Experimental Validation for Energy Consumption in Machining of Aluminum 6061-T6 Alloy at Transitional Cutting Speeds

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Thesis Acceptance Certificate

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This Thesis work has been done at Gujranwala Tools Dies and Molds Centre (GTDMC) and Light Engineering Services Centre (LESC), Gujranwala under the thesis title" Experimental Validation for Energy Consumption in Machining of Aluminum 6061-T6 Alloy at Transitional Cutting Speeds" and is submitted in fulfillment of the requirements for the degree of Master of Science program in Design & Manufacturing Engineering (DME) at SMME, NUST University.

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DEDICATION

To my Beloved Parents,

Without whom none of my success
would have been possible

&

To my Respected Teachers,

Who acted like compass
that activated the magnets of

Curiosity, knowledge and wisdom in me

Abstract

The environmental studies related to machine tools shows that mostly the environmental impacts are due to the consumption of electrical energy. It is a big challenge for modern industrial sector to improvise their existing manufacturing processes in order to reduce their energy consumption and increase profit margin. Machining is the most commonly used manufacturing process and is accountable for carbon footprints owing to their energy consumption.

This study presents an experimental validation for energy consumption in machining of Aluminum 6061-T6 alloy at transitional cutting speeds and selection of this alloy is based on its usage in automobiles, aerospace and bio-medical industries. Previously, most of energy consumption related work in machining was carried out on conventional cutting speeds so transitional cutting speeds (1000m/min – 1500m/min) were selected which are below high cutting speed but above conventional cutting speed ranges. The effect of feed, cutting speed and depth of cut was studied on specific cutting energy consumption, cutting power and surface roughness. Experimental trials were designed by Taguchi L9 orthogonal array and performed on two different machine tools using single point cutting technique. Power of machine tools was measured with the help of power analyzer that was attached to the main bus of the machine. In all experiments fresh cutting inserts were used to avoid the effect of tool wear during energy calculations. The main purpose of this research was to validate the benchmark results and acquire the minimum value of specific cutting energy consumption and surface roughness during turning of Al 6061-T6 alloy at transitional cutting speeds.

The experimental results were further analyzed with the help of ANOVA and main effects plots. During ANOVA analysis the feed rate was most prominent factor for minimizing the SCE consumption and surface roughness followed by depth of cut and cutting speed. In main effect plots, the best result for specific cutting energy consumption was obtained at highest level of feed rate and depth of cut while for surface roughness, it was achieved at lowest value of feed, depth of cut and cutting speed. These result were also totally endorsed by benchmark study.

Keywords: Aluminum 6061-T6 alloy, Specific cutting energy, Single point cutting, ANOVA, Main effect plots

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CHAPTER 1

1 Introduction

World is changing very fast and with the tremendous increase in population, technology demand is also increased. Globally, there is a concern over environmental degradation issues and rapid depletion of major energy sources. Energy consumption is a major contributor to various environmental problems. Mining raw material and building transport infrastructure involves massive interference with ecosystems. Furthermore, the use of fossil energy sources is the main driver of climate change. To mitigate these problems, energy consumption must fall.

Industrial sector consisting of manufacturing, mining, agriculture and construction sector consume major portion of the energy sources. Industrial sector is the main contributor to overall electricity energy consumption in the world. In manufacturing sector, the major consumer of electrical energy are manufacturing industries[1].Mostly electrical energy is produced by the use of fossil fuels which leads to the CO_2 emission in the atmosphere so this shows that higher the production of this sector ,greater the carbon footprints left by their products in the environment so there is an increase demand of developing energy efficient processes or exploring alternate energy sources[2].

Machining is mostly commonly used manufacturing process and in the past, efforts are being made to study its impact on the environment. Machining is unique kind of manufacturing process which is used in both creating and finishing products[3]. The most crucial point of sustainable machining is careful utilization of energy resources so it is obvious that material and energy consumption in any machining process are main concern[1]. According to the earlier environmental studies carried out for machine tools used in turning and milling operations, the environmental impacts are mainly because of the utilization of electrical energy in these operations. In account for improving energy efficiency of any manufacturing process, we should consider the amount of energy consumed by both cutting process and machine tool[4]. The input energy used by machine tools to perform any function is basically electrical energy so attention is on optimizing the consumption of electrical energy during any manufacturing process in order to reduce the overall carbon footprints of machine tool[5].Development of energy efficient processes has been added in the objective of manufacturing industries with quality, costs and time.

In any machining process, energy provided to the machine will be utilized into two portions. One portion of the supplied energy will be used by the machine tool itself in commanding different functions in which different auxiliary components of machine will be involved and remaining portion of this energy will be consumed in actual machining process in which material will be removed from the workpiece[1]. Extensive efforts are being made in developing energy efficient machine tools but attentions should also be done in optimizing existing machining parameters which could reduce energy consumption in any machining process[6][3].

Energy consumed in removing $1cm^3$ of the material is called “Specific Cutting Energy”[7][8] and it is mostly used to describe the efficiency of any material removal process. It can be calculated by dividing cutting power with material removal rate which shows that it is different from other response parameters i-e cutting speed because it is independent of the efficiency, make and type of the machine tool [9], but now some studies have shown that specific energy value may differ for different machining process although the work part material properties remain same[10].

Machining at high cutting speeds is getting attention from past decade because it can benefit us in in form of better surface finish, high production rate, low cutting forces and cutting temperatures[11].These properties are basic requirements for aerospace applications in which mostly aluminum based alloys are used.[12]

1.1 Research Aims

The aim of this research is to validate the results of Specific Cutting Energy Consumption and Surface Roughness in machining of Aluminum alloy Al 6061-T6 at transitional cutting speeds on different machine tools.

1.2 Research Objectives

The objectives of research work are followings:

- Literature review on previous work done in energy consumption of machining process.
- Literature review to analyze the effect of cutting parameters on energy consumption and surface roughness in machining of aluminum alloys at transitional and high cutting speeds.
- Selection of input and response variables and preparation of experimental design

- To examine the behavior of SCE at different levels of cutting parameters.
- To examine the behavior of surface roughness at different levels of cutting parameters.

CHAPTER 2

2 Literature Review

Earlier studies regarding optimization of machining process in order to reduce carbon footprints are usually fall in two categories [13]

1. Direct Energy Modeling
2. Energy Optimization

2.1 Direct Energy Modeling

Direct energy modeling is done both empirically and mechanistically[13].

2.1.1 Empirical Modeling

Draganescu et al.[14] performed different experiments was to determine the statistic modeling of machine efficiency and energy consumed in machining. The functions of different machining parameters include the machine efficiency, consumed energy and specific consumed energy. The results of the experiments were statistically modeled in order to create the relationship between the parameters that have been given above. For this purpose, “Response Surface Methodology” (RSM) was used. The working parameters of machine and the power it consumed collectively helped in obtaining the results of the experiments. The resulting data was used for anticipating the coefficients of the models and in their statistical analysis.

Velchev et al.[15] studied the best available cutting variables for curtailing direct energy consumption. This research paper presents the results of the experimental study. The study discusses the use of energy by material removal rate on turning of steel by Computerized Numerical Controlled (CNC) and an empirical method. Improved empirical method is used to create a model of direct energy consumption. Minimum energy criterion has been applied for making a formula for the efficient cutting speed. Minimum energy consumption during turning is the most significant factor of this study.

2.1.2 Mechanistical Modeling

Gutowski et al.[6] studied show that how much specific electrical energy is required for an extended range of production processes. The results of the study contain three important factors. First, the assumption of many life cycle analyses that the specific energy requirements for manufacturing processes are constant, is wrong. According to this study, the energy requirements are not constant. Second, this study tells that the process rate is the most important variable for estimating the energy requirement. Third, a great number of energy intensive processes are applied in manufacturing processes. The research shows that how the equipment's can become more energy efficient through redesigning.

Gutowski et al.[16] did another study about manufacturing processes and the purpose being this research is to show the energy and material transformations that take place during this process. Energy and exergy has been used as measures in this study. The thermodynamics data for manufacturing processes has been summarized in three aspects which are efficiency of material and energy transformation, the energy requirements for material used and the required energy for manufacturing processes

In Mori et al.[17] study ,it is discussed that energy is consumed at a very high rate in manufacturing processes. In industries, it is very challenging to reduce the consumption of energy. The problem can be solved if the machine tool manufacturers develop such tools that may advance the functioning of machines in a way that they start consuming less energy. Power consumption had been evaluated in different conditions and it was concluded that energy consumption can be minimized by changing cutting conditions. It is applied either on deep hole machining, milling or regular drilling. A new method was also developed to decrease energy consumption. In this method the feed system was synchronized with spindle acceleration. The experiments gave such results which verified the authenticity of these methods.

The modelling approaches used in [6][16][17] were collectively utilized to make a more characteristic energy usage model. The purpose of this study was to make contributions in such an important development. This research tracked the carbon footprint in machining process by tracking the energy dependence. Similar models and their limitations have been reviewed in this study along with the assessment of energy usage and the effect of machine modules and machine codes on the usage of energy. This study addressed the limitations of existing models and developed a mathematical model for the use of electrical energy. The model was applied on milling tool path and remained successful. This research is helpful in making the machine tools more energy efficient and hence reducing the costs of electricity. The study provides useful information about the effects of machine modules on electrical energy usage.[10].

The concept of traditional cost model was used by some researchers. Rajemi and Mativenga[18] did a study and a new model emerged with the aim of the model to develop energy footprints for a product that has been manufactured by the machine. This research finds the variables that help in reducing the energy consumption and eventually the cost of energy used. Moreover, this study indicates the effect of system boundaries in evaluating the optimum machining condition as well as the relation between economic and environmental considerations.

Mativenga and Rajemi[19] shown that it is important to optimize the energy and carbon footprint of products made by machining for the sake of environmental sustainability. The minimum energy criterion was exploited in forming and application of a method for selection of most suitable cutting conditions. This methodology and its effect on energy saving was compared to the practices which were already in use. The research also found the relationship between lowest energy solutions and lowest cost. The study shows how the carbon dioxide emission can be minimized by minimizing the strength of energy and cost of a fraction formed by machine.

