to investigate the effects of cutting speed and coating of tool on tool wear and surface roughness. They found that coated carbide cutting tools are more resistant to tool wear than uncoated carbide tools and uncoated cutting tools produced better surface finish.

Generally according to the literature review, the PCD is considered as the best cutting tool material for machining of aluminum alloys followed by tungsten carbide cutting tools. In this study carbide cutting tool was used for the turning operation.

2.5. Tool Life and Tool Wear when Machining of Aluminum Alloy

Smooth, safe and economic machining requires prevention of premature and catastrophic failure of the cutting tools and reduction of rate of tool wear. Cutting tools generally fail by one of the following three reasons [37]:

Mechanical breakage or fracture failure: This mode failure occur due to excessive forces and shocks. Such kind of tool failure is random and catastrophic in nature and hence are extremely detrimental.

Plastic deformation: This mode of failure occur due to intensive stresses and temperature. In this mode of failure the cutting tool tip will soften due to the increased temperature and stress which leads to plastic deformation and loss of the sharp edge.

Gradual wear: This mode of failure occur due to gradual wear of the cutting tool at its flanks and rake surface. The first two modes of tool failure are very harmful not only for the tool but also for the job and the machine tool. Hence these kinds of tool failure need to be prevented by using suitable tool materials and geometry depending upon the work material and cutting condition. But failure by gradual wear, which is inevitable, cannot be prevented but can be slowed down only to enhance the service life of the tool.

There are two types of gradual wear: crater wear and flank wear.

Crater wear is a wear in the rake face of the tool due to the action of the chip sliding against the surface. And flank wear is a wear on the flank or relief face of the tool due to the rubbing between the newly generated work surface and the flank face adjacent to the cutting edge. The crater wear can be measured either by its depth or its area while flank wear is measured by the width of the wear band, FW. In machining process tool wear is a combination of several tool wear mechanisms. Tool wear mechanisms in machining process mainly includes abrasive wear, adhesive wear, oxidation wear, and diffusion wear [2].

Abrasive wear: In abrasive tool wear mechanism tool material is removed away by the mechanical action of hard particles in the contact interface passing over the tool face.

Adhesive wear: Adhesive wear is caused by the formation and fracture of welded asperity junctions between the cutting tool and the workpiece.

Diffusion wear: Diffusion wear caused when atoms move from the tool material to the workpiece material due to the concentration difference between the two materials. The rate of diffusion and temperature are directly related.

Oxidation wear: This type wear mechanism is wear at high temperature when soft oxide layers are formed which then taken away by the chip and the workpiece.

Based on the temperature distribution on the tool face, Xie et al. [38] assumed that abrasive wear, diffusion wear and oxidation wear are the dominant wear mechanisms for crater wear, but abrasive wear was assumed to be the dominant wear mechanism for flank wear due to hard particles in the workpiece material. It have been a major task for researchers to understand tool wear during machining as tool wear in cutting operations involves complex wear mechanisms. Many researcher have tried to investigate the tool life from cutting parameters like cutting speed, feed rate, and depth of cut. Many tool life models and tool wear rate models were developed by researchers to express tool wear in quantity. Tool life can be defined as the length of cutting time that the tool can be used before failure. Tool life models give the relationship between tool life and cutting parameter. Taylor's tool life equation states that tool life and cutting speed has exponential relation [39], see equation 2.1.

$$VT^n = C \tag{2.1}$$

where, V-cutting speed, m/min (ft/min); T- tool life, min; and n and C are parameters whose values depend on feed, depth of cut, workpiece material, tooling and the tool life criterion used.

Considering feed and depth of cut equation 2.1 can be rewritten as:

$$VT^{n}\, d^{x} f^{y} = C \qquad (2.2)$$

where, d = depth of cut (mm)

f = feed of the tool (mm/rev)

x, y: must be determined experimentally for each cutting condition

Rearranging the above equation:

$$T = c^{\frac{1}{n}} v^{-\frac{1}{n}} d^{-\frac{x}{n}} f^{\frac{y}{n}} \qquad (2.3)$$

Tool wear rate models provide information about rate of wear growth due to wear mechanisms. Tool wear rate models also relates the rate of volume loss from rake or flank face per unit contact area per unit time to cutting process parameters [40]. Astakhov and Outeiro [41] have developed a tool wear curve to describe the relation of flank/ rake wear with cutting time and overall length of cut. They have stated that the tool wear curve has three regions. The first region (I in Fig. 2.4 (b)) is the region of primary or initial wear. In this relatively there is high wear rate. The second region (II in Fig. 2.4(b)) is the region of steady-state wear. This is the normal operating region for the cutting tool. The third region (III in Fig. 2.4(b)) is known as the tertiary region. In this region tool wear is accelerated due to high cutting force and temperature.

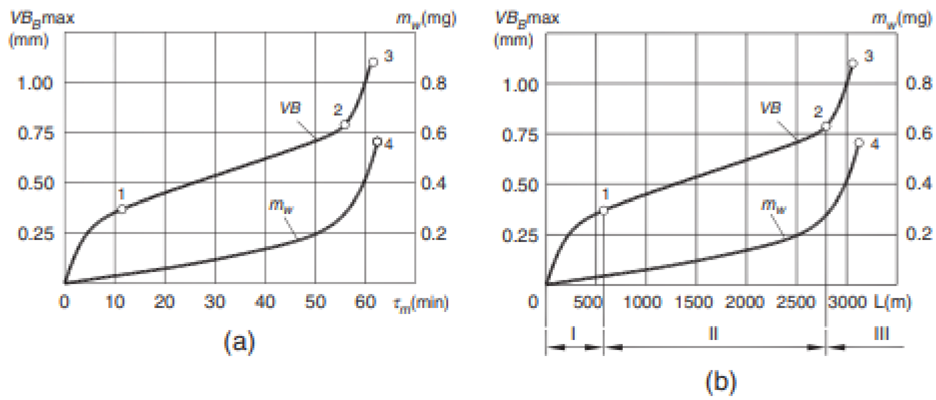


Fig 2.4. Typical tool rate curves for flank wear: (a) as a function of time and (b) as a function of cutting path [41]

During machining of aluminum alloys usually good tool life can be attained even at higher cutting speed and problem of cutting tool wear occurs in the machining of aluminum alloys containing hard particles like aluminum oxide, silicon carbide, and silicon [2]. During machining of aluminum alloys containing hard particles adhesive and abrasive wear mechanisms are accelerated due to the contact of hard particles against the cutting surface [2]. The amount of hard particle in the aluminum alloy has a significant effect on the cutting tool performance and cutting tool wear rate. The machining temperature of aluminum alloys is relatively low due to the low melting point of aluminum and its alloys which protect the tool from thermally activated wear mechanisms [2], [22]. Zakaria et al. [42] have studied tool wear during turning of Al-6063 under dry and wet condition using CVD coated tool. It was found that CVD coated better resist tool wear in wet condition as cutting fluid reduce temperature. No crater wear was observed in the wet condition.

Wear rates when machining aluminum alloy can be reduced by improving the cutting conditions, using suitable tool material and applying adequate lubrication/cooling. Jayal et al. [43] used cutting fluids during machining of aluminum alloy containing up to 18 % wt. Si. They found that there is reduction of flank wear due to the cutting fluid used. Kannan and Kishawy [44] also found the same result in machining of aluminum alloy containing 20 % vol. SiCp. Flank wear can be greatly reduced by using diamond-based tools rather than both coated and uncoated straight grade cemented carbide (WC-Co) cutting tools [21], [45]. Liang et al.

[46], tried to investigate the effect of type of tool and tool coating on tool wear when machining aluminum-silicon alloy containing 18 % wt. Si using coated, uncoated and diamond based tools. They used (1) uncoated WC 6 wt% Co (cobalt) insert, (2) WC 6 wt% Co insert, coated with ~35 μm nanostructured diamond film, and (3) polycrystalline diamond cutting tool. They reported that lower levels of flank wear was observed with the latter two cutting tools.

Cutting parameters like cutting speed, feed and depth of cut has their own influence on the tool wear during machining. Manna and Bhattacharyya [13] Performed an experiment to investigate the influence of cutting speed, feed rate, depth of cut during machining of aluminum 10 vol.%SiC-metal matrix composite (Al/SiC-MMC). They suggested that using cutting speeds of about 60 to 100 m/min and feed rates of 0.5 mm/rev minimize cutting tool flank wear. The result also shows that the flank wear increases with the increase in cutting speed as shown in Fig. 2.5.

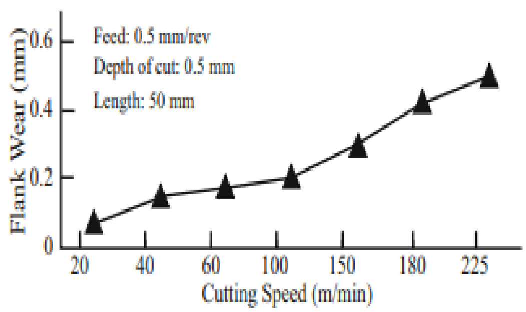


Fig 2.5. Influence of cutting speed on flank wear in turning A356 alloy [13]

Kannan and Kishawy [44] have obtained a reduction in flank wear of approximately 50 % with a coated cemented carbide tool by reducing the cutting speed from 240 to 60 m/ min when turning A356 aluminum alloy (20 % vol. SiCp) in dry machining. However, when turning at higher speeds, under wet conditions, the tool life was increased. This was mainly because of the dominance of the mechanical wear mechanisms at lower cutting speeds and the lack of formation of a lubricating layer/film that can reduce the friction between the abrasive particle and the cutting tool.

2.6. Surface Roughness and Material Removal Rate

A lot of research works has been performed to reduce the surface roughness of the machined component in machining of aluminum alloys. The following section discusses some of these relevant research works.

Abdallah [10] performed turning experiment with aluminum alloy 6061 material to optimize cutting parameters for low surface roughness value using Taguchi method. It was found that feed rate greatly affect surface roughness followed by cutting speed and depth of cut respectively. Alagarsamy and Rajakumar [47] determined the effect of cutting parameters on surface roughness while CNC turning of Aluminum Alloy 7075 using TNMG 115 100 tungsten carbide tool. It was found that surface roughness is mostly affected by feed. T. K. Durga Bhavani et al. [48] also found that the dominant factor affecting surface roughness during turning of aluminum by Tungsten Carbide tipped tool is feed. Çakır et al. [49] studied the effect of cutting parameters on surface roughness in the turning of AA7075 and AA2024 aluminium alloys. The samples were turned at four different cutting speeds (150, 187.5, 240 and 300 m/min), two different feed rates (0.1 and 0.2 mm/rev) and four different lubricant flow rates (0.25, 0.45, 0.90 and 3.25 ml/min). At the end of experiments, it was observed that increasing feed rate and cutting speed decreases the surface quality or increases the surface roughness. It was also found that increasing flow rate decreased surface roughness values and under the same condition, the surface roughness of AA7075 was found to be greater than that of AA2024. Kannan and Kishawy [44] studied the effect of cutting speed on roughness at constant feed of 0.05 mm/rev and the depth of cut of 0.2 mm during turning of aluminum alloy EN AW-2017 by using indexable inserts of cemented carbide cutting tool. During the turning process the cutting speed was changed in the range of 50 m/min to 550 m/min. the result shows that there is a slight decrease of the surface roughness values (Ra, Rz) as shown in figure.

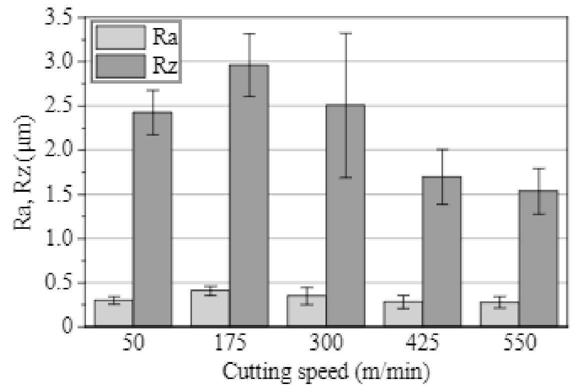


Fig. 2.6. Influence of the cutting speed on Ra and Rz [44].

Panthangi et al. [50] have optimized cutting parameters (feed, depth of cut and cutting speed) for improving surface finish in turning of LM9 Aluminum casting alloy under dry cutting condition. It was found that depth of cut is the most significant factor and feed rate is least significant factor influencing surface roughness. Palaniappan et al. [51] have experimentally investigated the effect of cutting parameters (feed, depth of cut and spindle speed) in CNC turning of Aluminium 6082 using tungsten carbide cutting tool. The most significant parameter for MRR was found to be speed while feed was found to be the most significant parameter for surface roughness. Patel et al. [52] used central composite design to investigate the effect of four machining parameters i.e. cutting speed, feed rate, depth of cut, and tool nose radius on the average surface roughness during turning of Al 7075. ANOVA was used to find the significant parameter. Increasing cutting speed was found to increase surface roughness due to the increase in cutting temperature, cutting force and vibration. Increasing tool nose radius found to reduce surface roughness and its effect was insignificant on MRR. Increasing depth of cut and feed rate was found to have negative effect on surface roughness and results increase in material removal rate.

2.7. Studies on Chip Formation

Studying chip formation during machining plays significant role in studying the machinability a metal as the type of chip produced affects the surface roughness of machined surface. Due to high deformable nature of aluminum alloys usually continuous chips are produced during machining of aluminum alloys. Different researchers have been trying to investigate chip formation during turning of different aluminum alloys.

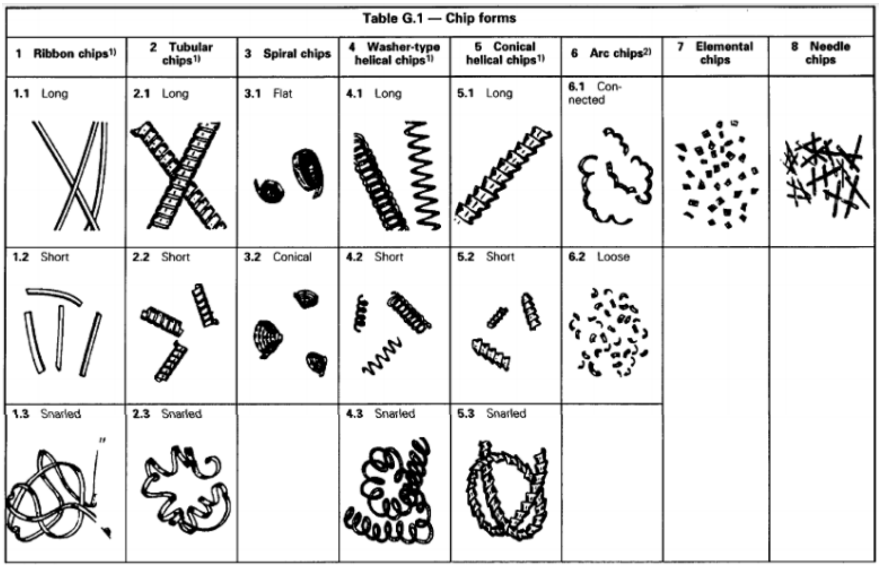


Fig. 2.7. ISO 3685 chip classification [53].

