CHAPTER 1: INTRODUCTION

1.1 Introduction

1.1.1 With the industrial revolution and automation, the involvement of human resource in the manufacturing and production setups has significantly reduced with a rapid increase in the production capacities and rates. The automation processes made manufacturing relevantly easy which in return increased the number of manufacturers/ producers while considering the immense potential of the products in terms of utilization and consumers. An ever increasing number of manufacturers/ producers has significantly contributed towards the competitiveness of the industry. In order to make products more viable and cheap, a large amount of effort has gone into cost cutting of manufacturing/ production through optimization of various resources and processes.

1.1.2 Moreover, utilization of natural resources have immense contribution in the cost of manufacturing and conservation of same is also considered vital not only for sustained businesses development but also sustained economic growth of the nations. International acknowledgement has been given to the optimum utilization of natural resources which is essential for sustained energy production. Manufacturing and production while being the biggest consumer of natural resource, with almost 75% of industrial electric power of USA being utilized in machining technologies, machining is considered most deserving for power consumption optimization in both domestic and industrial usage [1]. Figure 1.1 below shows the consumption portion of various fields in the United States as per the United States Energy Book of 2012. It can be observed that with almost 31% industrial utilization of energy in US, Industrial sector is the biggest consumer of energy in US as per the records of 2012. It can further be noticed that with in the industrial sector, machining is the largest consumer of electricity with almost 75% of the energy utilization.

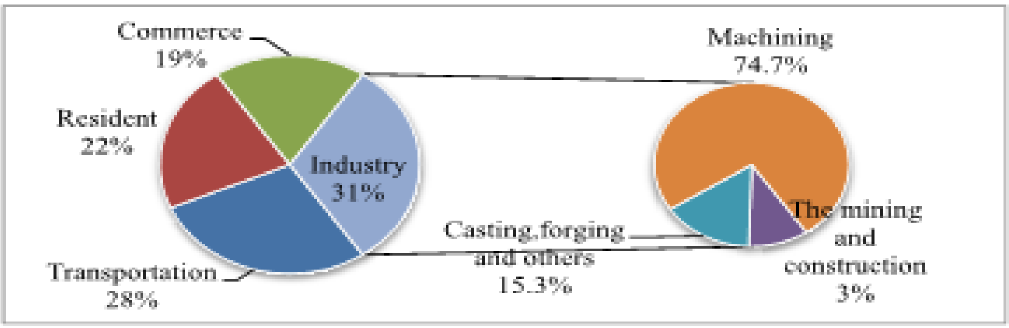


Figure.1.1: Electrical Energy Consumed by Machining Process [1]

1.1.3 With the increasing health awareness amongst the nations, industry has realized that significance of environmental friendly techniques for continuous productions. In consideration to the excessive consumption of natural resources and increase in disturbing environmental scenarios, industries have focused more on utilization of viable resources while keeping in to consideration the cost affects and social obligations. Cost of energy production has equally affected the manufacturers, thus, compelling them to comprehend the emerging requirement of economical energy consumption. In order to optimally address the problem of energy cost, manufacturers have focused on specific industries to reach the yearning objective.

1.1.4 Industrial sector takes its derive from various energy sources like natural gas, coal, oils, renewable energy sources, etc. and is the largest consumer of delivered energy (excluding transmission and other losses) worldwide. Based upon the energy consumptions, industrial sector can be divided into Energy Intensive Manufacturing, Non-Energy Intensive Manufacturing and Non-Manufacturing industries [2]. Figure 1.2 indicates the scope of industries covered in the industrial sectors based on energy consumptions.

Industry grouping	Representative industries
Energy Intensive Manufacturing	
Food	Food, beverage, and tobacco product manufacturing
Pulp and paper	Paper manufacturing, printing and related support activities
Basic chemicals	Inorganic chemicals, organic chemicals (e.g., ethylene propylene), resins, and agricultural chemicals; includes chemical feedstocks
Refining	Petroleum refineries and coal products manufacturing, including coal and natural gas used as feedstocks
Iron and steel	Iron and steel manufacturing, including coke ovens
Nonferrous metals	Primarily aluminum and other nonferrous metals, such as copper, zinc, and tin
Nonmetallic minerals	Primarily cement and other nonmetallic minerals, such as glass, lime, gypsum, and clay products
Non-Energy Intensive Manufacturing	
Other chemicals	Pharmaceuticals (medicinal and botanical), paint and coatings, adhesives, detergents, and other miscellaneous chemical products, including chemical feedstocks
Other industrials	All other industrial manufacturing, including metal-based durables (fabricated metal products, machinery, computer and electronic products, transportation equipment, and electrical equipment)
Non-Manufacturing	
Agriculture, forestry, fishing	Agriculture, forestry, and fishing
Mining	Coal mining, oil and natural gas extraction, and mining of metallic and nonmetallic minerals