There all always some losses in a machine tool so application of mechanistic models for optimizing energy utilization raises questions so alternate statistical approaches were also done. In such study, Li & Kara[5] told that in manufacturing sector, there is increased cost of energy and high energy consumption is leaving hazardous environmental effects. Now this is the need of time to optimize the energy efficiency of machine processes. A machine that performs that turning process consumes the energy which is required by the tool tip for material removal. Generally, the cutting force prediction equation estimates the required energy for the cutting process but this is confined to the energy consumption of the tool tip only. Therefore, the purpose being this study is to generate a reliable method which may estimate the total consumption of energy of a certain machine component that is involved in performing the turning process. In order to make comparison of energy consumption under various cutting conditions, the specific energy utilization has been defined as "the energy consumed to remove $1cm^3$ of material." Through this study an empirical model has been developed which can give reliable estimate of energy consumption for contain process parameters.

High energy consumption leaves deep impacts on environment. Many different awareness programmes has raised the concern of people in this regard and profound attention is being paid towards the issue and approaches are being developed to make the manufacturing processes less harmful for the environment. Estimates of energy consumption would help the industries to develop the strategies for saving energy during machine processes. This study[4] gives an empirical methodology which shows the association between energy usages and process parameters utilized in material removal processes. The methodology has been successfully applied on different turning and milling machine components. The model is 90% accurate.

There is a need to develop an energy model with well-defined coefficients and high accuracy. It is important to have a reliable energy consumption estimate under different machining conditions. This study[20] gives an energy consumption model that define the association between usage of energy and process parameters for material removal process based on empirical modelling and thermal equilibrium. This improved model was tested under different parameters. Moreover, the effectiveness of the model coefficients are clearly emphasized through Statistic Modelling. This model can be effectively used to anticipate the required energy by a machine for milling. Outcome of the experiment shows that this model can provide a reliable estimate of energy consumption and it's up to 95% accurate.

2.2 Energy optimization

Machining processes are leaving fatal impacts on environment. This is the reason that decreasing the consumption of energy has become a point of concern now. Environment friendly manufacturing is the need of hour. Now it is crucial to reduce the usage of energy in accordance with the other variables (i.e. obtained surface quality) in mind. In this study[21], a methodology has been presented which incorporates both energy usage and roughness of surface for optimizing the cutting variables.

Campatelli[22] explained that in machining, there are great environmental effects which are prevailing globally. There is an urgent need for minimizing these environmental issues and for this purpose researchers are trying their best. Manufacturing is the crucial sector because production machines consume the power on a large scale. This study pays attention to the skillfulness of accomplishing centers and presents and experimental desire to decide and use the process variables to lower the power usage carried out on a contemporary Computerized Numerical Controlled (CNC) Machine. The method evaluated using a "Response Surface Method" (RSM) to achieve a suitable model for the fine tuning of the process parameter. An oiling methodology is being selected based on old studies. All the foregoing tests were performed using dry lubrication.

Jihong Yong[23] shows that is vital to reduce energy consumption in manufacturing process. In the past no attention has been paid to environmental sustainability. All the focus was on economic and technological dimensions of manufacturing. The method that has been presented in this research is the multi-object optimization method which utilizes "Response Surface Methodology" (RSM) and weighted grey rational analysis. This methodology is applied in order to determine the rate at which produced, with cutting quality to optimize the cutting variables. This study optimizes three objectives: cutting energy, surface roughness and material dislodgement. Depth and width of cut, feed rate and spindle speed were assessed variables. A quantitative method named weighted grey rational analysis is used to obtain multiple responses. The results based on Response Surface Methodology (RSM) and weighted grey rational analysis showed that width of cut is the most dominant variable showing that low spindle speed cutting is less energy consuming as compared to cutting at starting speed for milling.

In Camposeco-Negrete[25] study, it is discussed in details that machines consume energy and this is the reason they contribute in environmental changes because of emission of hazardous gases. Cutting parameters were developed to decrease power consumption, cutting power or cutting energy. Energy requirement, which reflects the fitness of the machine, is not considered by these response parameters. Greater feed rate utilizes less energy but leads to higher surface roughness.

As the machining processes have been increased in modern production era, so the challenges of minimizing the environmental impacts have also increased. Environmental issues are arising because machines are consuming a large amount of energy due to which the CO_2 emission has largely increased. A lot of studies have been carried out to evaluate reduced power usage by machines. This article [26] presents an interventional study which relates to the development of the cutting variables such as feed and speed in turning of AISI 6061 T6 aluminum. In the experiment, the time required for removal of material by the procedure was increased to maximum while the surface roughness and energy consumption was lowered. Experiments were repeated by using Central Composite Design. On order to get the regression model for the energy utilized, Response Surface Method (RSM) was used.

Specific energy, surface roughness and material removal rate is also evaluated through RSM. As a result, we achieved quality of machining process and sustainability side by side.

Aggarwal [27] showed the results of an experiments about feed rate, cutting speed, depth of cut in turning of AISI P-20 steel. It has been revealed through the technique of Taguchi's and 3D plot of Response Surface Methodology that cryogenic environment is most important determinant in lowering the utilization of power by cutting speed. As compared to other factors, nose radius and feed rate have been found to be less important. Response Surface Methodology is considered to be better as compared to Taguchi's technique but both the techniques predict almost the same results.

The classic study of Herbert Schulz[12] takes a review of the developments that have been made in high speed machining in recent decade. It is now considered that the high-speed machining contributes the most in attaining a higher level of productivity or output. As the high-speed machining has been realized now, it demands modern solutions for machines and their parts. Time consumption of more than 50% can be reduced by using this manufacturing technique of high speed machining. Now it is very important to introduce the safety measure and precautions related to the machines.

Warsi et al.[2] explained that level of energy that has been used by the machines has been reported as the major contributor in negative effects on economy and environment. This paragraph gives an energy allocating approach which will help in evaluating specific cutting energy consumption. This study is different from the earlier approaches which are specified to machines only. This study helps in analyzing the consumption of energy by focusing on the synergy between the machine and the object being worked on. If we increase feed, it will result in higher shear angle. It will also lower the specific cutting energy. This is how we can save up to 29% of energy. The graph that has been created is very helpful in selecting the suitable machining parameters[2] .

Ahmad et al.[28] did orthogonal machining of aluminum 6061-T6 alloy at transitional cutting speeds ranges up to maximum 1000m/min which is above the conventional speed machining ranges. Previously most of the optimization work was done for conventional speed machining so there was a research gap. Feed and cutting speed were selected as two input variables of which effects were analyzed on responses i-e specific cutting energy and cutting power. ANOVA was used as a statistical tool to find out the relationship of feed plus cutting speed on responses specific cutting energy and cutting power. It is found from this study that feed is most important factor if response variable is specific cutting energy. Both feed and cutting speed effect the energy usage by machine tool because by increasing feed and cutting speed in any machining process, material removal rate will be increased which would eventually lead to higher energy consumption during the process although cutting time would be reduced .

Warsi et al.[1] In this work the consumption of SCE during high speed machining of Al 6061-T6 is evaluated. The values that have been analyzed are shown as an energy map .The developed map shows the different regions that have been identified by the consumption of energy. The map that had been created showed that in a lower energy consumption area, there was existence of a “very high energy area”. A comprehensive study was done to inspect the development of this intense energy area with increased built-up edge formation within this area. The zone is also named as avoidance zone.

In all above studies, it is discussed that energy consumption in machining is a major issue and its effect on profit of the manufacturer but also on the environment. Efforts are being made in the past and still researchers are trying to optimize the different machining processes to reduce the carbon footprints.

CHAPTER 3

3 Research Methodology

3.1 Material

Aluminium is abundantly used metal and comes second onto steel in terms of world consumption[29]. Aluminium is available both in pure and alloyed shapes. It is soft and weak material. Commercially aluminium is accessible up to 99.8 percent pure[30]. Both at low and elevated temperature, aluminium shows a weak strength. The main supremacy of aluminium is its small density, excellent strength to weight ratio, good workability, weldability & ductility,corrosion resistance, high conductivity & reasonable cost. It is regularly used for engineering purposes because of its properties of good surface finish and wonderful corrosive resistance. It can also be used for decorative purposes[31].

Aluminium alloy is basically a chemical composition of different elements in pure aluminium. These elements are added to enhance the properties of pure aluminium specially its strength. That's why aluminium alloy remarkably shows high strength as compared to pure aluminium. The following elements consist of silicon, manganese, magnesium, iron, copper & zinc and added up to 5% by weight in pure aluminium. Aluminium alloys have broadly used in aircraft and automobiles industries. The 2xxx and 6xxx series of aluminium alloys have regularly used for machine too applications [29][30] .Al 2011-T3 alloy is called free machining aluminium alloy because it is most easily machinable[32].

3.1.1 Aluminium Alloy

Alloys are given four digits's number; the 1st number represents the general class of alloying element. The series 1xxx composed of 99 percent pure aluminium and this series represent some eminent properties such as corrosion resistance, greater thermal and electrical conductivity. It is frequently used for transmission purpose. Copper is major alloying element in 2xxx series. Copper serve as thee principle alloying element gaining additional strength. They have no corrosive resistance against environment but show a valid combination of greater strength and toughness. These alloys are specially painted to avoid corrosion[33].

Magnesium is very effective alloying element used in 5xxx series and it is extensively used with aluminium. The combination of Al-Mg alloys extensively employed in construction work, storage vessels and pressure vessels. Alloys of this series exhibit an excellent property of weldability and corrosion resistance. Zinc is primary alloying element in 7xxxseries. It will become very high strength alloy when magnesium is appended in minor amount. The most ordinary alloys of 7xxx series are 7050 & 7075, are extensively used in aircraft industry[2].