The above Fig. 2.7. Shows the ISO classification of chip types during turning operation.

Cagan et al.[27] studied the chip formation in high speed turning of Al 7075-T6 three different cutting speed values (400 m/min, 450m/min and 500 m/min) in both dry and minimum quantity lubrication (MQL) conditions at constant depth of cut (1 mm) and feed (0.1 mm/rev). It was observed that ‘‘snarled” type chips were obtained in both dry and MQL conditions. There was a slight increase in the length of chip in MQL condition. This shows that there is a proper tool-chip interaction with temperature reduction due to MQL lubrication. Significant difference in chip was not observed due to increase in cutting speed as shown in Fig. 2.9. Saravanakumar et al. [54] studied the chip formation during turning of aluminum alloy 6063 with carbon nitride inserts at different spindle speed (800, 1000 and 1200 rpm), feed (0.15, 0.25 and 0.35 mm/rev) and depth of cut (0.2, 0.4, and 0.6 mm). It was found that continuous chips were formed at high cutting speed and discontinuous chips were formed at high depth of cut.

Fig. 2.8. Chip morphology images comparison at different machining environments [54]

Xu et al. [8] have studied chip formation in high speed orthogonal cutting of aluminum alloy 6061-T6 both experimentally and by developing theoretical model. Three type of chips were observed (continuous chip, curl chip and discontinuous chip). Increasing cutting speed resulted in the formation continuous chip and decrease in the chip thickness while increase in the feed rate increase chip thickness and changes chip type to curl chips.

Table 2.1 Literature summary

No	Reference	Material under study	Tool material	Parameter of study	Analysis method	Outcome/ result obtained
1	S Ohdar et al. (2016) [14]	Al-SiC	HSS	Cutting speed Feed Depth of cut	Taguchi and ANOVA	The surface roughness was highly influenced by depth of cut followed by feed and cutting speed. Cutting speed was the influential factor for power consumption and cutting force.
2	C. Veera Ajay and V. Vinoth (2020) [22]	Al 6061	HSS	Cutting speed Feed rate and Depth of cut	Central Composite Design and ANOVA	Both surface finish and cutting force were found to be highly influenced by feed rate and depth of cut. Increasing both feed rate and depth of cut increases both cutting force and surface roughness. Optimum combination was obtained at higher cutting speed and lower depth of cut and feed rate.
3	Abas, Muhammad et al. (2020) [26]	Al 6026-T9	Tungsten carbide insert	Cutting speed, Feed rate, Depth of cut, Positive rake angle in both dry and MQL condition	Taguchi and ANOVA	For both dry and MQL conditions, feed was found to be the most significant cutting parameters for surface roughness. The tool life was mostly influenced by cutting speed followed by feed rate while the MRR influenced by cutting speed, followed by depth of cut and feed rate.
4	Cagan et al. (2020) [27]	Al 7075-T6	DNMG 150604	Cutting speed, Feed rate, and Depth of cut in both dry and MQL condition		It was found that the surface quality obtained after the turning process in the MQL environment is better than the dry environment. The chips obtained after the turning process in the MQL environment have longer chip geometry compared to the dry environment. Surface roughness values

						for MQL environments were found to be up to 15% less than dry environments.
5	Hariharan et al. (2021) [32]	LM6 high silicon aluminium alloy	uncoated and AlTiN & DLC coated carbide inserts	Cutting speed, Feed rate, and Depth of cut in both dry and wet condition	Taguchi full factorial approach	Better surface finish was obtained in condition on comparing with dry conditions, and machining with coated tools under wet environment results in superior finish.
6	Abdallah Ali et al (2014) [10]	Aluminum alloy 6061	Uncoated carbide insert	Cutting speed, feed rate and depth of cut	Taguchi, ANOVA and RSM	Cutting speed was found to be the most influential parameter on surface roughness followed by depth of and feed rate respectively. The effect of cutting speed was more significant on surface roughness than material removal rate.
7	S.V.Alagarsamy and N.Rajakumar (2014) [47]	AA7075	TNMG 115100	Cutting speed, feed and depth of cut	Taguchi, ANOVA and RSM	It was found that only feed significantly influences surface roughness while speed and feed significantly influences MRR. The effect of depth of cut was found to be insignificant for both surface roughness and material removal rate.

2.8. Research Gap

From the above literature survey it can be seen that many researchers have been trying to investigate the machinability of different aluminum alloys with respect to cutting parameters, cutting tool and cutting force generated during machining. But, the machinability of AA7076 has not been studied yet. Therefore, it is important to study the machinability of this aluminum alloy to fill the identified gap. The main intension of this thesis is to make new contribution by studying the machinability of AA7076 which mainly includes the following points:

- ✓ Optimization of cutting parameters (spindle speed, feed rate and depth of cut) for minimum surface roughness and higher material removal rate.
- ✓ Identifying the most significant parameter that affect surface roughness and material removal rate.
- ✓ Studying chip morphology during turning of AA7076.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1. Introduction

This study was conducted to investigate problems in the machining of AA7076 aluminum alloy and optimize cutting parameters during machining of these alloys by using turning operation. The aim of this section is to present the detail of the experimental procedure which includes:

- Detail description of the material used in the experiment.
- Detail about the cutting tool and workpiece material and sample preparation.
- Introduction about Taguchi method design of experiment.
- The overall experimental procedure of the research.

Every section of the chapter are discussed by using appropriate photograph image and diagram with detail explanation.

3.2. Equipment Used

Generally the following equipment were used in this study.

- CNC lathe machine
- Tungsten carbide cutting tool insert
- Surface Profilometer
- Minitab 18 software
- MS excel 2013
- Vernier caliper
- DEFORM 3D software

The application and detail of the equipment is discussed in the next sections of the chapter.

3.3. Experimental Procedure

The overall procedure of the experimental studies of optimization of cutting parameters in turning process of AA7076 is shown in Fig. 3.1.

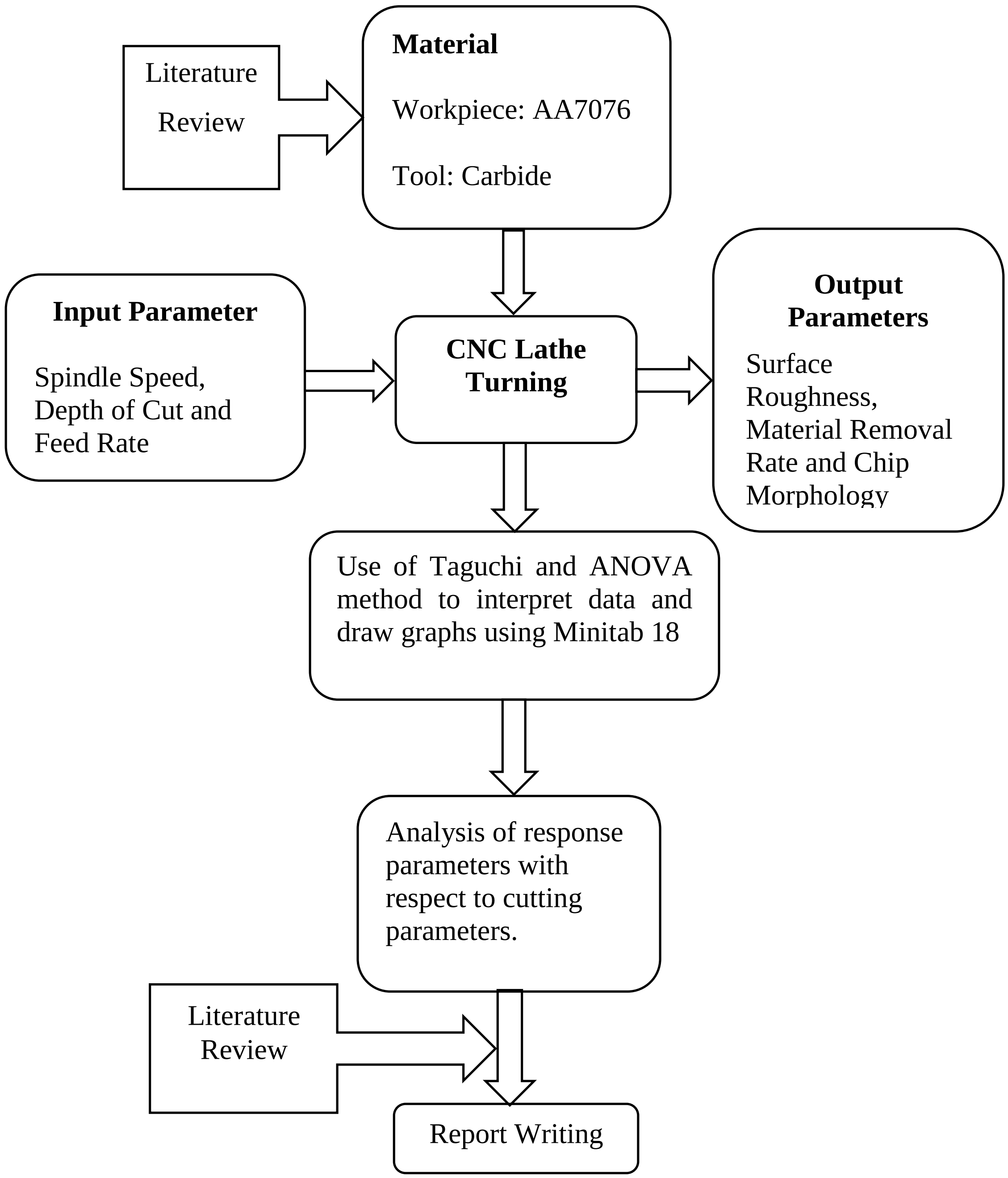


Fig. 3.1. Overall Experimental Procedure

3.4. Workpiece Material

The materials used for this study was round bar AA7076 aluminum alloy with diameter of 40.3 mm. This workpiece material was selected as it is one of the highest strength aluminum alloy and used in in high performance applications such as aerospace, aircraft, sporting equipment and etc. The chemical composition of the material was tested in Spectrotest machine with model of SPECTROTEST TXCO2 shown in Fig. 3.2. The result reported in Table 3.1.

Table 3.1 Chemical Composition of AA7076

Element	Si	Fe	Cu	Mn	Mg	Zn	Ni	Cr
Content (%)	0.314	0.58	0.185	0.345	1.51	7.84	1.17	0.089
Element	Ag	B	Bi	Cd	Sr	Li	Co	Zr
Content (%)	0.007	0.029	0.026	0.091	0.003	0.86	0.03	0.009
Element	Pb	Ga	V	Sn	Ti	Al		
Content (%)	0.045	0.021	0.012	0.089	0.085	86.7		

Fig. 3.2. SPECTROTEST TXCO2 Machine

The workpiece materials used for this study was a high strength series seven aluminum alloy AA7076 which has huge application in aerospace and aircraft industries. The aluminum alloy of 500 mm in length and 40.3 mm in diameter was prepared and it was turned with 0.15 mm depth of cut to remove any corrosion and irregular parts on its surface. And then nine experiments with length of 50 mm with different combination of cutting parameters (depth of cut, feed rate and spindle speed) which were selected by design of experiment orthogonal array were done for experimental study. In all experiments new carbide inserts were used to discard the effect of tool wear on surface roughness.

3.5. Cutting Tool Material

In this research work uncoated tungsten carbide with ISO specification TNMG 220408 cutting tool was used. Tungsten carbide cutting tool was selected based on literature review. According to the literature review, the tungsten carbide is considered as the best cutting tool material for machining of aluminum alloy that does not contain hard particles.

Specification of cutting insert (TNMG 220408)

T: Triangular

N: 0^0 relief angle

M: ± 0.08 mm tolerance

G: clamping system cylindrical hole

22: Length of cutting edge

04: Insert thickness

08: 0.8 mm corner radius

Table 3.2 Material parameters for carbide cutting tool [54]

Properties	Value
Density (kg/m^3)	15000
Thermal Expansion Coefficient (10-6 °C)	4.5
Young Modulus (GPa)	620
Thermal Conductivity (kW/m.K)	0.105
Poisson's ratio	0.22
Specific Heat (kJ/kg°C)	0.67

Fig. 3.3. Tungsten Carbide Insert and Tool Holder

3.6. Cutting Fluid Used

As stated in the literature review there is no recommended coolant for machining of aluminum alloys. But, different researchers have been using different types of coolant on their study and found that aluminum alloys cannot be dry machined due to their high ductility. In this study Aquatex 3180 general purpose soluble oil was used as a cutting fluid. The coolant was prepared by mixing the oil with two third water as recommended by the manufacturer. The mode of cooling employed was flood cooling.

Properties of the coolant

Density at 20 ^{0}C = 0.89 Kg/l

Ph at 5% dilution at 20 ^{0}C = 9.4

3.7. Turning Process

CNC (computer numerical control) lathe machine was used for experimental study of AA7076 aluminum alloy. The machine tool was manufactured by Dalian Machine Tool Group Corporation and its model is CKE6150 and its main technical specifications are reported in Table 3.3. Fig. 3.4. Shows the photograph image of the machine.

Table 3.3 Main Technical Specifications of the CNC Machine Tool

Description	Dimension
Maximum workpiece length	1000 mm
Spindle center height	250 mm
Power	24 KVA
Voltage rating	380 V
Power frequency	50 Hz
Full load current	34 A
Spindle speed range	45 RPM – 2000 RPM
Overall dimension (L×W×H)	2830 × 1750 × 1620
Machine weight	2600 Kg

Fig. 3.4. Photograph Image of the CNC Machine Tool

For turning process to be performed by CNC lathe part program needs to be developed. In this study part program was inserted by using program input device of the CNC machine tool.

3.8. Design of Experiment

To design experimental runs, it essential to establish levels for each factor. So, in this study, the process parameters (cutting speed, feed rate, depth of cut), are taken at three different levels, as shown in Table 3.4. Levels are set based on literature review. Taguchi orthogonal array L9 (having nine experimental runs) is designed as tabulated in Table 3.5. For each experimental run, a new insert was used, and the corresponding average values of responses (i.e., surface roughness parameter (Ra), and material removal rate (MRR) are measured. In the design of the experiment (DOE), the Taguchi method is mostly used in the optimization of process parameters because it can minimize experimental runs and find out significant factors in a shorter time. Taguchi also minimizes the number of trials in comparison with the other methods by using orthogonal arrays.

Taguchi approach estimate the percent contribution of each factor and predict the response according to the optimum conditions by analyzing the experimental results and establishing the optimum conditions for a product/process.

3.8.1. Taguchi Design

Taguchi method is a standard approach for determining the best combination of inputs to produce a product or service. Taguchi concept of robust design states that products and services should be designed so that they are inherently defect free and of high quality. Taguchi approach for creating robust design is a three step method consisting of concept design, parameter design and tolerance design.

Concept Design or System Design: Concept design is the first step in the Taguchi design which involves both the conceptual and functional design of the product. The conceptual design includes process technology choices and process design choices.

The functional design involves the identification of various sub tasks and their integration to achieve the functional performance of the end product. It is usually a prototype design (physical or mathematical) which developed by applying scientific and engineering knowledge.