Construction	Construction of buildings (residential and commercial), heavy and civil engineering construction, industrial construction, and specialty trade contractors

Figure.1.2: Energy Based Classification of Industry [2]

1.1.5 As per the U.S Energy Information Administration (International Energy Outlook 2016), eceomic activities of sectors and industries are disaggregated to estimate the industrial sector energy consumption through real inflation-adjusted gross output. Provisioning of data on all industry links that make up the economic activity, third party services for production and resources like energy and material are included in the gross output. The concept of gross output and their variation over time are utilized to predict and analyze the industrial sector energy consumptions.

1.1.6 The total gross output includes all economical activities; however, varies on the basis of region and over time. Figure 1.3 indicates the variation on the basis of total gross output in three different industrail sectors over time using predictive analysis. It can be observed that growth of the industrial sector as predicted for 2040 shows an ennormous increase as compared to 2012 with the maximum increase in non-energy intense manufacturing sector [2]. In a long-term shift in variation of the composition of gross output in the IEO2016 Reference case, a general long-term trend is observed towards a worldwide economy that is slightly less dependent on agricultural and mined natural resources (two of the three nonmanufacturing industries). In develooped economies, a shift from resource based or agriculture based outputs has long been observed and same is now anticipated for emerging economies of the world which results in more focus towards manufacturing industries for growth of the national output.

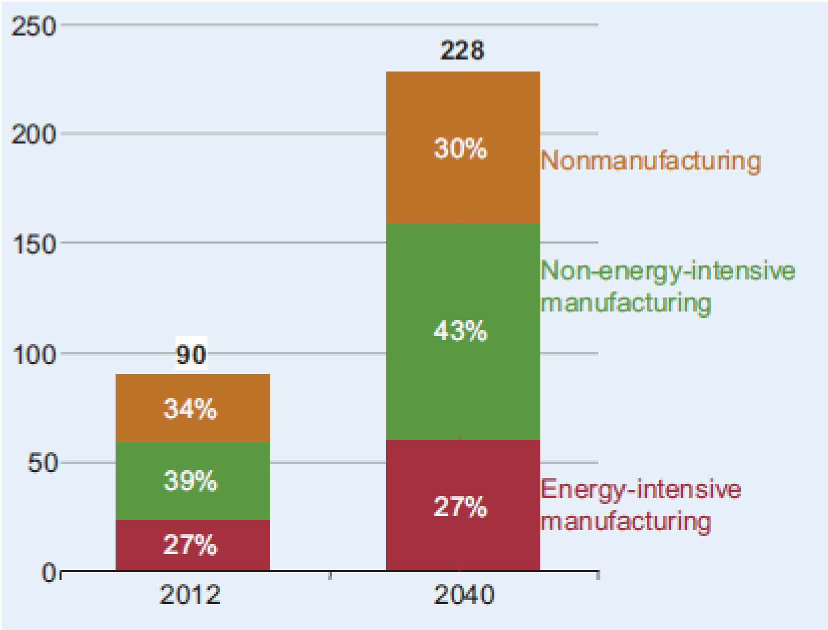


Figure.1.3: Global Gross Output by Industrial Sectors[2]

1.1.7 According to the International Energy Outlook 2016 (reference case), the energy consumption by the world industrial sector is likely to be increased by an average of 1.2%/ year, therefore from 222 quadrillion British thermal units (Btu) in 2012 to 309 quadrillion Btu in 2040 [2]. Figure 1.4 highlights the increase in industrial energy consumption with respect to urban population growth in China from 1990 till 2012. In can be observed that with the advent of 21st century, for a small growth of urban population, the industrial consumption of energy has greatly increased. Pakistan being part of this international industrial paradigm shift cannot disregard the importance of increased industrial energy utilization which calls not only for development of methodologies of cheap and increased energy production but also requires optimization of energy resources at consumer end. It is considered essential that advance techniques to reduce the energy consumption rate be established not only for product competitiveness in the international market but also for the national economic growth.