Table 1: Major Alloying elements in different series of Aluminum Alloys[33]

Series	**Major Alloying Element**	**Secondary Alloying Elements**
1xxx	Commercially Pure 99%	None
2xxx	Copper (Cu)	Mg, Mn, Si
3xxx	Maganese (Mn)	Mg, Cu
4xxx	Silicon (Si)	None
5xxx	Magnesium (Mg)	Mn, Cr
6xxx	Magnesium(Mg) & Silicon(Si)	Cu, Mn
7xxx	Zinc (Zn)	Mg, Cu, Cr

Magnesium and silicon are the major alloying elements in 6xxx series. 6061 is mostly used alloying element of this series and it is widely employed in truck and marine frame. Alloys of this series have shown some mechanical and chemical properties such as good formability, weldability and superb corrosion resistance. Extrusion products of 6xxx series are frequently used in structural applications**.** Structure applications of 6061 alloy are due to its good weldability.

Table 2: Mechanical & physical properties of Aluminum 6061 alloy[34]

Sr.No	**Mechanical Properties**		**Physical Properties**	
1	Tensile Strength	310 MPa	Density	2.70 g/cm^3
2	Proof Stress	270 MPa	Thermal Expansion	$23.4x10^{-6}/K$
3	Shear Strength	190 MPa	Modulus of Elasticity	70 GPa
4	Elongation	12%	Thermal Conductivity	166 W/Mk
5	Hardness (Vicker)	100 HV	Melting Point	650^0C

Owing to higher consumption in industrial sector, Al 6061-T6 Alloy is used in this research.

Table 3: Comparison of chemical composition of Al 6061-T6 with other work materials[33]

Alloy		**Chemical Composition**									
Al 6061-T6	Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	others	Al
	%	0.62	0.22	0.29	0.07	1.1	0.18	0.01	0.01	<0.5%	Balance
Al 2011-T3	Element	Si	Fe	Cu	Bi	Zn	Pb	Others			Al
	%	0.4	0.7	5.5	0.4	0.3	0.4	0.7			Balance
Al 7075-T6	Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others	Al
	%	0.4	0.5	1.2	0.3	2.5	0.22	5.5	0.2	0.15%	Balance
AISI 1117	Element	C		Mn		P(max)		Si(max)		S	
	%	0.18		1.2		0.040		0.1		0.1	
AISI 4140	Element	C	Mn	P	S	Cr	Si		V	Mo	
	%	0.4	0.9	0.035	0.04	1.0	0.25		_	0.2	
Type 416	Element	C	Mn	P	S	Si	Cr		Se	Mo(max)	
	%	0.15	1.25	0.06	0.15	1	13.00		_	0.60	
Ti-6Al-4V	Element	Al	V	Fe	C	O	H	N	Y	Ti	
	%	5.86	4.02	0.2	0.01	0.12	0.0023	0.007	<0.005	Balance	
Inconel 718	Element	Cr	Cb	Mo	Ti	Al	Fe	Mn	Si	C	Ni
	%	18.6	5.0	3.1	0.9	0.4	18.5	0.2	0.3	0.04	53

Table 4: Comparison of physical and mechanical properties of Al 6061-T6 with other workpiece materials [30][33]

Property	**Material**							
	Al 6061-T6	**Al 2011-T3**	**Al 7075-T6**	**AISI 1117**	**AISI 4140**	**SS 416**	**Ti-6Al-4V**	**Inconel 718**
Denisty (g/cm3)	2.7	2.83	2.81	7.87	7.85	7.75	4.42	8.22
Hardness (HB, HRC)	95 HB	95 HB	7 HRC	130 HB	197 HB	262 HB	37 HRC	42 HRC
UTS (MPa)	310	379.2	572	450	1590	517	950	1350
Yield Strength (MPa)	275	296.5	503	310	1460	276	880	1170
Modulus of Elasticity(GPa)	69	70.3	71.7	200	207	300	113.8	200
Ductility (%)	Dec-14	15	11	20	12.5	30	14	16
Thermal Conductivity (W/Mk)	167	226	130	51.9	35.8	26.8	6.7	11.4

Al6061-T6 alloy is used as work sample for experimental evaluation. The purpose of this work is to validate the result of benchmark up to the range of transitional speed machining.

3.2 Transitional Speed Machining

The ranges of cutting speed for different materials are taken from previous research [12]. Cutting Speed for machining different is categorized into three areas; conventional, transition, and HSM range.

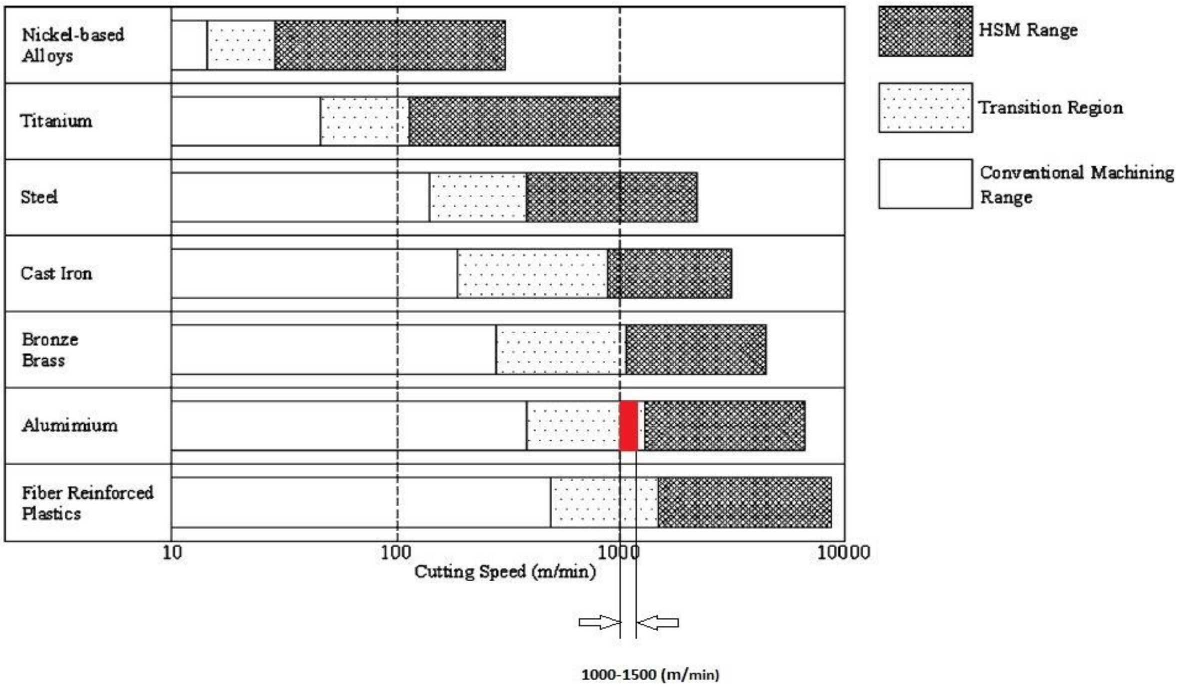

Figure 1: Cutting Speed ranges for machining of different materials[12]

In the figure, transitional cutting speed for aluminum is clearly seen and we have chosen the cutting speed for our experimental work that lies in this range.

3.3 Machine Tools

Experimental work is carried on all these experiments were carried out at three different CNC turning machines having a distinctive feature of turret centre. These machines are manufactured by different companies and their specifications are also different. First trial of experiments was performed on CNC turning machines (Model: DOOSAN PUMA 280 ML) manufactured by *DOOSAN* Intrapore Machine Tools Korea, at Gujranwala Tools, Dies and Moulds Centre (GTDMC). Second trial of experiments were carried out on Turning Centre (Model: CK 6150) manufactured by Nanjing Erjichunang CNC Machine Tool China at Light Engineering Services Centre (LESC) Gujranwala.

Figure 2: DOOSAN PUMA 280 ML Turning Centre (GTDMC)

Figure 3: Turning Centre (Model: CK 6150) at LESC Gujranwala

Table 5: Specifications of Machine Tools used in Experimental Work

Description	Items	PUMA 280LM	CK 6150
		Specifications	Specifications
Machine capacity	Max turning Dia Max turning length	420 mm 1078 mm	300 mm 1000 mm
Axis's Travel	X-axis travel Z-axis travel	242 mm 1100 mm	260 mm 600 mm
Main spindle	Spindle speed	3500 rpm	30-1600 rpm
Turret	No. of stations Max tool size	12 25 x 25	4 or 6 16 x 16
Motor	Main spindle motor	18.5-22 kW	7.5 kW

3.4 Cutting Tool

CCMW 09 T3 04 H13A uncoated plain cutting inserts without chip breakerand with 0^0 rake angle, supplied by Sandvik, were used for all experimental trails under the dry cutting conditions. For each experiment, a fresh cutting insert was used.

3.5 Experimental Setup

A shafts of Aluminum Alloy 6061-T6 having diameter 160mm and cutting length in the range of 65mm used as a work-piece material in this research. All these experiments were carried out at GTDMC and LESC Gujranwala on CNC turning machines (Model: DOOSAN PUMA 280 ML) manufactured by *DOOSAN* Infracore Machine Tools Korea and Turning Centre (Model: CK 6150) manufactured by Nanjing Erjichunang CNC Machine Tool China respectively.

All these tests were done with cutting insert (uncoated) H13A. Fresh cutting tips were used for every experiment. Due to fresh cutting insert, tool wear effect has not been avoided for energy consumption anlysis. All these experiments were performed under dry cutting conditions. Single point cutting methodology was employed for these experiments.