Parameter Design: Parameter design includes the selection of control factors and the determination of optimal level for each of the factors.

Tolerance Design: Tolerance design is the process of determining the tolerance around the nominal setting identified in parameter design process.

Taguchi method uses a statistical measure of performance known as signal-to-noise (S/N) ratio, which takes into consideration both the mean and the variability and it offers three categories of signal to noise ratio as follows [55];

- Nominal is the best characteristics,

$$\frac{\mathrm{S}}{\mathrm{N}} = 10 \log \frac{\bar{y}^{\,2}}{S^2} \quad (3.1)$$

  - ✓ The quality characteristics is continuous and positive (non - negative). It can take value between 0 and - ∞.

- Smaller is the better characteristics,

$$\frac{S}{N} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} yi^2\right] \quad (3.2)$$

  - ✓ It is appropriate for surface roughness, tool wear, unit cost etc.

- Larger is the better characteristics,

$$\frac{S}{N} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} \frac{1}{yi^2}\right] \quad (3.3)$$

  - ✓ It is applicable for material removal rate, fuel efficiency, etc.

where y = observation, n = total number of observation and yi = ith response, $\bar{y} =$ is the average of observed data, $s^2 =$ the variation of y.

Cutting parameter and their level for turning of aluminum alloy were selected based on literature review, tool manufacturer recommendation and current industrial practice and experience. The selected cutting parameters were shown in Table 3.4.

Table 3.4 List of parameters and their levels

Cutting parameters	Parameters designations	Level		
		1	2	3
Spindle speed (rpm)	A	800	1200	1600
Depth of cut (mm)	B	0.5	1.0	1.5
Feed rate (mm/rev)	C	0.08	0.12	0.16

3.8.2. Selection of Orthogonal Array

The turning experiments were carried out on CNC lathe machine by using cemented carbide cutting tool inserts for machining of aluminum alloy workpiece with selected cutting parameters within three levels given in the Table 3.4.

The selection of a particular orthogonal array was based on the number of levels of various factors. Here, to conduct the experiments 3 factors each at 3 levels were selected. Now the Degree of Freedom (DOF) can be calculated by the formula as given below [55].

$$DOF = P * (L - 1) \tag{3.4}$$

where, DOF= degree of freedom, P = number of factors and L = number of levels

$$DOF = 3 * (3 - 1) = 6 \approx L_9 \tag{3.5}$$

However, the total number of experiments of the orthogonal array (OA) should be greater than or equal to the total DOF required for the experiment. Thus, the L9 orthogonal array has been selected.

Table 3.5 Experimental Layout Using an L-9 Orthogonal Array

Exp. No.	Spindle speed (rpm)	Depth of cut (mm)	Feed (mm/rev)
1	800	0.5	0.08
2	800	1	0.12
3	800	1.5	0.16
4	1200	0.5	0.12
5	1200	1	0.16
6	1200	1.5	0.08
7	1600	0.5	0.16
8	1600	1	0.08
9	1600	1.5	0.12

3.8.3. Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) is a statistical method used to interpret experimented data and make decisions about the parameters under study. In this study ANOVA was used to find the effect of cutting parameters (spindle speed, depth of cut and feed rate) on surface roughness of turned samples and material removal rate during turning. In the analysis of variance, the percentage contributions of each cutting parameters were used to measure the corresponding effects on the surface roughness and material removal rate during turning process. The significance level of 5 %, i.e. for 95 % level of confidence was considered in this analysis.

The basic equation of ANOVA is given by the following equation [55]

$$SS_{Total}=SS_{Factors}+SS_{Error} \tag{3.6}$$

where: SS_{Total} is total sum of square, SS_{Factor} is sum of square due to factors and SS_{Error} is sum of square due to error.

Percent contribution measures the contribution of each factor under study (cutting parameters in this case) relative to the total sum of squares. From the ANOVA table percentage contribution of each cutting parameter (spindle speed, depth of cut and feed rate) was calculated by the following formula [56].

$$P(\%) = \left[\frac{SSTR}{SST}\right] * 100 \tag{3.7}$$

where SSTR = treatment sum of square, SST = total sum of square and P(%) = percent contribution

In this study ANOVA table was developed for both surface roughness and material removal rate by using Minitab 18 software.

3.9. Surface Roughness Measurement

Surface roughness is an important measure of product quality and greatly influences the total production cost and so the machine tool productivity. During machining cutting parameters greatly influence the surface roughness of the machined product. The final product of every machining process needs to have low surface roughness (high surface finish). Because good surface finish improve wear resistance, corrosion and surface strength of the machined product.

In this study the surface roughness of all samples after turning were measured by using surface roughness tester and analyzed by using Minitab 18 software to find the optimum cutting parameter combination which results in good surface finish. During the measurement of surface roughness, every sample measurement was repeated at least four times at different new locations on a rod bar surface in order to ensure the repeatability and reproducibility of the result.

Fig. 3.5. Photograph Image of contact type Surface Roughness Tester with Model 657111

3.10. Calculation of Material Removal Rate (MRR)

Material removal rate (MRR) is the amount of material removed per time unit. It directly determines the productivity of the machining process as it directly related to the amount of material removed per unit time. In machining process high material removal means the removal of large amount of material per a given time which maximize the production rate. But high production rate only does not mean economic machining because increasing material removal rate usually results in high surface roughness, high tool wear rate, and high tool tip temperature which negatively affect the overall economy of the machining process. In this study, the following formula has been used to compute the material removal rate [48].

$$\text{Material removal rate MRR} = \frac{\text{Total volume of material removed (V)}}{\text{Total cutting time (t)}} \quad (3.8)$$

But, $V = \frac{\pi}{4}(D^2 - d^2) * l$ and $t = \frac{l}{Nf}$

Then Material removal rate $MRR = \frac{\pi}{4}(D^2 - d^2) * Nf$ (3.9)

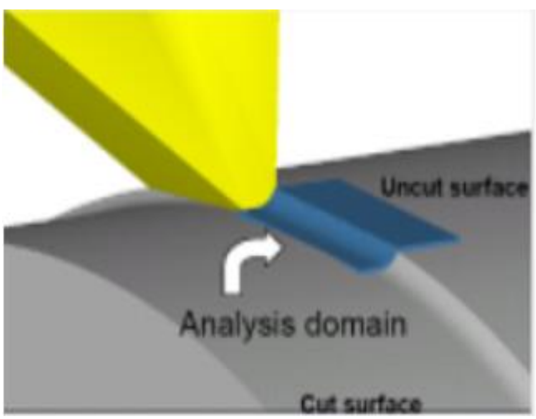
where: D is initial workpiece diameter, d is final workpiece diameter, N is spindle speed and f is feed rate.

3.11. Study of Chip Morphology

In this experimental investigation chips were collected at the end of each experiment for further study. The types of chips observed were classified based on the ISO 3685 chip classification. The chip thickness, and chip width were also measured by using Vernier Caliper which measures to the accuracy of 0.02 mm.

3.12. Finite Element Modeling

In this study, Finite Element Method (FEM) was used to simulate the orthogonal turning of aluminum alloys 7076 using the DEFORM 3D software. The model shown in Fig. 3.6 was developed for analysis by using DEFORM 3D software.



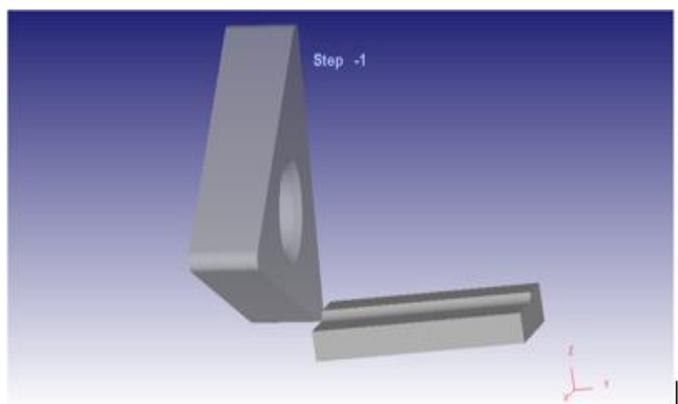


Fig. 3.6. Developed Finite Element Model

In the developed finite element model the workpiece was considered as having elastic-plastic behavior and meshed with 6000 elements and the minimum element size was set to be 25 percent of feed. The tool was considered as rigid and was meshed with 5000 elements.

The heat transfer between the tool and workpiece is given by the heat conduction equation given below [56].

$$Q = h_{cond}\,(T_{wp} - T_t) \tag{3.9}$$

where h_{cond} is heat transfer coefficient, Twp and Tt are the workpiece and tool's temperature at the tool chip interface. In this study, a heat transfer coefficient of 10^7 $W/m^2\ {}^oC$ was used. The initial temperature for both tool and workpiece was set to be 20 °C (room temperature). The heat transfer between the environment and the workpiece was given by convective heat transfer equation 3.10: [56].

$$Q = h_{conv}\,(T_{wp} - T\mathrm{a}) \tag{3.10}$$

where h_{conv} is convection heat transfer coefficient, and Twp and Ta are the workpiece and ambient (room) temperature. In the present work, h was taken 20 $W/m^2\ {}^oC$. The effect of cutting fluid was not considered in the simulation analysis.

CHAPTER FOUR

4. RESULTS AND DISCUSSION

4.1. Introduction

Experimental work was conducted to investigate the effect of main machining cutting parameters (cutting speed, feed rate and depth of cut) on the surface roughness, material removal rate, and chip morphology of aluminum alloy 7076 material during CNC turning process. The experiments were carried out on CNC lathe machine by using cemented carbide cutting tool. The design of the experiment (DOE) was used to identify the optimum cutting parameters and the most influential cutting parameters on surface roughness.

In this chapter the outcomes of the whole experiment were discussed in detail.

4.2. Samples after Turning Process

Turning process was done on CNC lathe machine at different combination of cutting speed, feed and depth of cut. The diameter of the workpiece prepared for experimental work was 40.3 mm and initial pre experiment turning was done to remove any irregularities and create smooth surface for the experiment and so the diameter became 40 mm and after turning process the diameter reduced to 39mm, 38mm, and 37mm. Experiment number 1, 2 and 3 were operated by similar cutting speed of 800 rpm but, with different feed (0.08, 0.12 and 0.16 mm/rev respectively) and depth of cut (0.5, 1.0 and 1.5 mm respectively). By similar manner experiment number 4, 5 and 6 were operated by similar cutting speed of 1200 rpm but with different feed rate (0.12, 0.16 and 0.08 mm/rev respectively) and depth of cut (0.5, 1.0 and 1.5 mm respectively). And the last three experiments were also operated by similar cutting speed of 16000 rpm, but with different feed rate (0.16, 0.08 and 0.12 mm/rev respectively) and depth of cut (0.5, 1.0 and 1.5mm respectively).

Fig. 4.1. Samples after turning process

4.3. Analysis of Surface Roughness

In this experiment, the average surface roughness values (Ra) and S/N ratios were obtained in turning of AA7076 according to the L9 orthogonal array of the Taguchi experimental design method of three spindle speeds, depth of cut and feed rates using cemented carbide cutting tools as shown in Table 4.1. The S/N ratios were calculated according to the Taguchi's "the-smaller-the-better" quality characteristics by using Minitab 18. The experimental results of surface roughness (Ra) values for each specimen and their mean values are discussed in Table 4.1. In this study, each surface roughness (Ra) value is the average of four trial readings. The mean surface roughness value of each experiment was calculated by adding trial surface roughness values and dividing by the total number of trials. For example the mean surface roughness value of the first experiment was calculated as:

$$Ra_1=\frac{1.20+1.26+1.25+1.28}{4}=1.2475\mu m$$

Fig. 4.2 shows the value of average surface roughness at each experimental runs. From the figure it can be seen that higher surface roughness value (1.9850 µm) was obtained at experiment three and the minimum surface roughness value (0.9875 µm) was obtained at experiment eight. The surface roughness values of the remaining experiment lies in between these two extremes.

Table 4.1 Experimental result for mean value of surface roughness

Experiment No.	Spindle Speed(rpm)	Depth of Cut (mm)	Feed Rate (mm/rev)	Surface roughness (μm)				Average Ra (μm)	S/N ratio(dB)
				Meas.1	Meas.2	Meas.3	Meas.4		
1	800	0.5	0.08	1.2	1.26	1.25	1.28	1.2475	-1.92081
2	800	1.0	0.12	1.65	1.61	1.49	1.56	1.5775	-3.95939
3	800	1.5	0.16	2.03	1.95	2.0	1.96	1.9850	-5.95521
4	1200	0.5	0.12	1.23	1.25	1.17	1.22	1.2175	-1.70938
5	1200	1.0	0.16	1.39	1.46	1.44	1.43	1.4300	-3.10672
6	1200	1.5	0.08	1.42	1.43	1.41	1.39	1.4125	-2.99977
7	1600	0.5	0.16	1.58	1.51	1.53	1.56	1.5450	-3.77857
8	1600	1.0	0.08	1.04	0.94	0.95	1.02	0.9875	0.10926
9	1600	1.5	0.12	1.54	1.47	1.52	1.51	1.5100	-3.57954
Average performance mean value								1.4347	-2.9889

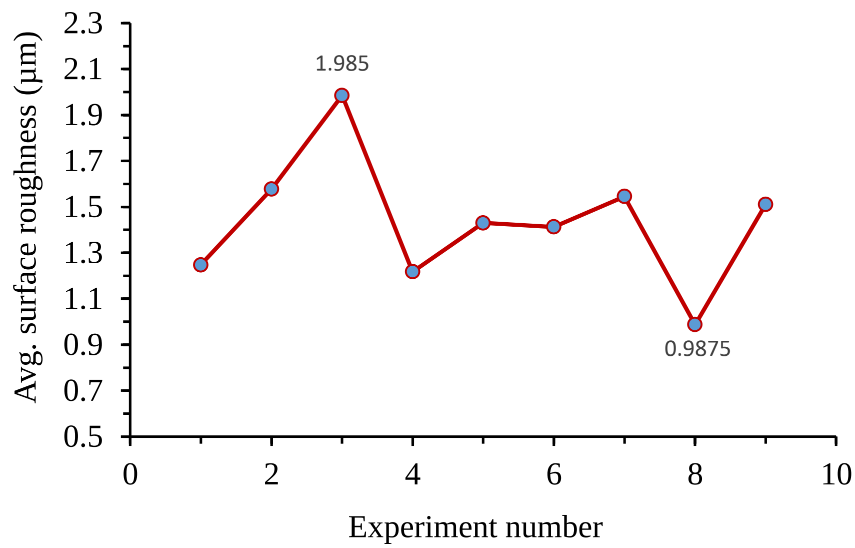


Fig. 4.2. Average surface roughness value at different experiments

4.3.1. Analysis of Mean

Design of experiment was used to analysis of average mean values of surface roughness for each factors i.e. cutting speed (A), feed rate (B) and depth of cut (C). The mean value of surface roughness for each factor i.e. Cutting speed (A), Feed rate (B), and Depth of cut (C) at each level were obtained and the results were listed in response Table 4.2.