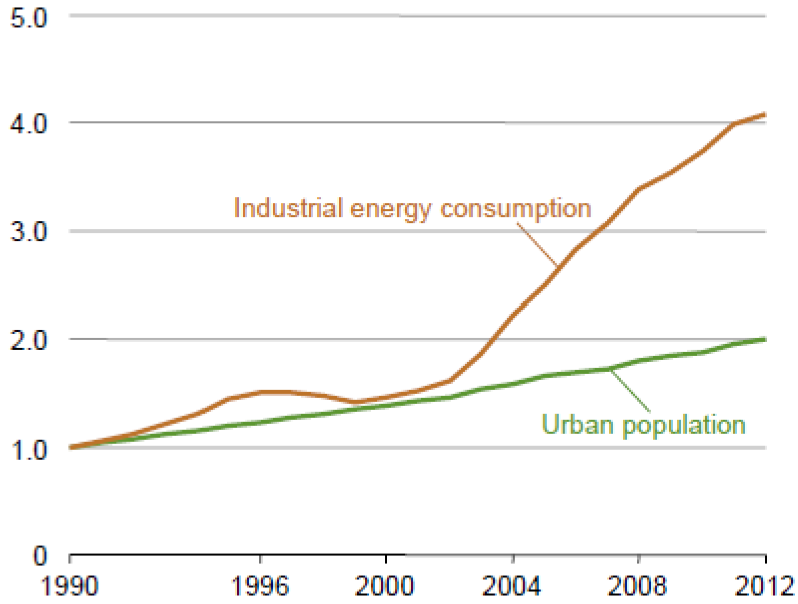


Figure.1.4: Industrial Energy Consumption and Population Growth in China from 1990-2012 (Index: 1990=1.0) [2]

1.1.8 **Thesis Aim.** Considering the milling as one of the most important and widely used machining process, the aim of this thesis is to analyse and optimize the energy consumption during milling machining process by validating the produced energy regions with variation in machining parameters.

CHAPTER 2: LITRATURE REVIEW

2.1 Introduction.

2.1.1 Being the most important part of the industry, a major part of the energy and resource are consumed by machining. In addition to being the major consumer of energy resource, it also is a big contributor of dangerous environmental emissions. All across the globe, manufacturing industries has been focused for reduction in environmental pollution and optimization of consumed energy resource because of the associated repercussions.

2.1.2 Manufacturing industries were forced to look into the energy efficiency of material processing techniques due to significant amount of delivered energy consumption out of the total energy supplied to the industries. Machine tool being the primary device in manufacturing industries was the area of most concern. A typical machining setup is shown in Figure 2.1 below.