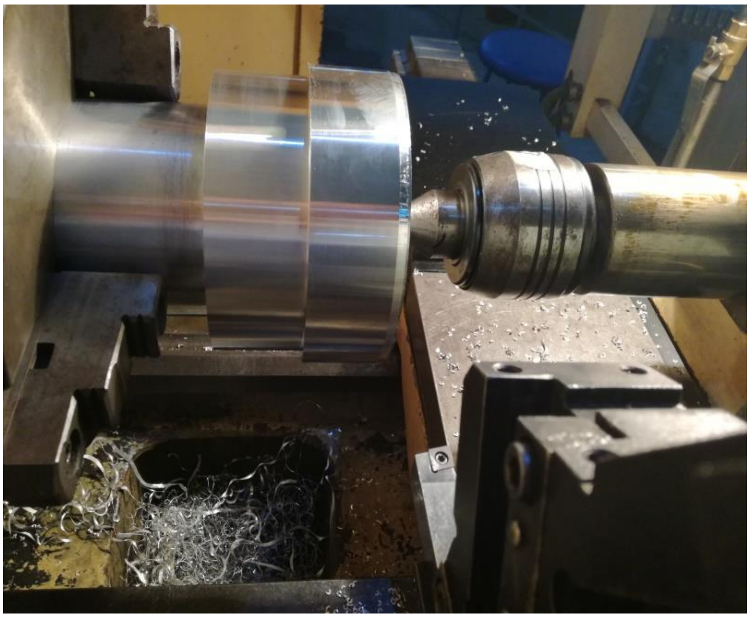

Figure 4: Single point cutting setup

Cutting parameters are varied in the ranges described by manufacturer of tool. As this present research work was aimed to validate the benchmark at transitional speed range so cutting speeds were set accordingly. The basic purpose of these experiments is to measure the machine power during running state. The power meter Yokogawa CW 240-F has been used to measure the power consumption during process of machining and it was installed at the main bus of machine tool. It measured the following factors voltage, current and Power after 0.1s interval of time.

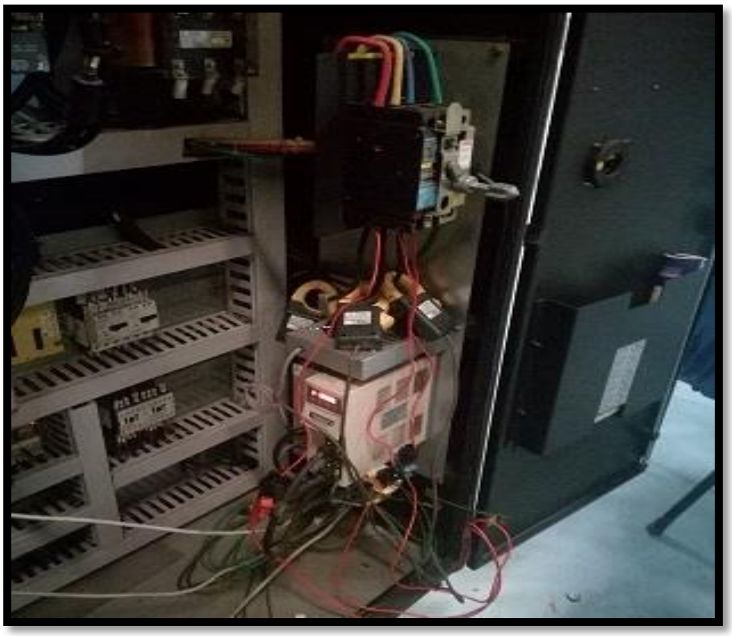

Figure 5: Power analyzer setup

For every experiment, Specific cutting Energy (SCE) calculated by given formula

$$\text{SCE}\ (\text{J/mm}^3) = \frac{P_{\text{cut}}\ (\text{W})}{\text{MRR}\ (\text{mm}^3/\text{s})}$$

In this equation P_{Cut} is the actual power that consumed in the duration in which workpiece material and cutting tool are in contact with each other. It is calculated by given formula

$$P_{cut} = P_{actual} - P_{air}$$

Material Removal Rate (MRR) was calculated by following formula

$$MRR\,(\text{mm}^3/\text{sec}) = \text{v f d}$$

Where

V = Cutting Speed (m/min)

f = feed (mm/rev)

d = depth of cut (mm)

3.6 Design of Experiments

Design of experiments (DOE) is an orderly technique to decide the connection between factors influencing a procedure and the yield of that procedure. As such, it is utilized to discover circumstances and end results connections. This data is expected to oversee process contributions to request to improve the yield. A comprehension of DOE initially requires learning of some measurable instruments and experimentation ideas. Although a DOE can be broken down in numerous product programs, it is critical for experts to comprehend fundamental DOE ideas for appropriate application[35].

There are multiple types of techniques and procedures to devise the setup methods for experimentation, which come under the umbrella of Design of Experiments. The two most suitable techniques, Full Factorial & Taguchi methods, are discussed below.

3.6.1 Full Factorial

A full factorial DOE measures the reaction of each conceivable blend of elements and factor levels. These reactions are examined to give data about each fundamental impact and each association impact. A full factorial DOE is functional when less than five elements are being researched. Testing all blends of factor levels turns out to be excessively costly and tedious with at least five elements[36]

3.6.2 Taguchi Methodology

Taguchi methods were developed by Genichi Taguchi to analyse the data based on optimized statistical approaches. Taguchi's plans are generally exceedingly fractionated, which makes them extremely appealing to specialists. Completing a half-division, quarter-portion or eighth part of a full factorial outline enormously lessens expenses and time required for a planned examination.

In Taguchi Methodology, quality is measured by the deviation of a characteristic from its target value. A loss function is developed for this deviation. Uncontrollable factors, known as noise, cause such deviations which eventually lead to loss. Since the elimination of noise factors are impossible, the Taguchi method seeks to minimize the effects of noise and to determine the optimal level of the important controllable factors which are actually based on the concept of robustness[25]

The design of experiments was done through Taguchi L_9 orthogonal arrays through 3-level design by using Minitab® version:18.1 software. Machining parameters were selected according to Sandvik Coromant,2015 and their level selection according to tool manufacturer. Three cutting parameters selected are feed, cutting speed and depth of cut. The levels of machining parameters have shown in the table

Table 6: Machining parameters and their level

Parameters	Level 1	Level 2	Level 3
Cutting speed (m/min)	1000	1250	1500
Feed (mm/rev)	0.1	0.2	0.3
Depth of cut (mm)	1	2	3

3.7 Analysis of Experimental Data

After performing experiments on machine tools, analysis of result have done to examine the effect of input variables i-e feed, speed and depth of cut on response variables; specific cutting energy (SCE), material removal rate (MRR) and surface roughness. Minitab® version: 18.1 software is used to perform all analysis on experimental results.

3.7.1 Main Effect Plots

These plots are very useful in showing the trend or shift of individual variable for response variable. Minitab creates the main effects plots by plotting the means for every individual variable. A solid line connects the points for each variable. If this solid line is horizontal then there will be no main effect present and when line is not horizontal then a main effect present[37]. The steeper the slope of the line shows that greater will be the magnitude of the main effect. As we have three input variables; speed, feed and depth of cut in this research so all these three variables are plotted individually for response variable; specific cutting energy (SCE).

3.7.2 Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) is a statistical technique, developed by Ronald Fisher in 1918 is used to explain the experimental data and also employed to check the variance in average performance of groups of items tested. Researchers use ANOVA in different ways according to their research requirements. Mainly ANOVAS are used in three ways; one way ANOVA, two way ANOVA and N way ANOVA. It tells us about the contribution ratio of each input variable[35].In this research, ANOVA is applied on experimental data in order to find out the contribution ration of three input variables; speed, feed and depth of cut for response variable; specific cutting energy (SCE).

CHAPTER 4

4 Results and Discussions

As described earlier this research work is the experimental validation of benchmark study carried out for turning of Aluminium Al 6061-T6 alloy at transitional speeds. Turning is more common process as compared to orthogonal machining in terms of its utilization in industrial sector therefore it is chosen for experimental validation of benchmark studies.

4.1 Specific Cutting Energy (SCE)

Table 7: Benchmark results of experimental data by using Taguchi L_9 orthogonal array

Sr No.	Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Cutting Power (KW)	MRR (mm3/sec)	SCE (J/mm3)
1.	1000	0.1	1	1.35	1666	0.81
2.	1000	0.2	2	4.11	6664	0.62
3.	1000	0.3	3	8.70	14994	0.58
4.	1250	0.1	2	3.00	4165	0.72
5.	1250	0.2	3	7.75	12495	0.62
6.	1250	0.3	1	3.89	6247.5	0.62
7.	1500	0.1	3	5.37	7497	0.72
8.	1500	0.2	1	3.33	4998	0.67
9.	1500	0.3	2	9.20	14994	0.61

Table 8: Experimental results for validation test at GTDMC by using Taguchi L_9 orthogonal array

Sr No.	Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Cutting Power (KW)	MRR (mm3/sec)	SCE (J/mm3)
1.	1000	0.1	1	1.42	1666	0.85
2.	1000	0.2	2	4.13	6664	0.62
3.	1000	0.3	3	8.55	14994	0.57
4.	1250	0.1	2	3.22	4165	0.77
5.	1250	0.2	3	8.54	12495	0.68
6.	1250	0.3	1	3.48	6247.5	0.56
7.	1500	0.1	3	5.80	7497	0.77
8.	1500	0.2	1	3.55	4998	0.71
9.	1500	0.3	2	8.35	14994	0.56

4.1.1 Main Effect Plots for Specific Cutting Energy (SCE)

These plots are very useful in showing the trend or shift of individual variable for response variable. Minitab creates the main effects plots by plotting the means for every individual variable The main effects analysis is basically used to check the effects of individual factor on response variable. Main effects plots recognize us the level of each factor that allocate the minimum value of response variable.

4.1.1.1 Main effect plots for validation test at GTDMC

In this main effects plots three factors (depth of cut, cutting speed and feed) was used as a input but the response variable was specific cutting energy. The value of energy consumed by machine tool during single point cutting was minimized at highest level of feed rate, depth of cut and cutting speed.