An example of calculation has shown below for factor B (depth of cut):

$$Ra_{B1} = \frac{1\cdot 2475+1.2175+1.5450}{3} = 1\cdot 337$$

$$Ra_{B2} = \frac{1.5775+1\cdot 4300+0.9875}{3} = 1\cdot 332$$

$$Ra_{C3} = \frac{1.9850+1.4125+1\cdot 51}{3} = 1\cdot 636$$

Delta is the difference between maximum mean and minimum mean.

$$\text{Delta} = (\text{Maximum mean} - \text{Minimum mean}) \tag{4.1}$$

Table 4.2 Response table for mean effects

Level	Cutting speed	Depth of cut	Feed rate
	Symbol		
	A	B	C
1	1.603	1.337	**1.216**
2	1.353	**1.332**	1.435
3	**1.347**	1.636	1.653
Delta	0.256	0.304	0.437
Rank	3	2	1

Table 4.2 shows the Taguchi result of response for mean effect of factors on surface roughness for smaller is better characteristics. As it can be seen from the table, from the three factors feed rate has the greatest effect on surface roughness (Delta = 0.437, Rank = 1) and spindle speed has the least effect on surface roughness (Delta = 0.256, Rank = 3). This response table for mean used to adjust the parameters for better result. As it can be seen from the table **A3B2C1** can be the possible combination for better surface roughness. This shows that the significant factors in the order of increasing by affecting surface roughness are spindle speed, depth of cut, and feed rate.

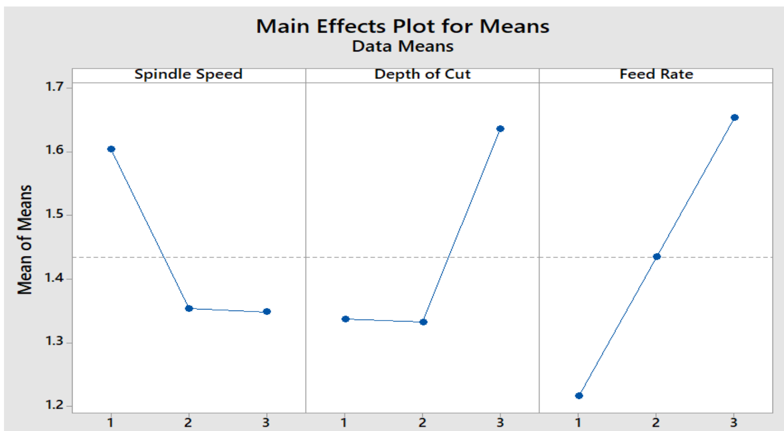
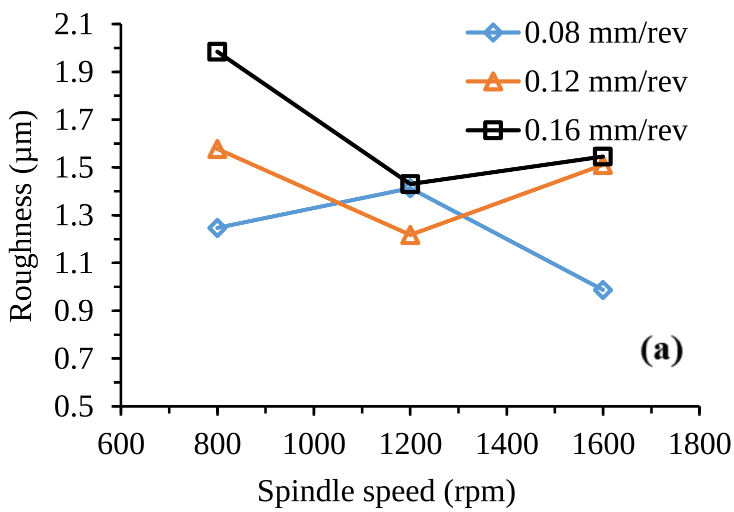


Fig. 4.3. Main effect plot for means

Fig. 4.3 shows the Taguchi result of main effect plot for means. The minimum point in the graph for each turning parameters is the optimum condition for better surface finish. The minimum point for spindle speed is at level three which is equal to 1.347, for depth of cut the minimum point is at level two which is equal to 1.332, and for feed rate the minimum point is at level one which is equal to 1.216. This shows that the optimum turning parameters for better surface finish are at high spindle speed, at medium depth of cut and at low feed rate.

Fig 4.4 (a) shows the effect of spindle speed on surface roughness at different feed rate values. From the graph it can be seen that at 0.08 mm/rev, the surface roughness first increased from 1.2475 to 1.4125 and then to 0.9875 µm as the spindle speed increased from 800 to 1200 and then to 1600 rpm respectively. At both 0.12 and 0.16 mm/rev, the surface roughness first highly decreased as the spindle speed increased from 800 to 1200 rpm and started to increase slowly as the spindle speed increased to 1600 rpm. Figure 4.4 (b) also shows the effect of spindle speed on surface roughness at different depth of cut values. It can be seen that at 0.5 mm, surface roughness first decreased from 1.2475 to 1.2175 and then increased to 1.545 µm as the spindle speed increased from 800 to 1200 and then to1600 rpm respectively. At 1.0 mm, the surface roughness decreased significantly from 1.5775 to 0.9875 µm as the spindle speed increased from 800 to 1600 rpm. At 1.5 mm also the surface roughness first decreased significantly from 1.985 to 1.4125 and then increased very slowly to 1.545 µm as the spindle speed increased from 800 to 1200 and then to 1600 rpm respectively.

Generally surface roughness decrease as the spindle speed increased. This was mainly due to the increase of cutting temperature which reduce the strength of the workpiece which in turn reduce the cutting force resulting lower surface roughness. The other reason is that at lower cutting speed built up edge will be formed due to high ductility nature of the alloy which result in increase of surface roughness. But, further increase in spindle speed may result in deterioration of surface finish due to the initiation of chemical attraction between the aluminum alloy and the cutting at elevated temperature and also due to the increase of the ductility of the aluminum alloy.



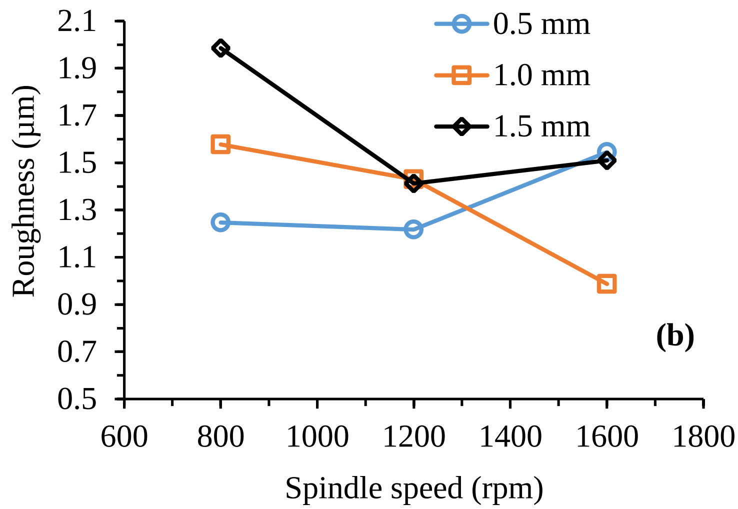


Fig. 4.4. Relationship between spindle speed and surface roughness: a**)** at different feed rate and b) at different depth of cut.

Fig. 4.5 (a) shows the effect of depth of cut on surface roughness at different spindle speed values. At 800 rpm, the roughness increased from 1.2475 to 1.5775 and then to 1.985 µm as the depth of cut increased from 0.5 to 1.0 and then to 1.5 mm. At 1200 rpm, the roughness first increased from 1.2175 to 1.43 µm and then decreased to 1.4125 µm as the depth increased from 0.5 to 1.0 and then to 1.5 mm respectively. At 1600 rpm, the roughness rapidly decreased from 1.545 to 0.9875 µm as the depth increased from 0.5 to 1.0 mm and then rapidly increased to 1.51 µm as the depth increased to 1.5 mm. Fig. 4.5 (b) shows the effect of depth of cut at different feed rate values. The surface roughness first decreased slightly as depth of cut increased from 0.5 to 1.0 mm and then increased rapidly as the depth of cut increased to 1.5 mm at both 0.08 and 0.16 mm/rev. But at 0.12 mm/rev, the surface roughness increased from 1.2175 to 1.5775 µm as the depth increased from 0.5 to 1.0 mm and then decreased slightly to 1.51 µm as the depth increased to 1.5 mm.

Generally, depth of cut influence surface roughness positively. Increasing depth of cut increase surface roughness mainly because of the increase of the cutting force as a result of the increase in plastic deformation. The increased cutting force (especially trust force) push the chip against the machined surface which results in increase of surface roughness.

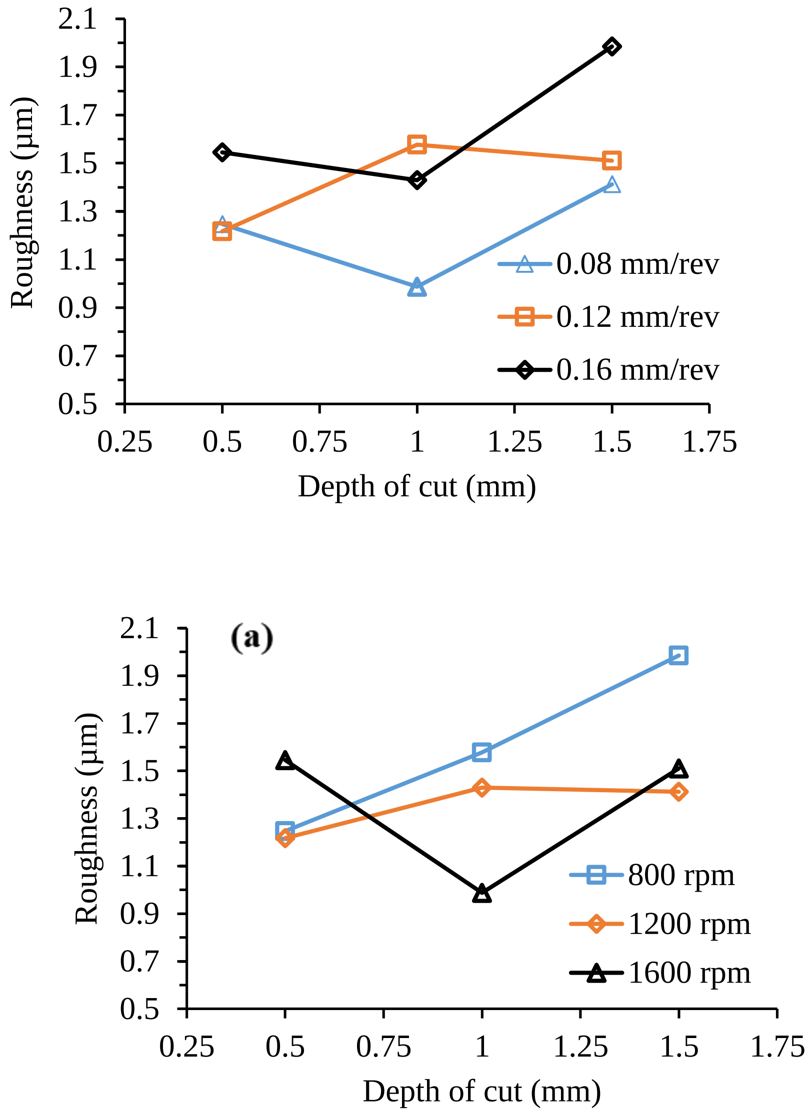
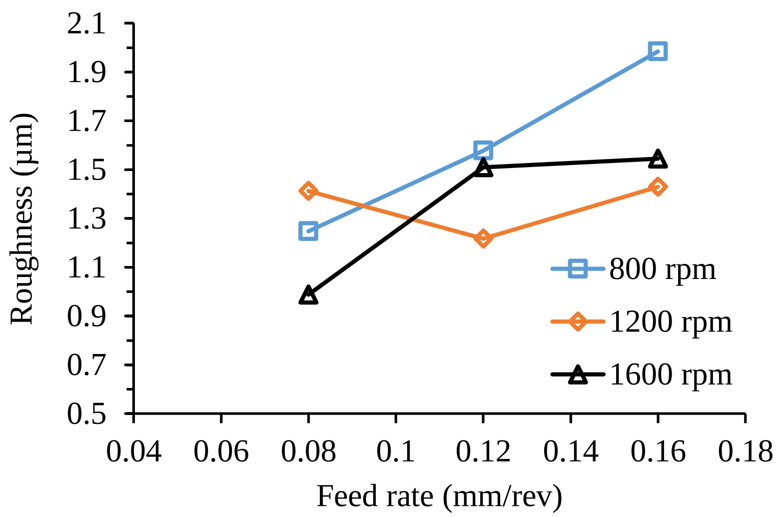


Fig. 4.5. Relationship between depth of cut and surface roughness: a) at different spindle speed and b) at different feed rate.

Fig. 4.6 (a) shows that the surface roughness increased as the feed rate increased from 0.08 to 0.16 mm/rev at 800 and 1600 rpm respectively. But, the increment was more for 800 rpm than that of 1600 rpm. At 1200 rpm the surface roughness was decreased from 1.4125 to 1.2175 µm as the feed rate increased from 0.08 to 0.12 mm/rev and then increased to 1.430 µm as the feed rate increased to 0.16 mm/rev. Fig. 4.6 (b) shows the effect of feed rate on surface roughness at different depth of cut values. At 0.5 mm, the roughness decreased slightly from

1.2475 to 1.2175 and then increased to 1.5450 µm as the feed rate increased from 0.08 to 0.12 and then to 0.16 mm/rev respectively. At 1 mm, the roughness first increased significantly from 0.9875 to 1.5775 µm and then decreased to 1.430 µm as the feed rate increased from 0.08 to 0.12 and then to 0.16 mm/rev respectively. At 1.5 mm, the roughness slightly increased from 1.4125 to 1.510 µm as the feed rate increased from 0.08 to 0.12 mm/rev and then rapidly increased to 1.9850 µm as the feed rate increased to 0.16 mm/rev.

Generally, increasing feed increase surface roughness during turning of aluminum alloy. This is mainly due to the increase in cutting force as the feed rate increases. As the feed rate increased, the plastic deformation also increases which increases cutting force. The increase of cutting force results in increase of machine tool vibration and tool wear which increases surface roughness.