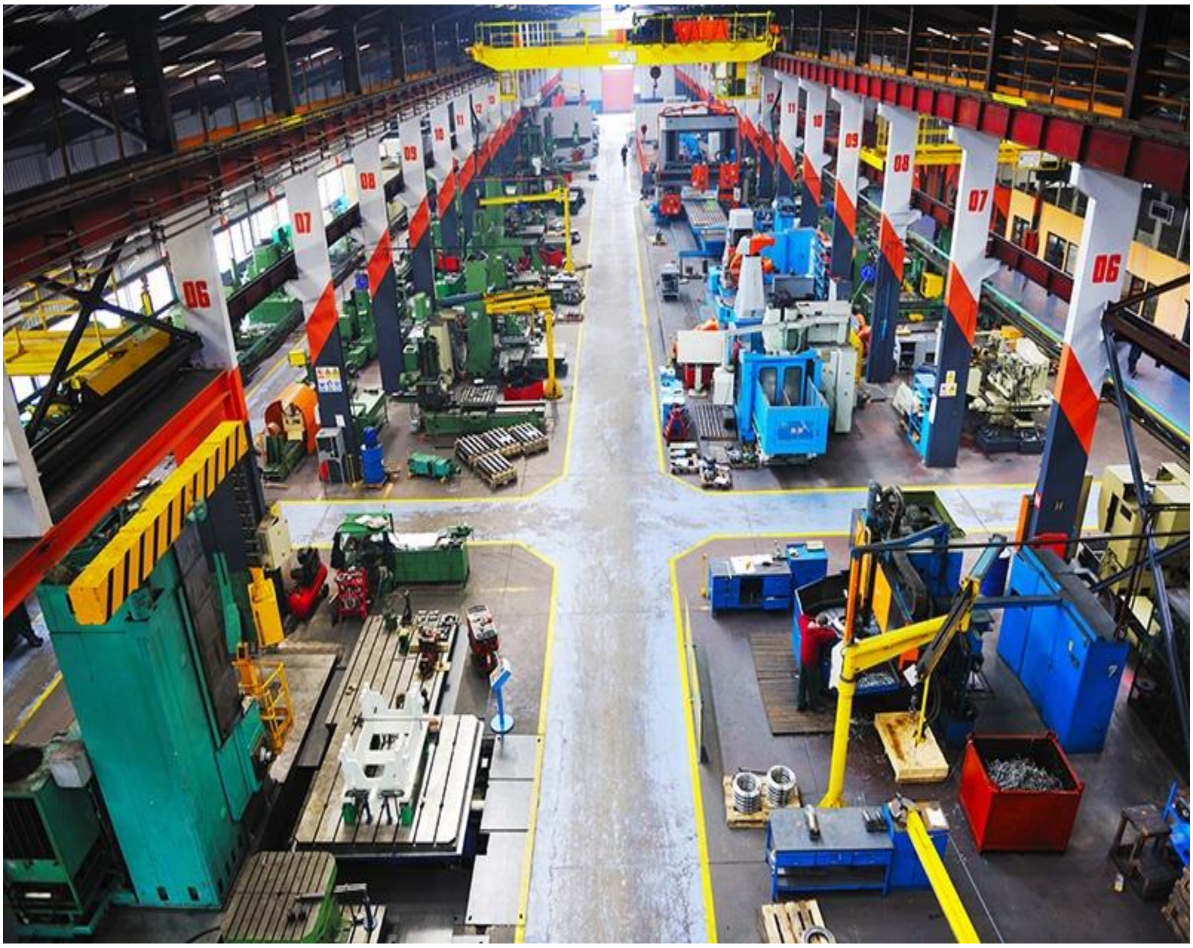


Figure.2.1: A General View of Machining Setup [13]

2.1.3 The emission produced by the machine tools while consuming electrical energy needs to be addressed [1] because the carbon dioxide (CO_2) emitted by machine, like CNC machine shown in figure 2.2, if operated for one year with 22 KW power, is equal to emission produced by 61 SUV cars [11].

Figure.2.2: CNC Milling Machine [15]

2.1.4 Due to this very fact, the researchers have increased their focus on reducing the impact of manufacturing on the environment through effective ways [6]. The ISO standard “Environmental Evaluation of Machine Tool” by International Organization of Standardization (ISO 14955-1:2017) gave guidelines for energy consumption test procedure of metal cutting and design methodology for energy efficient machine tools.

2.1.5 Natural resources are to be utilized with optimum care in order to lessen the impact of manufacturing in general and machining in specific on the environment. Utilization of renewable energy like solar and wind mill energies (Figure 2.3) can also help in optimization of utilized resources. In recent past, due to arising importance and awareness regarding importance of machining, environment and scarcity of natural resources, genetic algorithms have been generated for the assessment of machining on environment [6].

Figure.2.3: A Solar & Wind Power Generation Units [8]

2.2 Energy Consumption.

2.2.1 Recent studies have shown that the environment is greatly affected by the electrical energy production, a more than 90% of which is being consumed by manufacturers for machining processes [6]. While considering the fact, detailed studies are required to be performed to optimize the utilization of electrical energy in machining processes. Such studies will not only contribute towards the conservation of energy and green and clean environment but will also help manufacturers to reduce the production costs a great amount of which goes into the electricity bills.

2.2.2 In pursuit of the reduced environmental factors and production cost for machining processes, following two factors have been largely concentrated upon:

(a) Material availability and reuse capability

(b) Reduction in power consumption during a machining process

2.2.3 The materials which are available in sufficient quantity and can also be recycled include various alloys of Aluminum, Steel, Titanium, etc. Out of these, while considering the machining time, Aluminum is the most economical machined material. Moreover, it is provided with extra strength and corrosion resistance due to formation of extra protective layer on interaction with atmosphere [9]. Strength to weight ratio and cost competitiveness makes the aluminum alloys most widely used in machining processes for manufacturing of parts relating to a number of major industries.