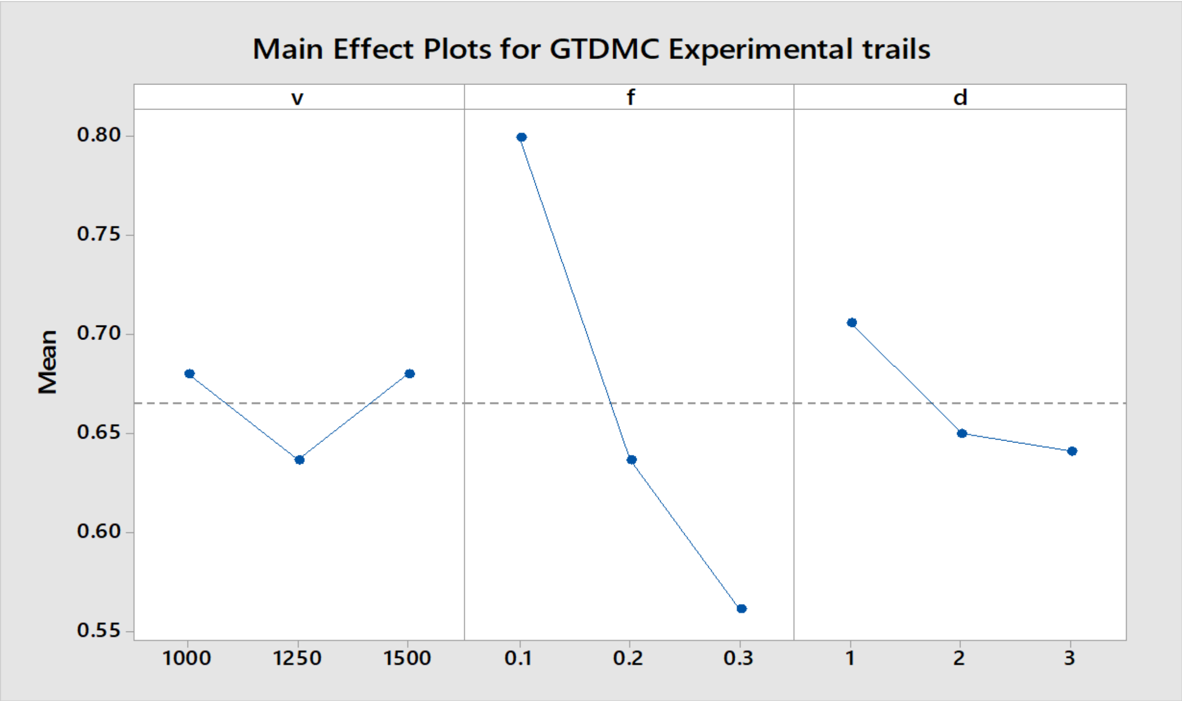

Figure 6: Main effect plots for validation test at GTDMC

When this result was compared with the original result of main effects plots then the result was totally endorsed.

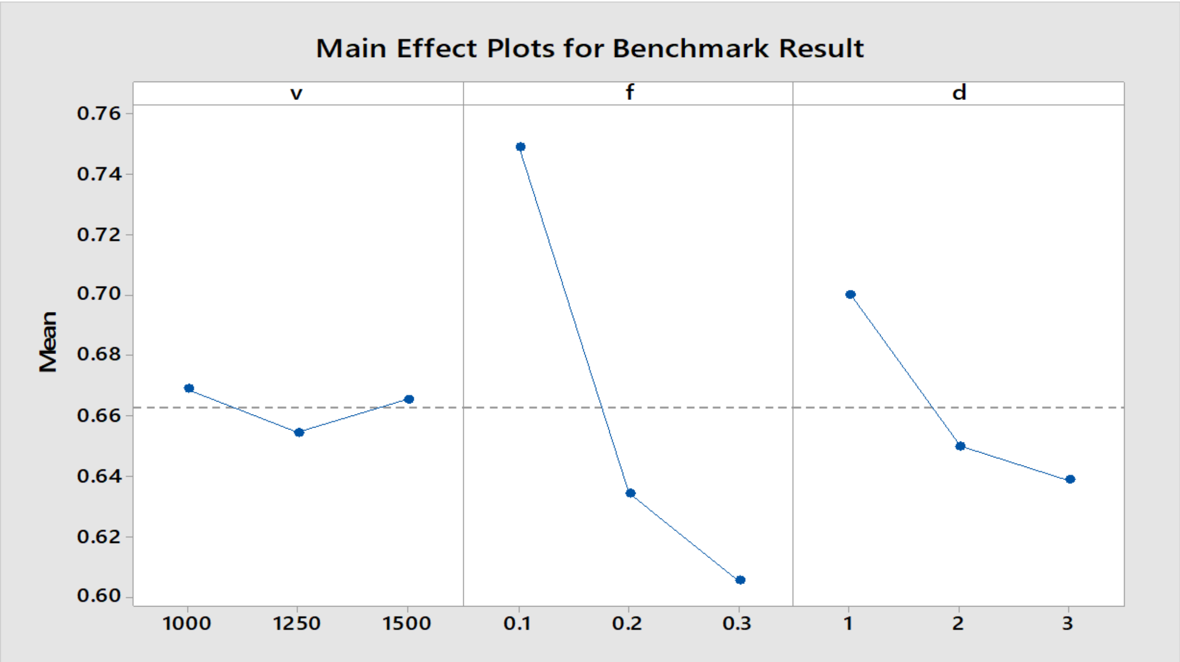

Figure 7: Main effect plots of Benchmark study

4.1.1.2 Main effects plots for validation test at LESC

To check further validation of experimental data on another machine tool was used. The value of energy consumed after the experimental runs has shown in the table

Table 9: Experimental result for validation test at LESC by using Taguchi L_9 orthogonal array

Sr No.	Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Cutting Power (KW)	MRR (mm3/sec)	SCE (J/mm3)
1.	1000	0.1	1	1.35	1666	0.82
2.	1000	0.2	2	4.13	6664	0.62
3.	1000	0.3	3	8.55	14994	0.57
4.	1250	0.1	2	3.12	4165	0.75
5.	1250	0.2	3	7.12	12495	0.57
6.	1250	0.3	1	4.00	6247.5	0.64
7.	1500	0.1	3	6.15	7497	0.81
8.	1500	0.2	1	3.50	4998	0.70
9.	1500	0.3	2	9.90	14994	0.66

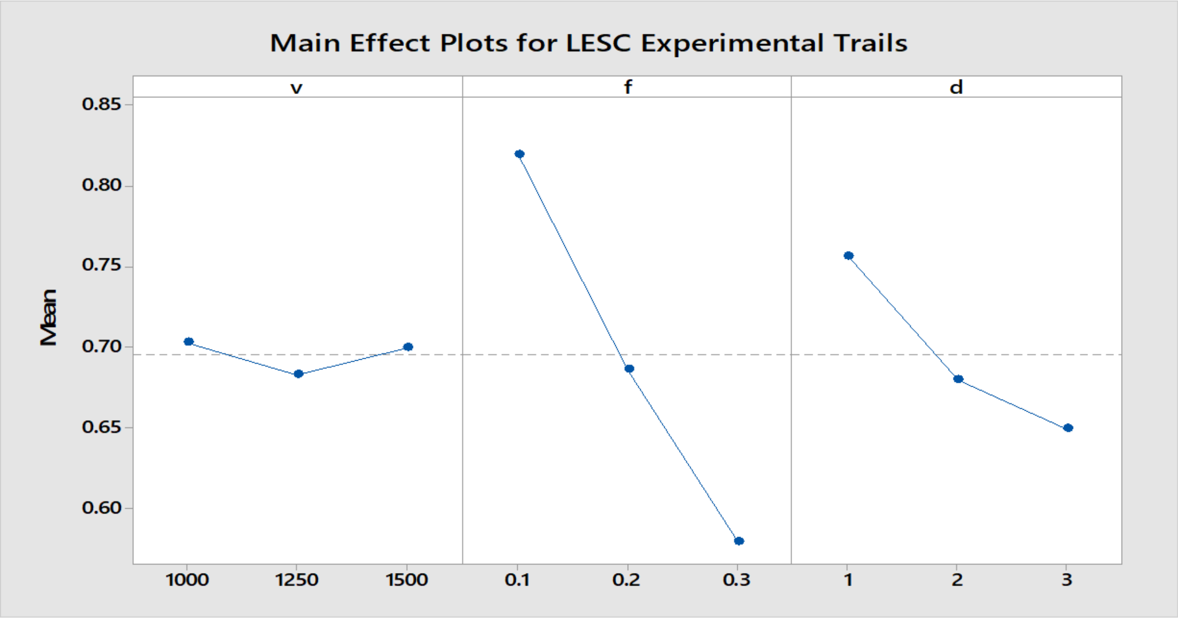

Figure 8: Main effect plots for validation test at LESC

The main effects plots were used to check the drift of each factor on energy consumption. In this case the trend of input parameters is obtained is similar to previous one. So the value of energy consumed during turning was minimized when the feed rate, depth of cut at their highest level and cutting speed shows parabolic shift. The amount of energy consumption was determined when the machining time taking into account. The value of energy consumed was minimum when feed rate at his highest level. At high level of feed rate, the overall time required to machine the work-piece was decreased. So therefore a less amount of energy was required for machining purpose high level of depth of cut also consumed minimum value of energy. When value of depth of cut was at highest level, greater volume of material was removed from the surface of work-piece in a single pass. So overall the time required to machine the work-piece was reduced. Therefore, the value of energy consumed was also reduced.