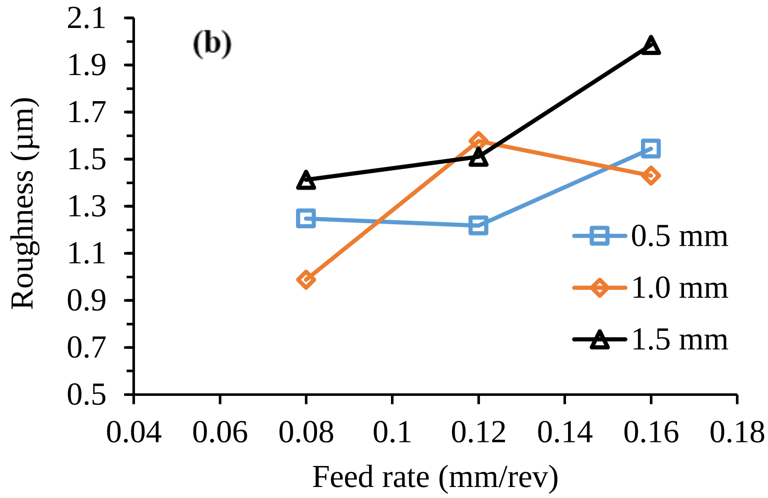


Fig. 4.6. Relationship between feed rate and surface roughness (a) at different spindle speed and (b) at different depth of cut.

Fig. 4.7 demonstrate the combined effect of spindle speed and depth of cut on surface roughness. From the contour plot it can be seen that good surface finish which is under 1µm of the turned part generated from medium depth of cut between 0.75 mm and 1.25 mm and higher spindle speed of greater than 1450 rpm. It also reveals that high depth of cut (> 1.25 mm) and low spindle speed (< 875 rpm) generated bad surface finish which is above 1.8 µm.

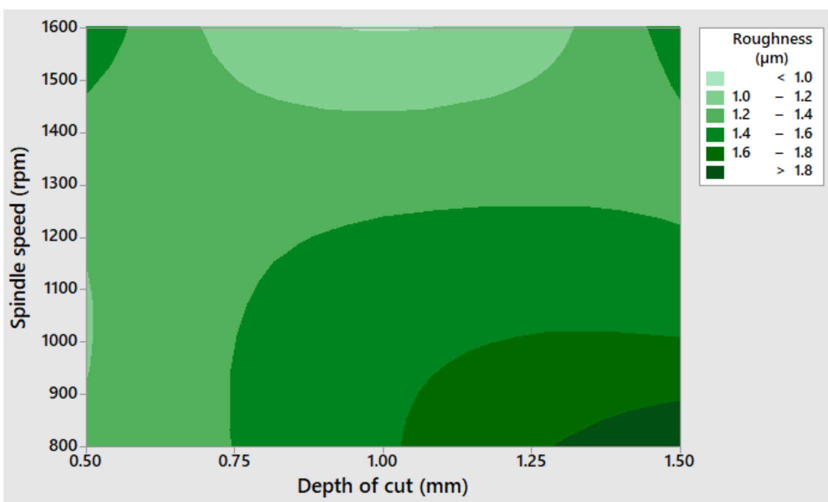


Fig. 4.7. Effect of combination of spindle speed and depth of cut on surface roughness

Fig. 4.8 shows the combined effect of spindle speed and feed rate on surface roughness. It demonstrate that good surface finish generated at higher spindle speed (> 1470 rpm) and low feed rate (< 0.09 mm/rev). It also shows that the high surface roughness value was obtained at high feed rate (> 0.125 mm/rev) and low spindle speed (< 900 rpm).

Fig. 4.9 shows the interaction effect of depth of cut and feed rate on the surface roughness. from the contour plot it can be seen that good surface finish which is less than 1 μm was obtained at medium depth of cut around 1 mm and low feed rate around 0.08 mm/rev.

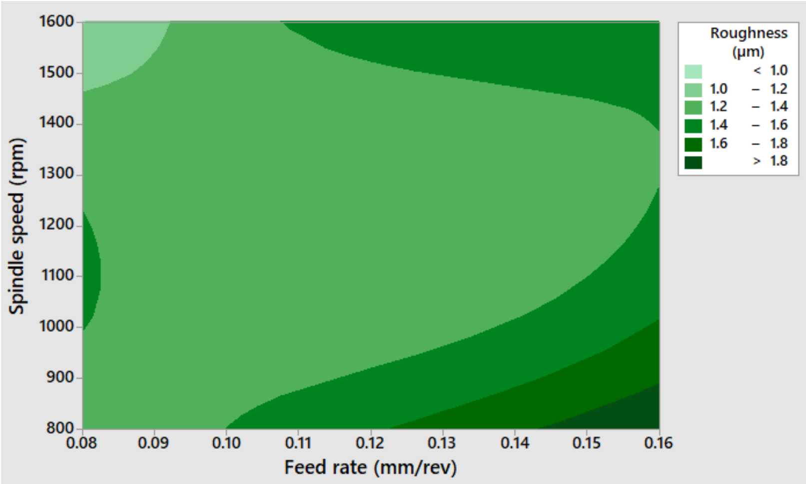


Fig. 4.8. Interaction effect of spindle speed and feed rate on surface roughness

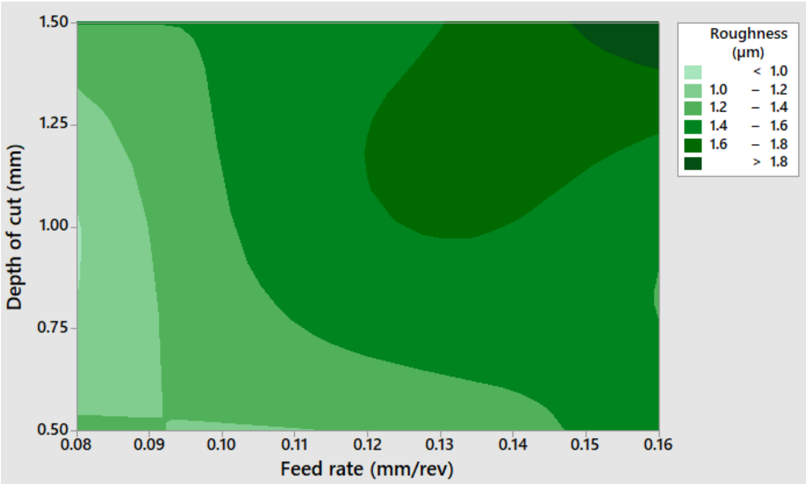


Fig. 4.9. Interaction effect of feed rate and depth of cut on surface roughness

4.3.2. Performance at Optimal Levels of the Mean Value

For predicting the optimum response approximately, three factors of parameters were selected by low mean value. **A3B2C1** is the optimum levels of parameters mean value for surface roughness value. To find out predicted values of the response (surface roughness value) the following linear regression equation was used [55].

$$Yopt = m + (mA - m) + (mB - m) + (mC - m) \quad (4.2)$$

where: $Yopt$ = predicted optimum value of surface roughness, m = average performance mean value for surface roughness, mA = optimum level value for parameter A, mB= optimum level value for parameter B, mC= optimum level value for parameter C.

$$Yopt = m + (mA3 - m) + (mB2 - m) + (mC1 - m)$$

$$Yopt = 1.4347 + (1.347 - 1.4347) + (1.332 - 1.4347) + (1.216 - 1.4347)$$

$Yopt = 1.0256$ (Predicted mean value for surface roughness value.

4.3.3. Analysis of S/N Ratios

Taguchi design used to identify control factors that reduce variability in a product or process by minimizing the effects of noise factors. Control factors are those design and process parameters that can be controlled. Noise factors cannot be controlled. The Taguchi method uses the S/N ratio to measure the variations of the surface roughness value in experimental design. Higher values of the signal-to-noise ratio (S/N) identify control factor settings that minimize the effects of the noise factors. Table 4.1 presents the signal-to-noise ratio of the study.

Fig 4.10 shows the normal probability plot, versus fit histogram and versus order of SN ratio of surface roughness all in one. It can be seen that the SN values are normally distributed to the mean values that shows the model is adequate.

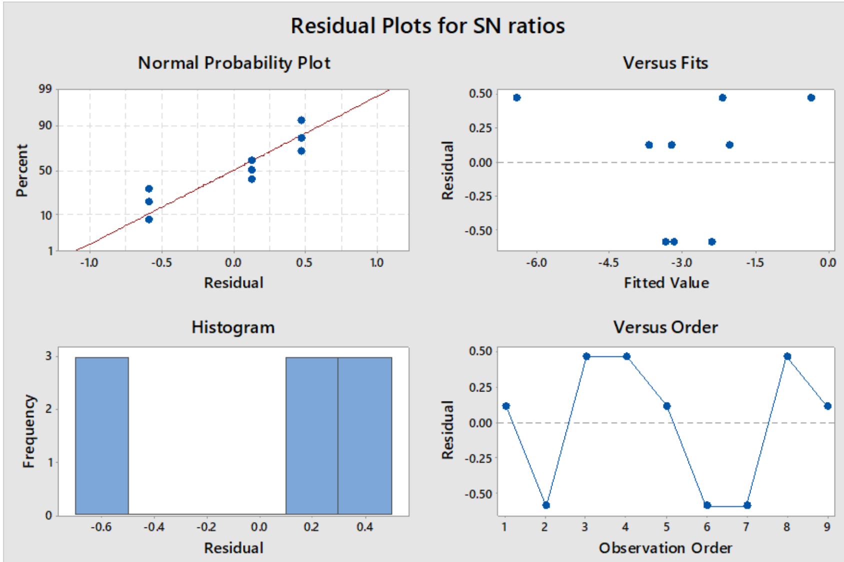


Fig. 4.10. Residual plot for SN ratio

Table 4.3 presents the response table for a signal to noise ratios for smaller is better for this study. The results are obtained from Minitab 18 software. Example of manual calculation for response table for signal to noise ratio for factor A (Spindle Speed) shown below.

$$S/N_{A1} = \frac{(-1.92081)+(-3.95939)+(-5.95521)}{3} = -3.945$$

$$S/N_{A2} = \frac{(-1.70938)+(-3.10672)+(-2.99977)}{3} = -2.605$$

$$S/N_{A3} = \frac{(-3.77857)+(0.10926)+(-3.57954)}{3} = -2.416$$

Delta is the difference between maximum S/N ratio and minimum S/N ratio.

$$Delta = (Maximum\frac{S}{N}ratio - Minimum\frac{S}{N}ratio) \tag{4.3}$$

Table 4.3 Response Table for Signal to Noise Ratios

Level	Cutting speed	Depth of cut	Feed rate
1	-3.945	-2.470	**-1.604**
2	-2.605	**-2.319**	-3.083
3	**-2.416**	-4.178	-4.280
Delta	1.529	1.859	2.676
Rank	3	2	1

Table 4.3 shows that the optimal parameter combination on smaller is the better surface quality character is **A3B2C1**, and it's the possible parameter combinations for increasing the surface quality of specimens. The control factor's main effect plot for the surface roughness S/N ratio is shown in Fig. 4.11.

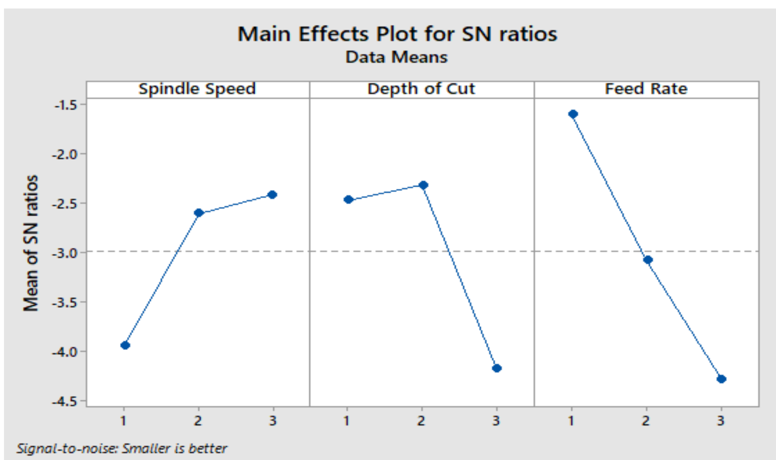


Fig. 4.11. Main effects plot for S/N ratio.

A steeper slope in the graphed S/N ratio effects (Fig. 4.11) indicates a greater effect of cutting parameter on the surface roughness (Ra). The graph indicate a much stronger effect on the Ra for feed rate than the other two parameters (cutting speed and depth of cut).

4.3.4. Performance at Optimal Levels of the S/N Result

To predict the optimum surface roughness value the selected level of cutting parameters based on low signal-to-noise ratio are used. **A3B2C1** is the optimum parameter combination based on S/N ratio for good surface roughness value. To find out the predicted optimum values of the surface roughness value, linear regression equation 4.2 was used:

$$y_{0pt} = m + (mA3 - m) + (mB2 - m) + (mC1 - m)$$

$$y_{0pt} = -2.989 + (-2.416 - (-2.989)) + (-2.319 - (-2.989)) + (-1.604 - (-2.989))$$

$$y_{0pt} = -0.361$$

4.3.5. Analysis of Variance (ANOVA) For Surface Roughness

Analysis of variance (ANOVA) has done to compare factors under study and identify the most significant factors which affects the surface roughness of the turned part. It was calculated by using Minitab 18 software and reported in Table 4.5. Percent contribution for each factors were calculated by equation 3.6. Where DOF= degree of freedom, SST=Total sum of squares, SSTR = Treatment Sum of squares, MSE = Mean square error and F = F- Ratio calculated by using Minitab 18 software.

Table 4.4 ANOVA for surface roughness

Source	DOF	SST	MSE	F	P	Percent contribution	Significance (α=0.05)
Spindle speed	2	0.128	0.064	4.18	0.172	20.52%	Less Significant
Depth of cut	2	0.182	0.091	6.83	0.128	29.18%	Significant
Feed rate	2	0.287	0.144	10.78	**0.085**	**46.03%**	Highly Significant
Residual error	2	0.027	0.013			4.27%	
Total	8	0.624				100%	

Table 4.4 presents the percentage contribution of effect of cutting factors under study on surface roughness. The factors under the study were spindle speed, feed and depth of cut. It is observed that among the three factors feed rate has greatest effect on the surface roughness value during CNC turning of Aluminum alloy at 95% level of confidence. It is clearly observed that the feed rate weight percentage (46.03%), depth of cut (29.18%) and spindle speed (20.52%) have significant influence on the surface roughness of AA7076 of circular specimens. Therefore, all the three parameters (factors) have significant effect on the surface roughness of AA7076 in turning process and feed rate found to be the most significant factor.

4.3.6. Determining the Optimum Condition

From the analysis of mean and analysis of S/N ratio it was found that the optimum parameter combination for surface roughness value is **A3B2C1** which is high cutting speed, medium depth of cut and low feed rate. The corresponding cutting parameter values are: 1600 rpm spindle speed, 1.0 mm depth of cut and 0.08 mm/rev feed rate. Table 4.5 presents the optimum parameters setting selected for surface roughness obtained from the design of experiment and experimental results.

Table 4.5 Optimum parameters setting levels and their values.

Controllable factors	Level selected	Value of level	Rank of affecting the response
Cutting Speed	3	1600 rpm	3
Depth of Cut	2	1.0 mm	2
Feed Rate	1	0.08 mm/rev	1

4.3.7. Confirmation Test

The final step in optimization process is testing of the final optimal parameter value for the required response. If the optimal combination of parameters and their levels coincidently match with one of the experiments in the Orthogonal Array, then no confirmation test is required. By considering this, the confirmation test was not required in this study because the optimum combination of parameters and their levels **(A3B2C1**) coincidently correspond to one of the trial conditions (Trial 8) of the experiment. The Optimum combination of parameters obtained was at 1600 rpm spindle speed, 1.0 mm depth of cut and 0.08 mm/rev feed rate as shown in table 3. Table 4 Presents the confirmation experiment and predicted results comparison for surface roughness measurements. From Table 4.6 it can be seen that the value of surface roughness predicted by using Taguchi approach strongly agreed with the experimental value.