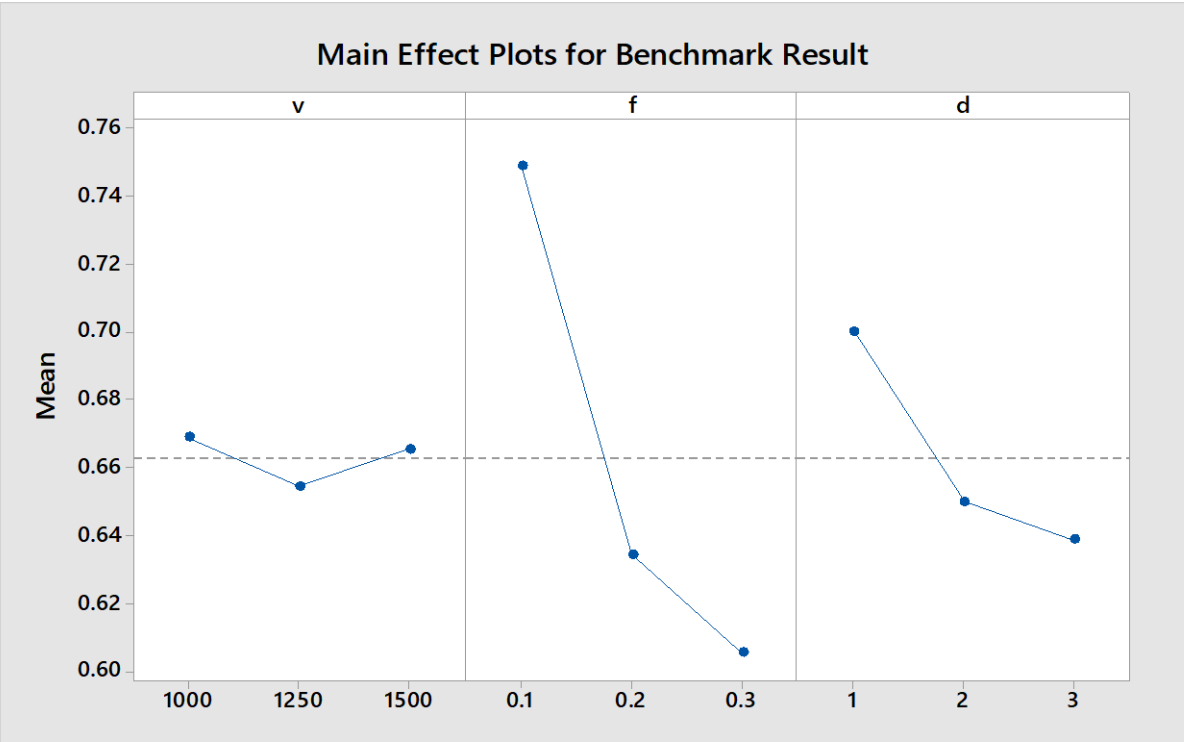

Figure 9: Main effect plots of benchmark study

4.1.1.3 Confirmatory Test for Specific Cutting Energy (SCE)

Main effect plots indicated the levels the levels of input variables (cutting speed, feed and depth of cut) on which minimum and maximum value of response variable (specific cutting energy) could be achieved. So these findings are shown in the table for SCE.

Table 10: Confirmatory Test Results for Specific Cutting Energy (SCE)

		Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	SCE (J/mm3)
GTDMC	**Best**	1250	0.3	3	0.55
	Worst	1000	0.1	1	0.85 (L9)
LESC	**Best**	1250	0.3	3	0.56
	Worst	1000	0.1	1	0.82 (L9)

4.1.2 Analysis of variance (ANOVA) for Specific Cutting Energy (SCE)

The purpose of ANOVA is to check the variation of individual factor relative to the total variation observed in the result. In ANOVA analysis, three factors (feed rate, depth of cut and cutting speed) was investigated to check the effect of response variable i.e. SCE.

ANOVA analysis was accomplished with Minitab version 18 software and determine the impact of input factors towards response variable i.e. SCE. The analysis was carried out at confidence level of 95%. In ANOVA analysis the value of P and F play a key role to decide the significance of factors. If the value of P is less than 0.05 then the factor was considered has significant. Moreover, the larger value of F showed the importance of input factor.

4.1.2.1 Analysis of variance (ANOVA) for validation test at GTDMC

In order to probe the sway of feed rate, depth of cut and cutting speed on energy consumption at conventional speed. Analysis of variance was conducted at 95% confidence level. The result of SCE consumption for validation test at GTDMC is shown below

Table 11: ANOVA-SCE for validation test at GTDMC

Analysis of Variance							
Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
v	2	0.011267	3.70%	0.011267	0.005633	20.53	0
f	2	0.265689	87.28%	0.265689	0.132844	484.05	0
d	2	0.021956	7.21%	0.021956	0.010978	40	0
Error	20	0.005489	1.80%	0.005489	0.000274		
Total	26	0.3044	100.00%				

The result of ANOVA table has confirmed that all the factors are significant for minimum energy consumption because value of P is less than 0.05 in all three factors. In benchmark research, the effectiveness of factors has shown in following way,

"Feed rate > depth of cut > cutting speed"

ANOVA result of previous work has expressed that feed rate has played more influence role on SCE consumption. So value of energy can be minimized by optimizing the feed rate. Depth of cut and cutting speed has also play some role for minimizing energy consumption.

Table 12: ANOVA-SCE for benchmark study

Analysis of Variance							
Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
v	2	0.00103	0.80%	0.00103	0.000515	2.29	0.027
f	2	0.10343	80.79%	0.10343	0.051715	230.03	0
d	2	0.019074	14.90%	0.019074	0.009537	42.42	0
Error	20	0.004496	3.51%	0.004496	0.000225		
Total	26	0.12803	100.00%				

According to ANOVA analysis depth of cut played a vital role as compared to cutting speed. So the following effective order has indicated here.

"Feed rate > depth of cut > cutting speed"

4.1.2.2 Analysis of variance (ANOVA) for validation test at LESC

Table 13: ANOVA-SCE for validation test at LESC

Analysis of Variance							
Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
v	2	0.002067	0.65%	0.002067	0.001033	11.07	0.001
f	2	0.260267	81.67%	0.260267	0.130133	1394.29	0
d	2	0.054467	17.09%	0.054467	0.027233	291.79	0
Error	20	0.001867	0.59%	0.001867	0.000093		
Total	26	0.318667	100.00%				

It is confirmed from table data that all three factors (feed rate, depth of cut and cutting speed) are significant as all the P values are less than 0.05. In all three factors, feed has more prominent effect on SCE due to small value of P comparatively to remaining factors. The role of other two factors was not so effective because of that their P-values have near to 0.05. So their contribution for the evaluation of response was not enough but the depth of cut has contributed a little bit more as compared to cutting speed. So the effective order of validation test at LESC is following:

"Feed rate > depth of cut > cutting speed"

Table 14: ANOVA-SCE for benchmark study

Analysis of Variance							
Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
v	2	0.00103	0.80%	0.00103	0.000515	2.29	0.027
f	2	0.10343	80.79%	0.10343	0.051715	230.03	0
d	2	0.019074	14.90%	0.019074	0.009537	42.42	0
Error	20	0.004496	3.51%	0.004496	0.000225		
Total	26	0.12803	100.00%				

The response that is direct recorded through machine and others that are calculated through equation are examined to check their inclinations in the data. Material removal rate directly depends upon cutting parameters such as feed, cutting speed and depth of cut. It values increased if any of its parameter increased.

4.2 Effect of MRR on Cutting Power

When values of cutting parameters were increased then machine required more power to cut the materials. In other words, cutting power increased.

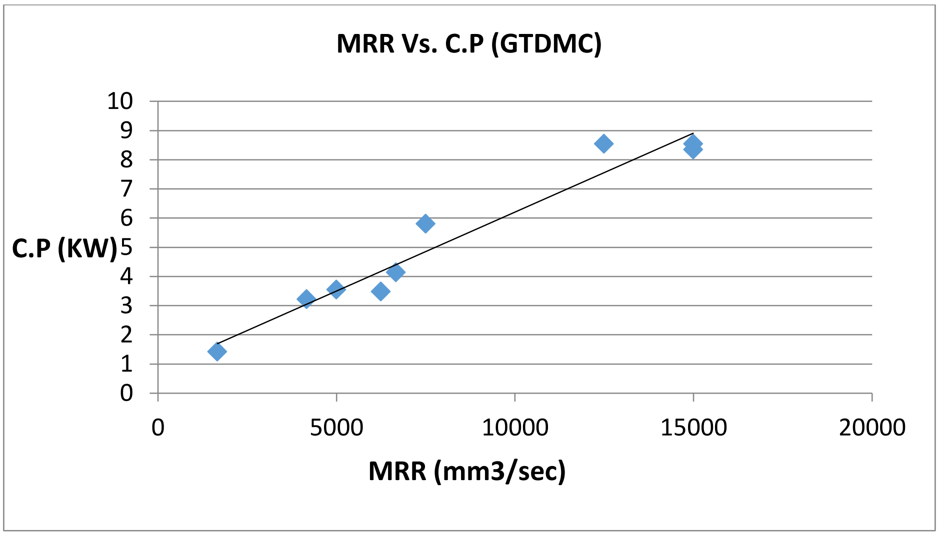

Figure 10: Cutting Power vs. Material removal rate for validation test at GTDMC

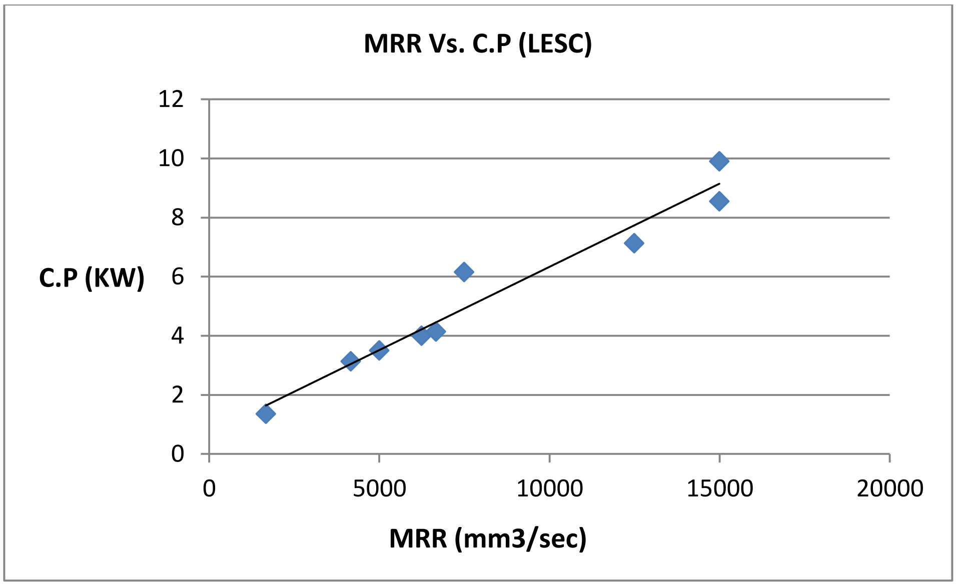

Figure 11: Cutting Power vs. Material removal rate for validation test at LESC

Both the response factors cutting power and MRR in Fig.10 & Fig.11 have direct relation with each other and their values also depend on the machining parameters. Both the responses increased in a non-linear way when machining parameters were at their higher values.