Table 4.6 Discussion on the predicted value and experimental value

Response	Optimal Parameter	Predicted Value	Experimental Value
Surface Roughness (µm)	A3B2C1	1.0256	0.9875

4.4. Analysis of Material Removal Rate (MRR)

Material removal rate (MRR) is the amount of material removed per time unit. For this study MRR was calculated by equation 3.9.

Material removal rate MRR $= \frac{\pi}{4}(\mathrm{D}^2 - \mathrm{d}^2) * Nf$

MRR for the first experiment can be calculated as shown below

$$\mathrm{MRR1} = \frac{\pi}{4}(40mm^2 - 39\mathrm{mm}^2) * 800rev/min * 0.08mm/rev$$

$$= \underline{\underline{3970.97\ \mathrm{mm}^3/\mathrm{min.}}}$$

The material removal rate for the rest experiments were calculated by the same manner and reported in table 4.7.

Table 4.7 Calculated Material Removal Rate

Exp. No.	Spindle speed (rpm)	Depth of cut (mm)	Feed rate (mm/rev)	MRR (mm^3/min).
1	800	0.5	0.08	3970.97
2	800	1.0	0.12	11762.12
3	800	1.5	0.16	23222.65
4	1200	0.5	0.12	8934.69
5	1200	1.0	0.16	23524.25
6	1200	1.5	0.08	17416.99
7	1600	0.5	0.16	15883.89
8	1600	1.0	0.08	15682.83
9	1600	1.5	0.12	34833.98

From equation 3.8 it can be seen that material removal rate is directly related to spindle speed, depth of cut and feed rate. So increasing one of these parameters increase the material removal rate as shown in Table 4.7. But only high material removal rate does not mean economical machining as economical machining requires good surface finish and less tool wear rate too. Therefore, the machining parameter optimization is highly needed. From Table 4.7 it can be seen that the material removal rate obtained at optimal parameter combination was 15682.83 mm^3/min.

4.4.1. Analysis of Mean

Design of experiment was used to analysis of average mean values of material removal rate for each factors i.e. cutting speed (A), feed rate (B) and depth of cut (C). The calculated material removal rate at each experiment was reported in Table 4.7. Fig 4.12 shows the normal probability plot, versus fit histogram and versus order mean of material removal rate all in one. It can be seen that the mean values are normally distributed which shows that the model is adequate.

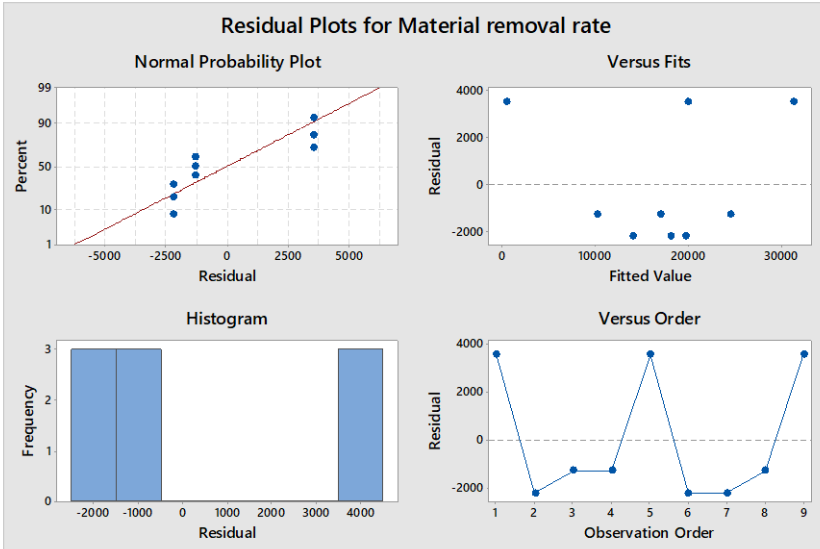


Fig 4.12. Residual plot for main effect of material removal rate.

Fig, 4.13 shows the effect of cutting parameters on material removal rate at each level. It can be seen that the mean material removal rate increased with increase of all parameters under study (spindle speed, feed rate and depth of cut).

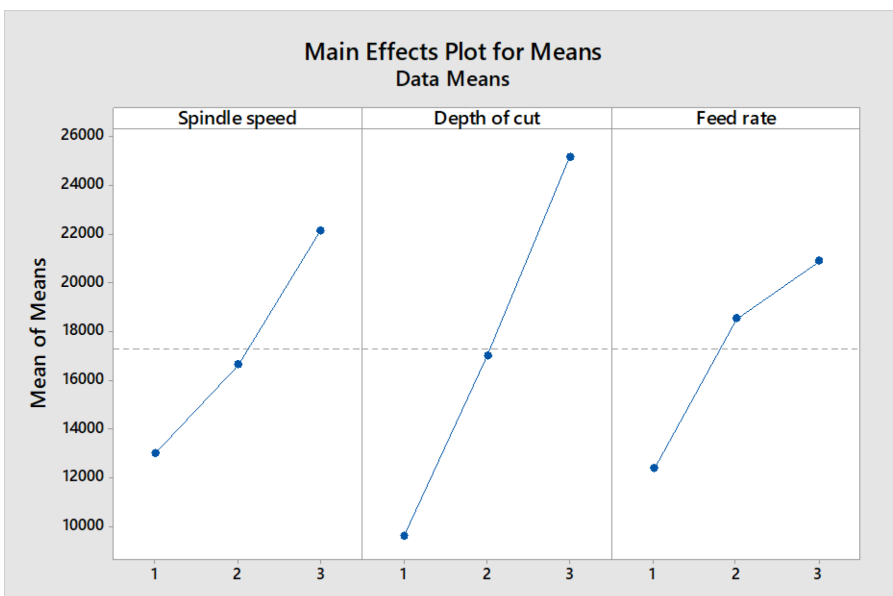


Fig. 4.13. Main Effect Plot for Means of MRR

Fig. 4.14 shows the effect of depth of cut on material removal rate at different spindle speed values. At both 800 rpm and 1600 rpm, the material removal rate increased linearly as the depth of cut increased from 0.5 to 1.0 and then to 1.5 mm. but, at 1200 rpm, the material removal rate first increased from 8934.69 to 23524.25 mm^3/min and then decreased to 17416.99 mm^3/min as the depth increased from 0.5 to 1.0 and then to 1.5 mm respectively. This decrease in material removal rate is mainly due to the decrease of feed rate from 0.16 mm/rev to 0.08 mm/rev as feed rate has direct relation with material removal rate. Generally, increasing depth of cut increase material removal rate due to the fact that increasing depth of cut increases the amount material to be removed in a single cut.

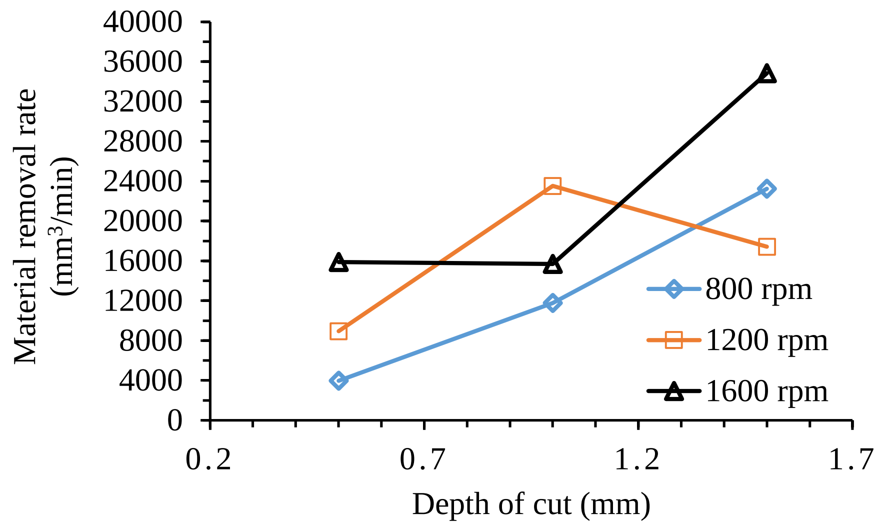


Fig 4.14. Effect of depth of cut on material removal rate at different spindle speed value

Fig 4.15 shows the effect of feed rate on material removal rate at different depth of cut values. From the figure it can be seen that material removal rate increase with increase in feed rate. At 0.5 mm linear increase observed while at 1.0 and 1.5 mm the increase was not linear. This was mainly due to the additional effect spindle speed and depth of cut on MRR. The increase in feed rate increase the rate of plastic deformation which increase the rate of material removal.

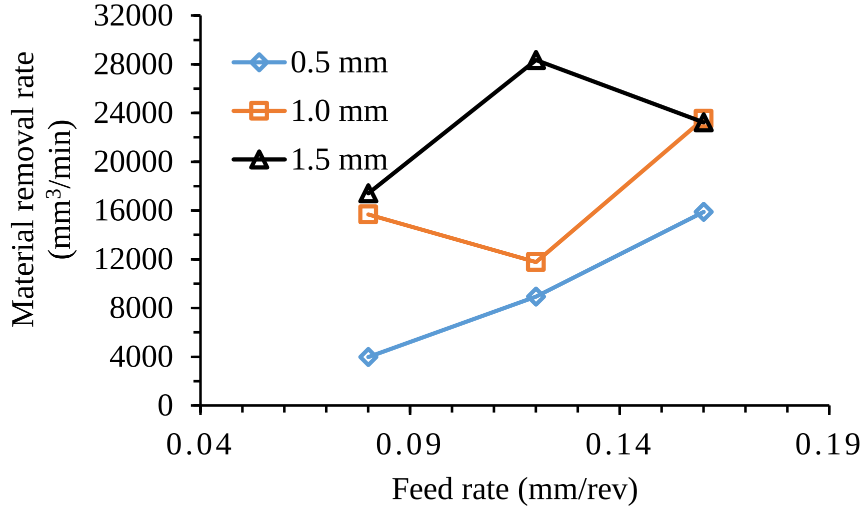


Fig 4.15. Effect of feed rate on material removal rate at different depth of cut values

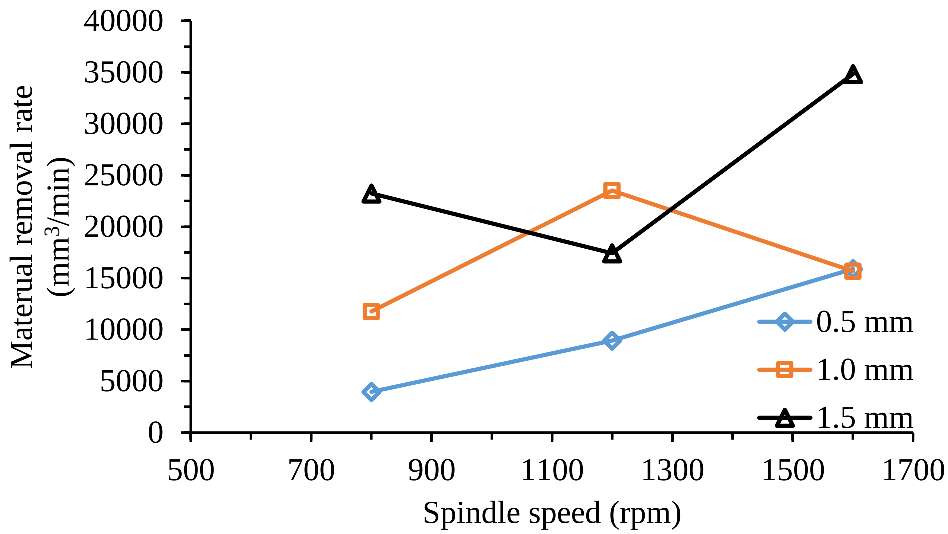


Fig. 4.16. Effect of spindle speed on material removal rate at different depth of cut values

Fig 4.16 shows the effect of spindle speed on material removal rate at different depth of cut values. At 0.5 mm, the MRR increased linearly from 3970.97 to 8934.69 and then to 15883.89 mm^3/min as the spindle speed increased from 800 to 1200 and then to 1600 rpm respectively. At 1.0 mm, the MRR first increased from 11762.12 to 23524.25 and then decreased to 15682.83 mm^3/min as the spindle speed increased from 800 to 1200 and then to 1600 rpm respectively. At 1.5 mm, the MRR first decreased from 23222.65 to 17416.99 which then significantly increased to 34833.98 mm^3/min at 1600 rpm. Generally material removal rate increase with increase in spindle speed as more material can be removed in lesser time. Increasing spindle speed usually increase the cutting temperature which reduce the strength of the workpiece which reduce the cutting force and facilitate material removal process.

4.4.2. Analysis of SN Ratios

The Taguchi method uses the S/N ratio to measure the variations of the material removal rate value in experimental design. Fig 4.17 shows the residual plot of SN ratio and it can be seen that the model is adequate. Fig. 4.18 shows the main effect plot for S/N ratio. It illustrate the significance of the effect of cutting parameters (spindle speed, feed rate and depth of cut) on material removal rate during CNC turning of AA7076 aluminum alloy. It can be seen that depth of cut has the most significant effect on material removal rate followed by feed rate and spindle speed. From the graph it can also be seen that all parameters has significant effect on material removal rate.