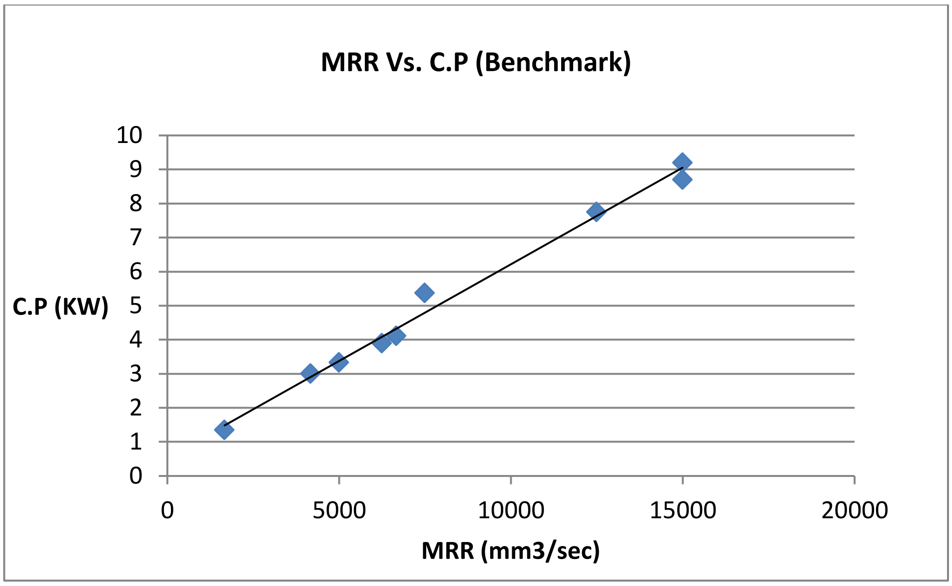

Figure 12: Cutting Power vs. Material removal rate for benchmark study

Fig.12 endorses the results shown in Figure 10 and Figure 11 for validation tests at GTDMC & LESC respectively.

4.3 Surface Roughness

Surface roughness is a part of surface texture. The value of surface roughness obtained after the experimental runs has shown in the table.

Table 15: Surface Roughness results for Benchmark and Validation tests

Sr No.	Cutting speed m/min	Feed (mm/rev)	Depth of cut (mm)	Benchmark Surface Roughness Ra (µm)	GTDMC Surface Roughness Ra (µm)	LESC Surface Roughness Ra (µm)
1.	1000	0.1	1	1.39	1.43	1.79
2.	1000	0.2	2	2.78	3.10	3.59
3.	1000	0.3	3	4.60	4.85	5.13
4.	1250	0.1	2	1.42	1.54	1.87
5.	1250	0.2	3	3.06	3.30	3.56
6.	1250	0.3	1	4.71	4.90	5.34
7.	1500	0.1	3	1.59	1.80	2.50
8.	1500	0.2	1	2.79	2.80	3.53
9.	1500	0.3	2	4.89	5.10	5.53

4.3.1 Main effects plot for Surface Roughness (Ra)

These plots are very useful in showing the trend or shift of individual variable for response variable. Minitab creates the main effects plots by plotting the means for every individual variable. The main effects analysis is basically used to check the effects of individual factor on response variable. Main effects plots recognize us the level of each factor that allocate the minimum value of response variable.

The main effects analysis is basically used to examine the effects of every factor on response variable. Main effects plot recognizes us the level of each factor that assign the minimum value of response variable. In this main effects plots three factors (depth of cut, cutting speed and feed) was used as an input and the response variable was surface roughness. These experiments were conducted to analyse the minimum value of surface roughness. In first validation test, feed rate minimized the value of surface roughness at its minimum level. Depth of cut and cutting speed has also some impact on response factor.

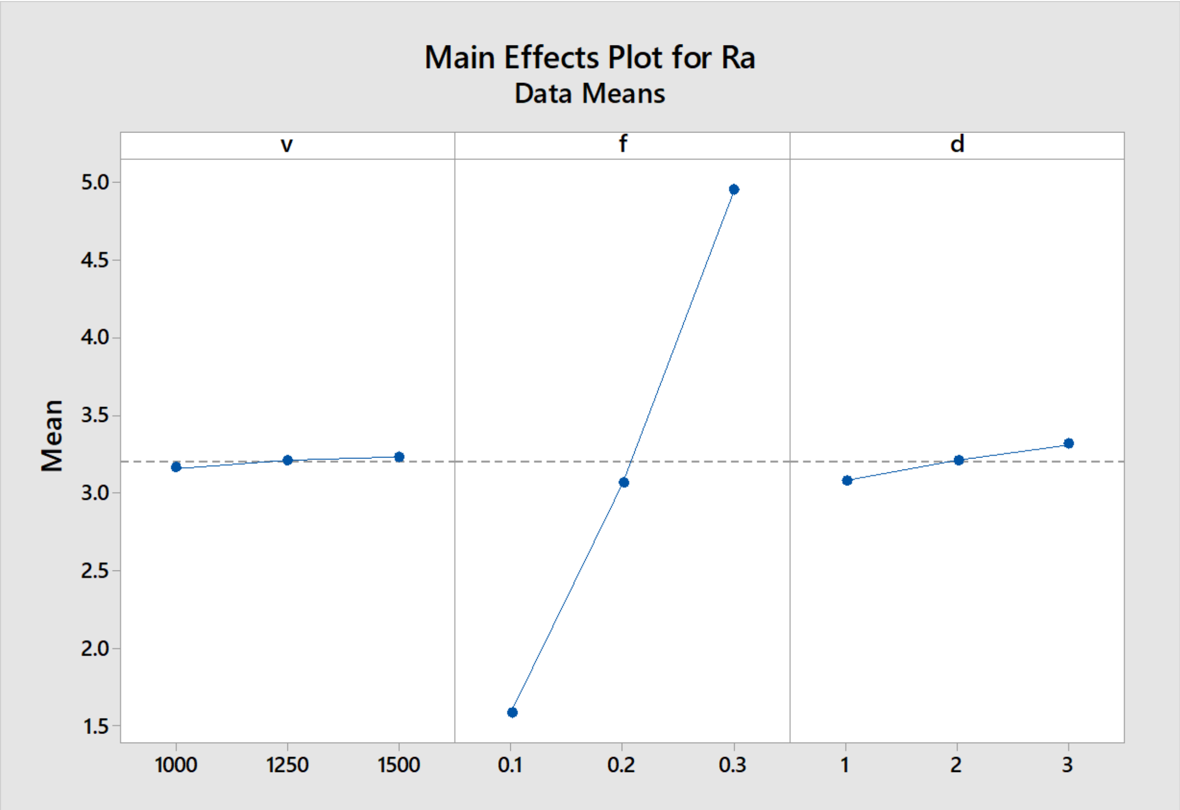

Figure 13: Main Effect Plot of Surface Roughness for Validation Test at GTDMC

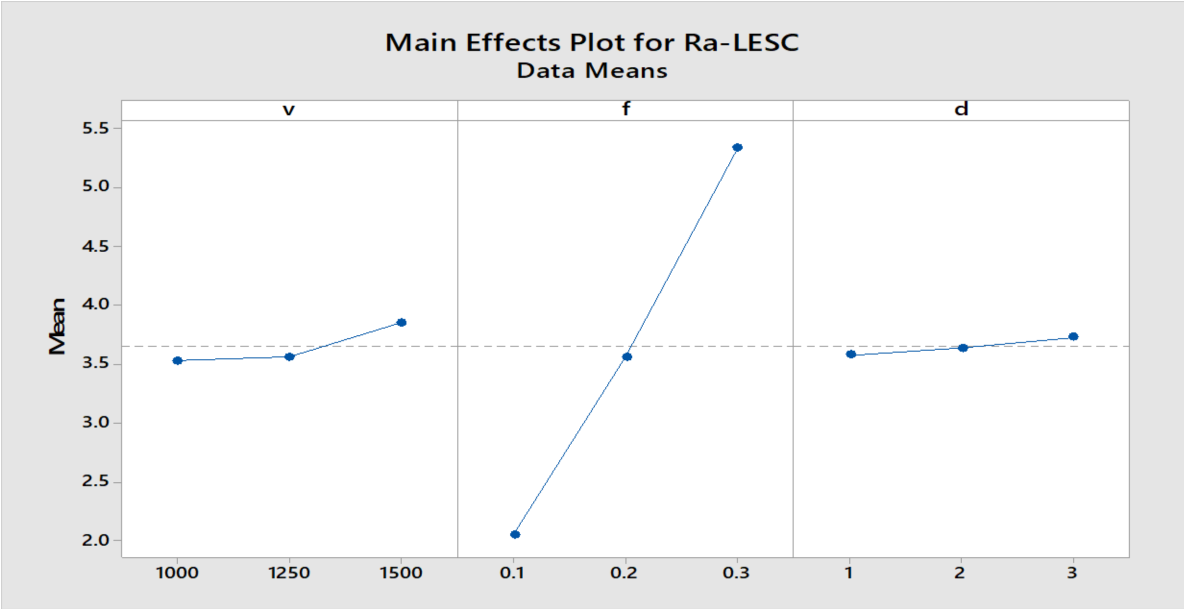

Figure 14: Main Effect Plot of Surface Roughness for Validation Test at LESC

In both validation tests at GTDMC & LESC, feed rate, depth of cut and cutting speed have minimized the value of surface roughness at its minimum level which is 1000 m/min cutting speed,0.1 mm/rev feed and 1 mm depth of cut. When it is checked by benchmark study result then same trend was shown in main effect plots in Figure 15 in which minimum value of surface finish was obtained at 1000 m/min cutting speed, 0.1 mm/rev feed and 1 mm depth of cut.