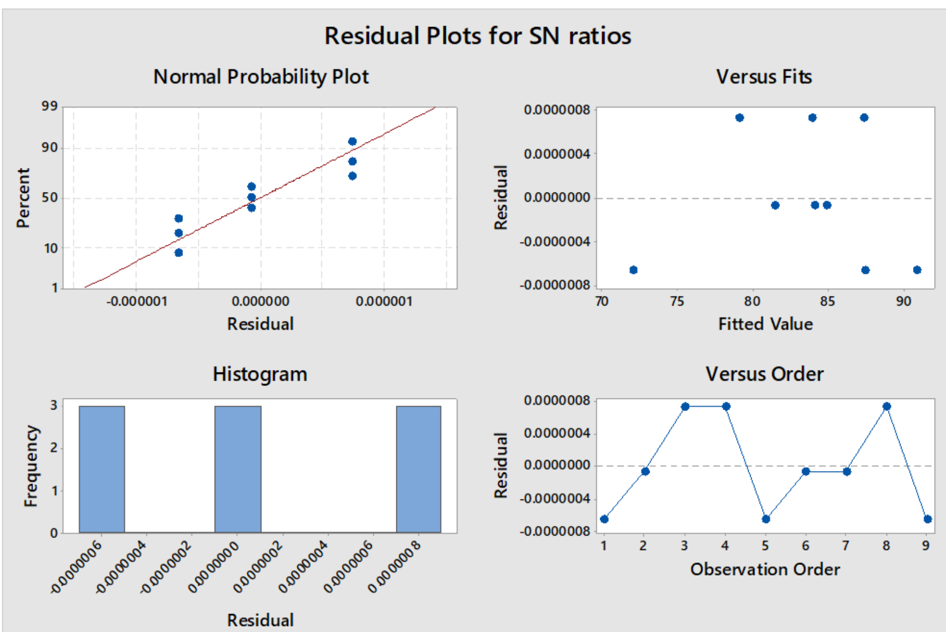


Fig. 4.17. Residual plot of SN ratio for MRR

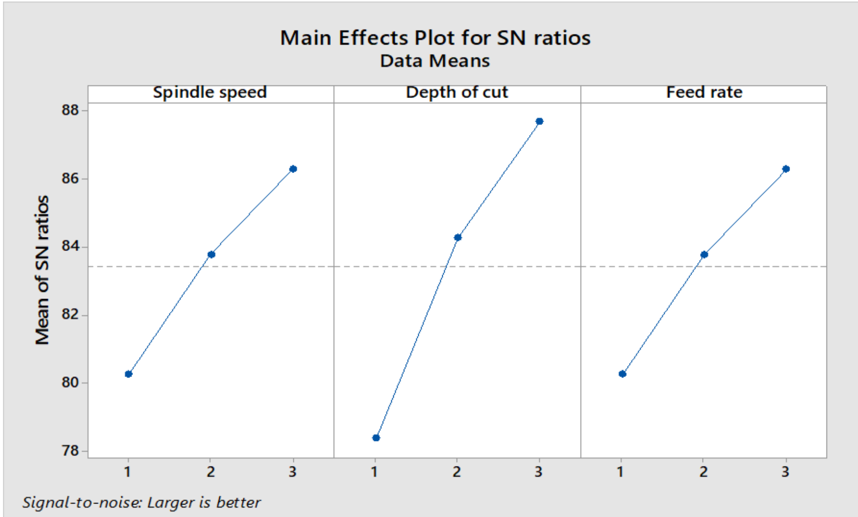


Fig. 4.18. Main Effect plot for SN ratio of MRR

Fig. 4.19 shows the interaction effect of spindle speed and depth of cut on material removal rate during CNC turning of AA7076 aluminum alloy. It can be clearly observed that the highest material removal rate was obtained at higher depth of cut and higher spindle speed combination. It also shows that lowest material removal rate was obtained at low depth of cut and low spindle speed combination.

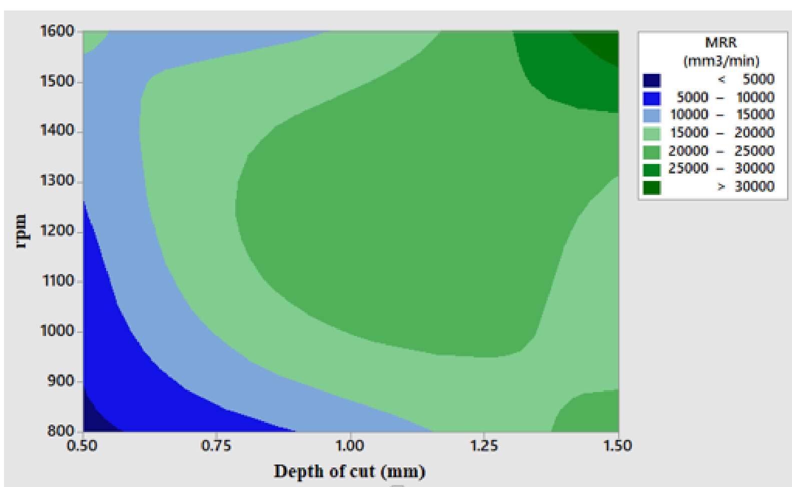


Fig. 4.19. Interaction effect of spindle speed and depth of cut on MRR

Fig. 4.20 shows the interaction effect of spindle speed and feed rate on material removal rate during turning of Al 7076 aluminum alloy. It can be clearly observed that the highest material removal rate was obtained at medium feed rate and higher spindle speed combination. It also shows that lowest material removal rate was obtained at low feed rate and low spindle speed combination.

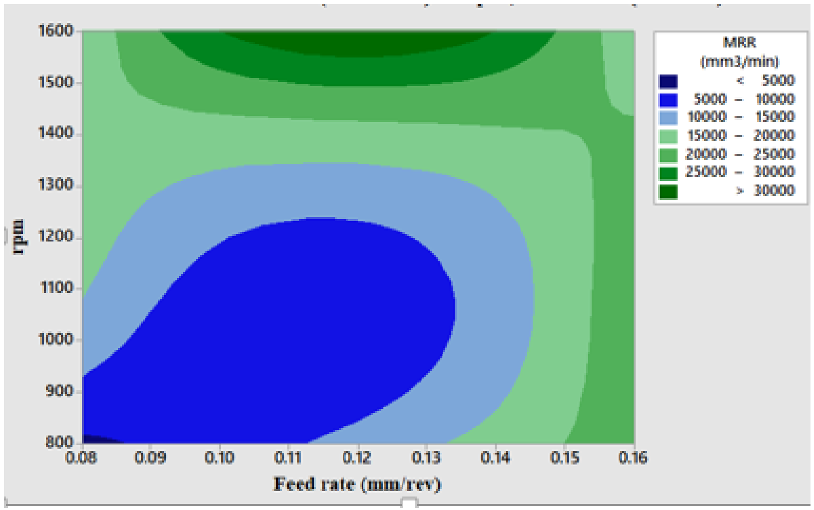


Fig. 4.20. Interaction effect of spindle speed and feed rate on MRR

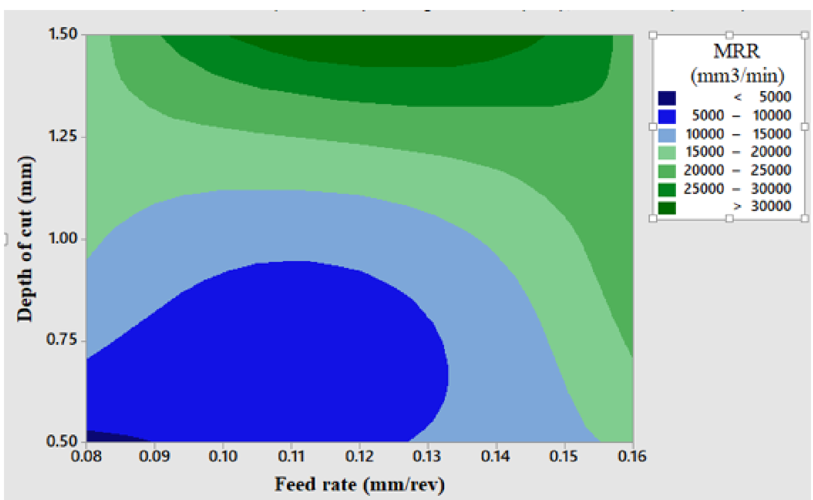


Fig. 4.21. Interaction effect of feed rate and depth of cut on MRR

Fig. 4.21 shows the interaction effect of feed rate and depth of cut on material removal rate during turning of AA7076. It was observed that the highest material removal rate was obtained at high depth of cut and high feed rate combination. It also shows that lowest material removal rate was obtained at low depth of cut and low feed rate combination.

4.5. Analysis of Variance for Material Removal Rate

Analysis of variance (ANOVA) has done to compare factors under study and identify the most significant factors which affects MRR of the turned part. It was calculated by using Minitab 18 software and reported in Table 10. Percent contribution for each factors were calculated by equation 3.6. Where DOF= degree of freedom, SST=Total sum of squares, SSTR = Treatment Sum of squares, MSE = Mean square error and F = F- Ratio calculated by using Minitab 18 software.

Table 4.8 presents the percentage contribution of effect of cutting factors under study on material removal rate. The factors under the study were spindle speed, feed and depth of cut. It was observed that among the three factors depth of cut has greatest effect on the material removal rate value during CNC turning of AA7076 at 95% level of confidence. It was clearly observed that the depth of cut weight percentage (54.734%), spindle speed (19.164%) and feed rate (17.473%) have significant influence on material removal rate of AA7076 of circular specimens.

Table 4.8 Analysis of variance for material removal rate

Source	DOF	SST	MSE	F	P	Percent contribution	Significance (α=0.05)
Spindle Speed	2	127282711	63641356	2.2	0.310	19.164%	Significant
Depth of Cut	2	363533985	181766993	6.34	0.136	54.734%	**Highly Significant**
Feed Rate	2	116055022	58027511	2.03	0.331	17.473%	Significant
Residual Error	2	57307370	28653685			8.62%	
Total	8	664179088				100.00%	

4.6. Analysis of Chip Morphology

4.6.1. Types of Chip Formed

Mostly continuous chips were observed during CNC turning of AA7076 due to high ductility of the material and smooth cutting process by CNC lathe machine. From Fig. 4.15 it can be seen that discontinuous chips was formed only at experiment five. At experiment five the increase in the feed rate results greater plastic deformation which harden the workpiece facilitating the formation of discontinuous chip. Generally based on the ISO 3685 chip classification [52], the following types of chips were observed in the study.

- At all experiments except at 3, 5 and 8 snarled tubular chip type were observed as it can be seen from the figure. This was mainly due to the ductility of the AA7076.
- At experiment 3, snarled ribbon type chip was observed.
- At experiment 5, combination of short washer type helical chips and loose arc chips were observed.
- At experiment 8, long washer type helical chips were observed.

From the these types of chips we can understand that higher depth of cut and feed rate accounts for the change of chip type from snarled tubular to snarled ribbon chip. Higher cutting speed at lower feed rate was the main reason for the formation of washer type helical chips.

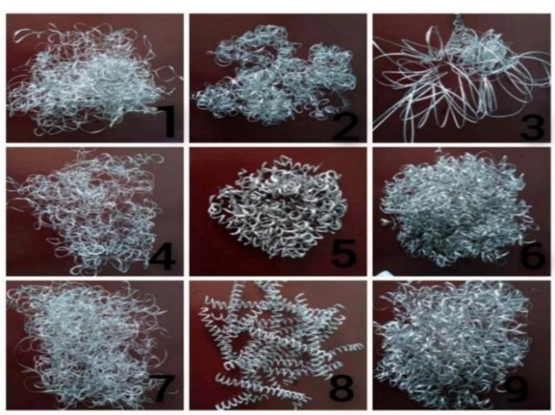


Fig. 4.22. Image of chips produced

4.6.2. Analysis of Chip Width

At the end of each experiment the obtained chips were collected for measurement of the chip width and chip thickness. Each experiment chips were measured randomly at three different area of the chip and the average chip width was taken and reported in Table 4.9.

Table 4.9 Measured chip width values

Exp. No.	Spindle speed (rpm)	Depth of cut (mm)	Feed rate (mm/rev)	Chip width (mm)			Average chip width (mm)
				Meas. 1	Meas. 2	Meas. 3	
1	800	0.5	0.08	0.55	0.50	0.55	0.533
2	800	1.0	0.12	1.10	1.15	1.10	1.1166
3	800	1.5	0.16	1.65	1.60	1.70	1.65
4	1200	0.5	0.12	0.60	0.55	0.60	0.5833
5	1200	1.0	0.16	1.25	1.30	1.30	1.2833
6	1200	1.5	0.08	1.55	1.60	1.55	1.566
7	1600	0.5	0.16	0.60	0.55	0.60	0.5833
8	1600	1.0	0.08	1.00	1.05	1.00	1.0166
9	1600	1.5	0.12	1.60	1.55	1.65	1.60

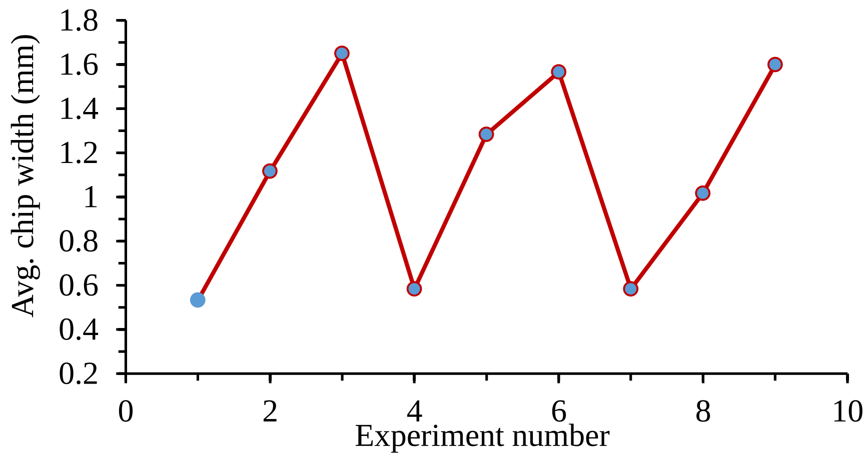


Fig. 4.23. Chip width obtained at different experiments.

Fig. 4.23 shows the chip width obtained at all experimental runs. It can be seen that the maximum chip width value (=1.65 mm) obtained at experiment number three and the minimum chip width value (=0.533 mm) obtained at experiment number one. The minimum chip width was obtained at minimum depth of cut, feed rate and spindle speed while the maximum was obtained at maximum cutting parameter values.

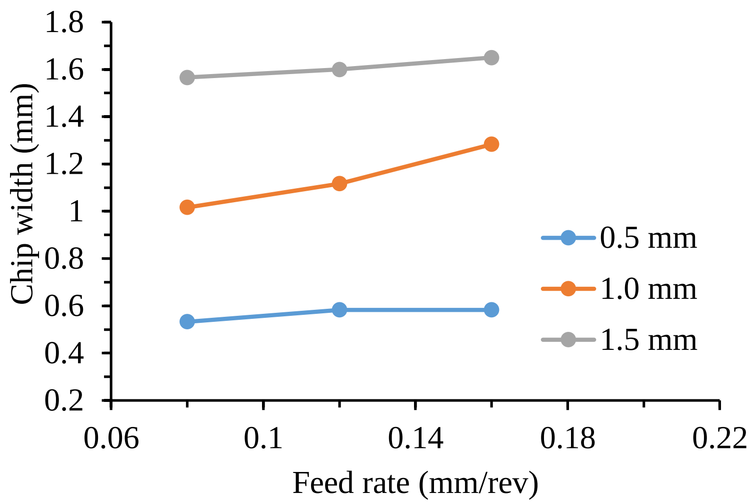


Fig. 4.24. Effect of feed rate on chip width

Fig. 4.24 shows that at all depth of cut values, chip width increased with the increase in feed rate. It also shows that chip width increased with increase in the depth of cut. Generally increasing depth of cut increases the cutting width which increases the cutting force, which means higher chip width is usually undesirable as it increase the machining force.

4.6.3. Analysis of Chip Thickness

Each experiment chips were measured randomly at three different area of the chip and the average chip thickness was taken and reported in Table 4.9. Fig 4.25 shows the effect of cutting parameters on chip thickness. It can be seen that as feed rate increased the chip thickness also gets bigger. This may be due to the increase of plastic deformation which results in the hardening of the workpiece which in turn results in the formation thick discontinuous chips. The figure also illustrate that chip thickness decrease with the increase in the spindle speed. This is due to the fact that the increase in cutting speed reduces the plastic deformation.