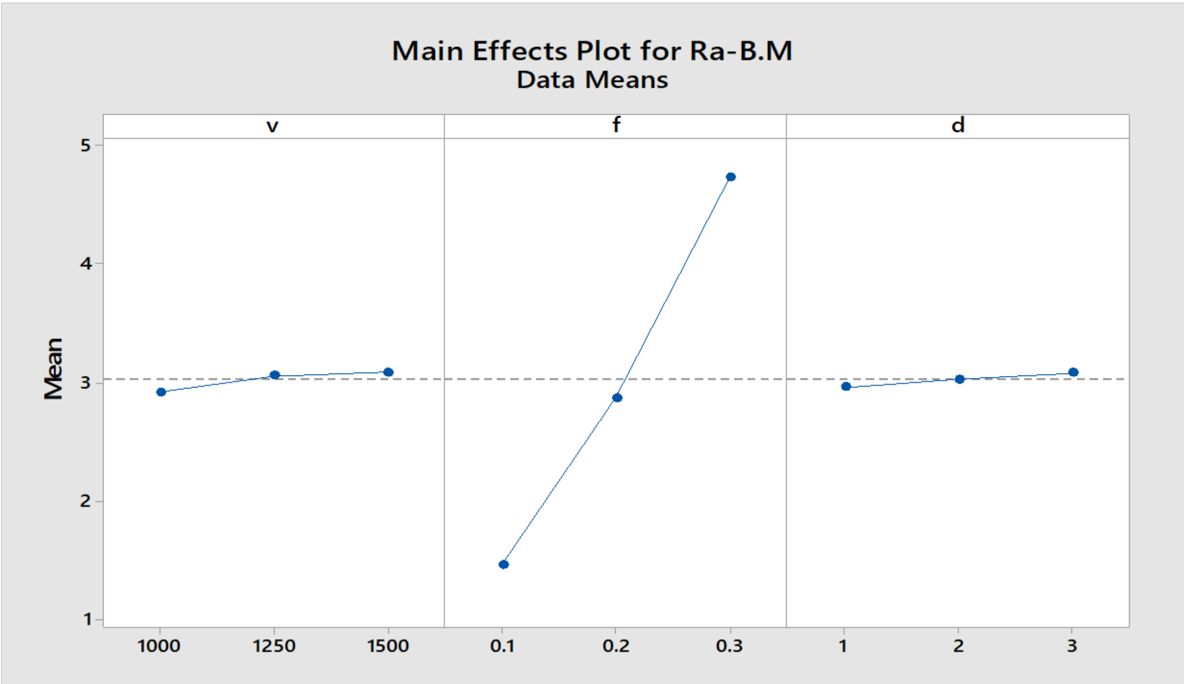

Figure 15: Main Effect Plot of Surface Roughness for Benchmark Study

4.3.1.1 Confirmatory Test for Specific Cutting Energy (SCE)

Main effect plots indicated the levels the levels of input variables (cutting speed, feed and depth of cut) on which minimum and maximum value of response variable (Surface roughness) could be achieved. So these findings are shown in the table for surface roughness Ra.

Table 16: Confirmatory Test Results for Surface Roughness (Ra)

		Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Surface Roughness Ra (µm)
GTDMC	**Best**	1000	0.1	1	1.43 (L9)
	Worst	1500	0.3	3	5.12
LESC	**Best**	1000	0.1	1	1.79 (L9)
	Worst	1500	0.3	3	5.61

4.3.2 Analysis of variance (ANOVA) for Surface Roughness (Ra)

Analysis of variance (ANOVA) was used to examine the key role of every factor. This analysis was done at confidence level of 95%. Feed rate is the most significant factor for optimizing the value of surface roughness (Ra). Less P-value and High F-value indicates the importance of feed rate for minimizing the Ra.

Table 17: ANOVA-Ra for validation test at GTDMC

Analysis of Variance							
Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
v	2	0.2264	0.30%	0.2264	11.32%	11.46	0
f	2	75.3992	98.47%	75.3992	3769.96%	3815.75	0
d	2	0.7512	0.98%	0.7512	37.56%	38.02	0
Error	20	0.1976	0.26%	0.1976	0.99%		
Total	26	76.5744	100.00%				

Table 18: ANOVA-Ra for validation test at LESC

Analysis of Variance							
Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
v	2	0.1033	0.21%	0.1033	0.0516	2.15	0.043
f	2	48.5195	97.68%	48.5195	24.2597	1009.84	0
d	2	0.5693	1.15%	0.5693	0.2846	11.85	0
Error	20	0.4805	0.97%	0.4805	0.024		
Total	26	49.6725	100.00%				

High feed rate minimized SEC consumption but will lead to maximize surface roughness. In ANOVA analysis feed is most significant factor followed by depth of cut and cutting speed. ANOVA analysis for both the test has shown in the table 15 and table 16 and their results were validated by applying ANOVA TO Benchmark Surface Roughness results and results were endorsed.

Table 19: ANOVA-Ra for Benchmark Study

Analysis of Variance							
Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
v	2	0.0651	0.13%	0.0651	3.25%	4.63	0.022
f	2	48.3193	99.28%	48.3193	2415.96%	3439.91	0
d	2	0.1443	0.30%	0.1443	7.21%	10.27	0.001
Error	20	0.1405	0.29%	0.1405	0.70%		
Total	26	48.6691	100.00%				

CHAPTER 5

5 Conclusion

This study presents the validation of Specific Cutting Energy Consumption and Surface Roughness at transitional cutting speeds on different machine tools during single point cutting. Al 6061 T6 used as work piece material for machining, uncoated cutting inserts of H13A are used for all the experiments. During investigation it was found the optimum values of cutting parameters were used to minimize the response variables i.e. SCE consumption and surface roughness. In order to found out the value of energy consumption, initially find the value of cutting power through proper calculation then divided by material removal rate to obtain specific cutting energy.

Surface finish is very imperative response variable because it gives the quality of product. Cutting parameters make sure that minimum value of surface roughness should be achieved regardless of energy consumption because if a product is rejected due to quality problems then it will go into scrap. It means re-machining is required so consequently more energy will be required to machine again.

Following conclusions can be drawn from experimental work.

5.1 Validation test at GTDMC Machine Tool

5.1.1 Specific Cutting Energy (SCE) consumption at GTDMC Machine Tool

- In main effects plot, Specific Cutting Energy (SCE) is inversely related to feed and depth of cut. The trend of specific cutting energy is in descending order shows that its value decreases while increasing the level of feed and depth of cut. Cutting speed shows a parabolic trend.
- The best results (minimum value) of SCE consumption were identified at feed 0.3 mm/rev, depth of cut 3 mm and cutting speed 1250 m/min.
- The worst results of specific cutting energy (SCE) were examined when feed, cutting speed and depth of cut are their lowest level. Highest value of SCE was at 0.1 mm/rev of feed, 250 m/min of cutting speed and 1 mm of depth of cut.
- In ANOVA analysis it was observed that the influence of feed was most significant followed by depth of cut and cutting speed.

- Feed was found most influential factor (87.28%) for minimizing SCE consumption, followed by depth of cut (7.21%) and cutting speed (3.70%).

5.1.2 Surface Roughness measurement at GTDMC Machine Tool

- In Main effects plot it was observed that feed, depth of cut and cutting speed have directly link with surface roughness. Its value increases by increasing the level of feed, depth of cut and cutting speed.
- The worst results (maximum value) of Surface Roughness were examined when feed, cutting speed and depth of cut were at their maximum level which was 0.3 mm/rev of feed, 1500 m/min of cutting speed and 3 mm of depth of cut.
- The best results (minimum value) of Surface Roughness were obtained at lowest value of feed (0.1 mm/rev) depth of cut (1 mm) cutting speed (1000 m/min).
- In ANOVA analysis, feed was found most effective cutting parameters for minimizing the value of surface roughness and other parameters depth of cut and cutting speed played very little role in minimizing surface roughness. Contribution of feed was 98.47%, depth of cut 0.98% and cutting speed 0.30%.

5.2 Validation test at LESC Machine Tool

5.2.1 Specific Cutting Energy (SCE) consumption at LESC Machine Tool

- In main effects plot, specific cutting energy follows the same pattern as inspected in validation test at GTDMC. A downward trend of SCE was observed when increased the value of feed and depth of cut. Cutting speed shows a parabolic trend.
- The best results (minimum value) of SCE consumption were identified at feed 0.3 mm/rev, depth of cut 3 mm and cutting speed 1250 m/min.
- The worst results of specific cutting energy (SCE) were examined when feed, cutting speed and depth of cut are their lowest level. Highest value of SCE was at 0.1 mm/rev of feed, 250 m/min of cutting speed and 1 mm of depth of cut.
- In ANOVA analysis the influence of feed on SCE consumption was most significant followed by depth of cut and cutting speed.
- Feed was found most influential factor (81.67%) for minimizing SCE consumption, followed by depth of cut (17.09%) and cutting speed (0.65%)

5.2.2 Surface Roughness measurement at LESC Machine Tool

- In Main effects plot it was observed that feed, depth of cut and cutting speed have directly link with surface roughness same as in validation test at GTDMC. Its value increases by increasing the level of feed, depth of cut and cutting speed.
- The worst results (maximum value) of Surface Roughness were examined when feed, cutting speed and depth of cut were at their maximum level which was 0.3 mm/rev of feed, 1500 m/min of cutting speed and 3 mm of depth of cut.
- The best results (minimum value) of Surface Roughness were obtained at lowest value of feed (0.1 mm/rev) depth of cut (1 mm) cutting speed (1000 m/min).
- In ANOVA analysis, feed was found most effective cutting parameters for minimizing the value of surface roughness and other parameters depth of cut and cutting speed played very little role in minimizing surface roughness. Contribution of feed was 97.68%, depth of cut 1.15% and cutting speed 0.21%.

Cutting power increased as the material removal rate increased although in a non-linear way.

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