From the table it can be seen that the maximum chip thickness of 0.41mm was obtained at experiment 3 while the lowest chip thickness of 0.21 mm obtained at experiment 6.

Table 4.10 Measured chip thickness values

Exp. No.	Spindle speed (rpm)	Depth of cut (mm)	Feed rate (mm/rev)	Chip thickness (mm)			Average chip thickness (mm)
				Meas. 1	Meas. 2	Meas. 3	
1	800	0.5	0.08	0.24	0.26	0.22	0.24
2	800	1.0	0.12	0.36	0.34	0.36	0.33
3	800	1.5	0.16	0.42	0.42	0.40	0.41
4	1200	0.5	0.12	0.24	0.22	0.24	0.23
5	1200	1.0	0.16	0.38	0.38	0.40	0.38
6	1200	1.5	0.08	0.22	0.22	0.20	0.21
7	1600	0.5	0.16	0.26	0.24	0.24	0.26
8	1600	1.0	0.08	0.18	0.20	0.2	0.19
9	1600	1.5	0.12	0.22	0.22	0.22	0.22

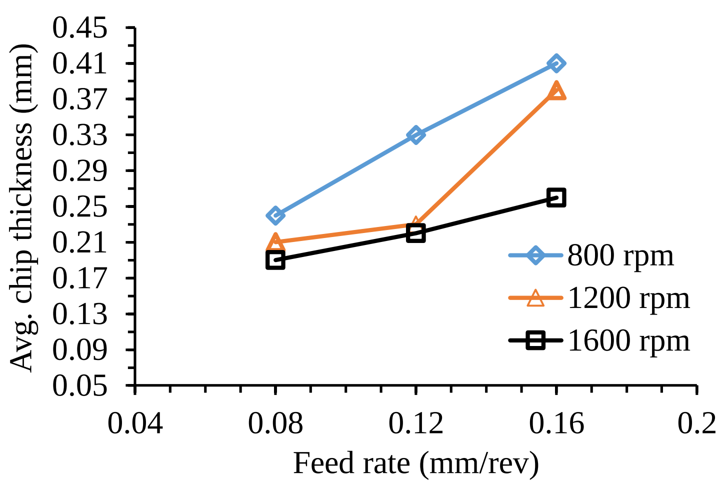


Fig. 4.25. Effect of feed rate and spindle speed on chip thickness

4.7. Finite Element Analysis

Finite element analysis to pridict the cutting force and cutting temperature was done for experiment number two using DEFORM 3D v13 software. The maximum cutting force for experment number 2 was 48.2 N as shown in Fig 4.27. It was expected that cutting force caused deformation of material to be removed from the work piece at different cutting parametrs. The cutting force showed a tendence of increasing when feed rate increased. However more cutting force may cause more wear to cutting tool that inturn create rough surface finish on the work piece. The obtained cutting force created surface roughness of 1.5775 micrometr for a sellected exprement conducted at 800 rpm spindle speed, 0.12 mm/rev feed and 1 mm depth of cut, respectively. The effect of cutting paramters on tool chip interface temperature was predicted using simulation as shown by Fig 4.26. The maximum temperature genereated at experiment number 5 with spindle speed 1200 rpm, depth of cut of 1.0 mm and feed of 0.16 mm/rev was 428 ^{o}C. While for experiment number 2 with spindle speed of 800 rpm, depth of cut of 1.0 mm and feed rate of 0.12 mm/rev was 368 ^{o}C. This shows that tempearture inceased with increase in feed rate and cutting speed. Increasing cutting speed increases cutting temperature which as a result reduces the mechanical strength of the material and facilitate the material removal, as a result it reduces the machining force. Since the workpice materials was aluminum alloy which has high thermal conductivity, temperature generated at tool workpice interface did not affect surface roughness. More heat generated was tranfered to work pice material due to its high thermal property.

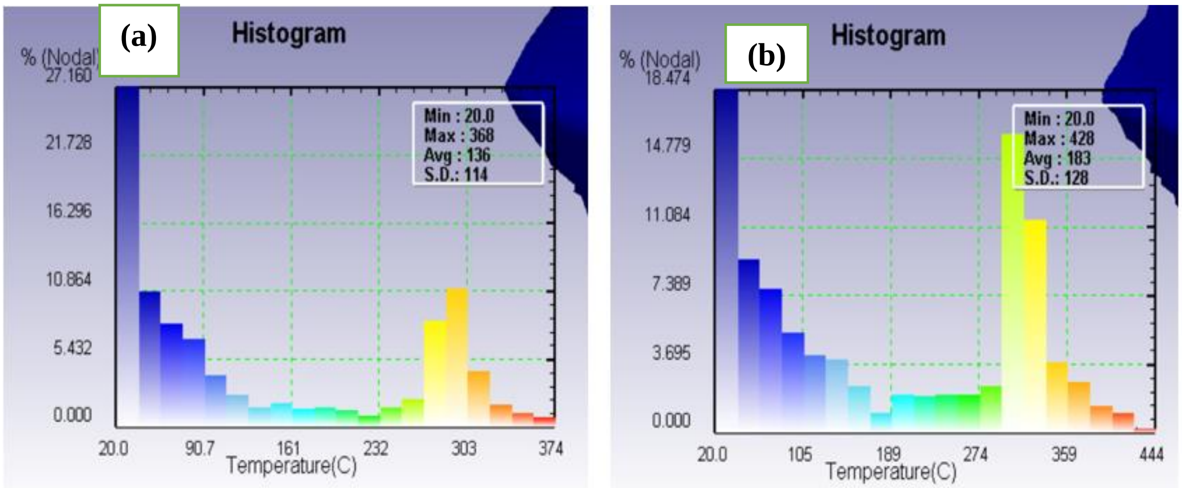


Fig. 4.26. Maximum temperature at **a)** experiment number 2, **b)** at experiment number 5

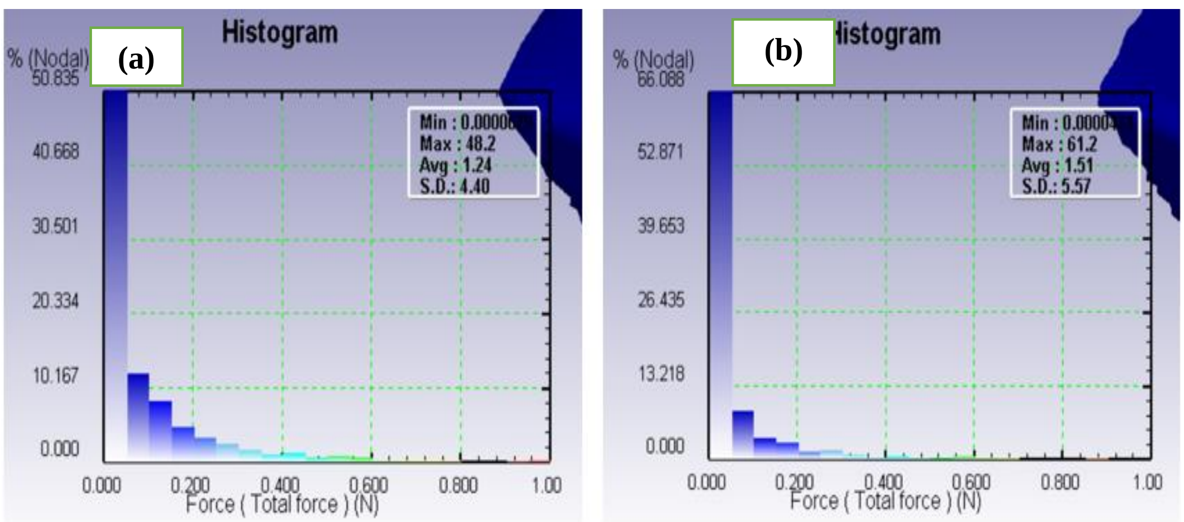


Fig. 4.27. Maximum force at **a)** experiment number 2, **b)** at experiment number 5

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

This study mainly focused on optimization of cutting parameters for surface finish and material removal rate during CNC turning of AA7076. Taguchi L9 orthogonal array based optimization has been utilized to determine the optimal cutting parameters for optimum surface finish and material removal rate. Analysis of variance (ANOVA) has been utilized to determine the influence of cutting parameters on surface roughness and material removal rate. The cutting parameters under study were feed rate, depth of cut, and spindle speed. Generally, the following conclusions are drawn from the experimental result of the study:

1. In CNC turning of AA7076 aluminum alloy, minimum surface roughness was obtained at higher spindle speed 1600 rpm, medium depth of cut at 1mm, and lower feed rate 0.08 mm/rev.
2. From the analysis of variance (ANOVA) for surface roughness it was found that the feed rate weight percentage of 46.03%, depth of cut of 29.18% and spindle speed (20.52%) have significant influence on the surface roughness.
3. From the analysis of variance (ANOVA) for material removal rate it was found that the depth of cut weight percentage (54.734%), spindle speed (19.164%) and feed rate (17.473%) have significant influence on material removal rate of AA7076 of circular specimens.
4. From the study, CNC turning of AA7076 using coolant and uncoated carbide tool found to generate good surface finish of 0.9875 micrometer which can be breakthrough for further study on the alloy.
5. From analysis of chip morphology generally snarled tubular, snarled ribbon, washer type helical, and arc type chips were observed. Higher depth of cut and feed rate accounts for the change of chip type from snarled tubular to snarled ribbon chip. Chip thickness was found to increase with both feed rate and depth of cut. The higher chip thickness was found to be 0.41 mm and the lowest chip thickness was found to be 0.21 mm.

6. The finite element simulation result used to predict maximum cutting force of 48.2 N for selected experiment number 2. The cutting force increased with feed rate and spindle speed. The effect of tool workpice temperature was predicted using simulation and maximum temperature generated was 428 ^{o}C for cutting parameters of spindle speed 1200 rpm, depth of cut of 1.0 mm and feed of 0.16 mm. For this experiment, more comparison of experiment and simulation did not conducted due to resource limitation and included for farther work.

5.2. Recommendation and Scope for Future Work

Based on the results found from this study, the researcher forwards the following recommendations in CNC turning of AA7076.

1. In this study the effect of cutting parameters (depth of cut, feed rate and spindle speed) has been studied. This can be further extended to the effect of other factors like cutting tool geometry, type of coolant and mode of application, tool coating and type of cutting tool material on surface roughness and material removal rate.
2. In this study the machinability of Al7076 has been studied. This can be further extended to other not much researched aluminum alloys to study the effect of cutting parameters on the surface roughness.
3. In the literature there is no recommended type of coolant for machining of aluminum alloys which needs a study to find the effect of different type of coolant during machining of aluminum alloys.
4. The experiment may be conducted in future by measuring other response parameters like cutting forces, power consumption, machining time and tool wear rate.
5. The study can be extended by using double tool turning to improve productivity.
6. This study was limited to single response optimization. So, a multi-response optimization of machining parameters for surface roughness needs to be studied.

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Appendix A: Taguchi result for Surface Roughness

↓	C1	C2	C3	C4	C5	C6
	Spindle speed	Depth of cut	Feed rate	surface roughness	SNRA1	MEAN1
1	800	0.5	0.08	1.2475	-1.92081	1.2475
2	800	1.0	0.12	1.5775	-3.95939	1.5775
3	800	1.5	0.16	1.9850	-5.95521	1.9850
4	1200	0.5	0.12	1.2175	-1.70938	1.2175
5	1200	1.0	0.16	1.4300	-3.10672	1.4300
6	1200	1.5	0.08	1.4125	-2.99977	1.4125
7	1600	0.5	0.16	1.5450	-3.77857	1.5450
8	1600	1.0	0.08	0.9875	0.10926	0.9875
9	1600	1.5	0.12	1.5100	-3.57954	1.5100

Response Table for Signal to Noise Ratios

Smaller is better

Level	Spindle speed	Depth of cut	Feed rate
1	-3.945	-2.470	-1.604
2	-2.605	-2.319	-3.083
3	-2.416	-4.178	-4.280
Delta	1.529	1.859	2.676
Rank	3	2	1

Response Table for Means

Level	Spindle speed	Depth of cut	Feed rate
1	1.603	1.337	1.216
2	1.353	1.332	1.435
3	1.347	1.636	1.653
Delta	0.256	0.304	0.438
Rank	3	2	1

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Spindle speed	2	0.12798	0.06399	4.80	0.172
Depth of cut	2	0.18204	0.09102	6.83	0.128
Feed rate	2	0.28711	0.14355	10.78	0.085
Error	2	0.02664	0.01332		
Total	8	0.62378			

Factor Information

Factor	Type	Levels	Values
Spindle speed	Fixed	3	800, 1200, 1600
Depth of cut	Fixed	3	0.5, 1.0, 1.5
Feed rate	Fixed	3	0.08, 0.12, 0.16

Appendix B: Taguchi result for MRR

↓	C1	C2	C3	C4	C5	C6
	Spindle speed	Depth of cut	Feed rate	MRR	SNRA1	MEAN1
1	800	0.5	0.08	3971.0	71.9779	3971.0
2	800	1.0	0.12	11762.1	81.4097	11762.1
3	800	1.5	0.16	23222.7	87.3182	23222.7
4	1200	0.5	0.12	8934.7	79.0216	8934.7
5	1200	1.0	0.16	23524.3	87.4303	23524.3
6	1200	1.5	0.08	17417.0	84.8195	17417.0
7	1600	0.5	0.16	15883.9	84.0191	15883.9
8	1600	1.0	0.08	15682.8	83.9085	15682.8
9	1600	1.5	0.12	34834.0	90.8401	34834.0

Factor Information

Factor	Type	Levels	Values
Spindle speed	Fixed	3	800, 1200, 1600
Depth of cut	Fixed	3	0.5, 1.0, 1.5
Feed rate	Fixed	3	0.08, 0.12, 0.16

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Spindle speed	2	127282711	63641356	2.22	0.310
Depth of cut	2	363533985	181766993	6.34	0.136
Feed rate	2	116055022	58027511	2.03	0.331
Error	2	57307370	28653685		
Total	8	664179088			

Appendix C: SPECTROTEST result

Program: Al-01
Comment: Globalcalibration-Al; Spark
Average (n=3)

Test by Tadele Abreham

Jo. no: 005/14,

05/13/2003 01:37:34 AM

Elements: Concentration

Sample name:
Requested by:
Approved by:

Type of Mt.:

7/11/13

	Si	Fe	Cu	Mn	Mg	Zn	Ni	Cr	Pb	Sn	Ti
	%	%	%	%	%	%	%	%	%	%	%
$\bar{x}$	0.314	0.58	0.185	0.345	1.51	7.84	1.17	0.089	0.045	0.089	0.085

	Ag	B	Be	Bi	Ca	Cd	Sr	Li	Zr	Co	V
	%	%	%	%	%	%	%	%	%	%	%
$\bar{x}$	0.007	0.029	0.000	0.026	<0.001	0.091	0.003	0.86	0.009	0.030	0.012

	Ga	Al
	%	%
$\bar{x}$	0.021	86.7

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