2.2.4 Resultantly, the two most significant factors which have an impact on the environment are material used and energy consumed during machining. While owing to the limitation of the material properties with respect to the end use of the final product, the energy consumption during machining because of its viability, flexibility and extended scope needs to be looked into while considering the environmental efficacy. The control of energy consumption during machining can not only help with the environmental improvement but can also result in the reduced cost of the production and conservation of fast depleting global assets.

2.3 Energy Optimization.

2.3.1 Reduction in electrical energy consumption of machining processes has got great significance while considering the total delivered energy consumed by the manufacturing industry. The reduction can likely be achieved by either of the 02 methodologies:

(a) by design and development of energy-efficient machines

(b) by optimizing existing machining processes

2.3.2 While considering the time and effort involved; the option of optimizing the existing machining processes is considered viable to generate more effective, fast and promising results. The literature review revealed the following two approaches for optimization of existing machining processes [6]:

(a) Energy consumption of machine tool by modeling it

(b) Optimization of machine process parameters

2.3.3 The first approach is focused towards the development of mathematical models to explain the process of energy consumption for a machine tool whereas, utilizing the second approach, optimum machining parameters resulting in minimal consumption of energy can be established.

2.3.4 While considering the fact that modern machine tool is a complex combination of many interconnected electrical and mechanical parts which makes it pretty much laborious and unauthentic when it comes to power optimization, the approach of optimizing the machine process parameters experimentally is supported. In order to optimize the machining parameters, the modeling of energy consumption for a machine tool is depended upon following two states:-

(a) Basic State

(b) Cutting state

2.3.5 In the basic state, the tool is moved from its basic position to a ready mode for operation; however; power consumed in this state is non-productive. In the cutting state, the tool actually moves on the work piece while cutting the work piece. The energy consumed during the cutting state is the sum of energy in basic state and actual energy to remove the material from work piece.

2.4 Similar Researches.

2.4.1 Researchers have performed researches into various areas to establish techniques for optimization of energy consumption during machining. A step wise energy analysis of a machining operation has been performed to establish energy consumption reduction methods through machining process improvement. Coolant related equipment has been identified as the most power consuming equipment out of peripheral equipment the effect of which cannot be nullified in continuous machining operations; however, can be reduced by using more efficient and less number of coolant pumps.[3] Researchers have also established that energy consumption and emission during a machining can be reduced during the process planning of a part by sequencing the features of a part in a way to reduce the machine idle time during a machining process.[4] Both the above techniques for energy optimization effect the machining process and machine components; however, none of them addresses the optimization of energy consumption through variation in the machining parameters.

2.4.2 Further literature review revealed that work has been done for optimization of energy consumption through variation in the machining parameters; however, it was only done for turning operation on a lathe machine the results of which were based upon the specific cutting energy.[6] Although mathematical models like Artificial Neural Network (ANN) model, Support Vector Regression (SVR) model,[5] etc. are available for predicting the energy consumption with variation in machining parameters during milling machining operation; however, no experimental analysis in this regard is available.

2.4.3 For experimental analysis with variation in machining parameters, the understanding of energy consumption for a specific machining process is very essential to achieve energy efficiency. This can be accomplished by utilizing the desired machining process and examining the total power consumed by the machine tool with its component such as spindle, feed drives and other supplementary equipment's. The measured results then can be linked with specific machining process and its energy consumption during the process [7].

2.4.4 During the literature review for machining power optimization through experiments with variation in machining parameters, while none of the related researches was found for milling; however, a similar research was made by Warsi el al. for the process of CNC turning on a lathe machine [6]. The methodology as utilized by Warsi et al. for measurement of actual power was adopted on the similar lines which included the measurement of power for an air cut followed by the measurement of power for the real cut. The difference of the power consumed by the real cut and air cut gave the cutting power required. An experimental work for cutting power analysis with variation in milling mode and number of inserts was also reviewed [10]. The research revealed that an increased number of inserts will enhance the cutting efficiency and the most efficient cutting mode will be the symmetrical cutting mode. The research also revealed that the actual cutting power accounts for low proportion of the total power and a lot of energy is wasted with auxiliary devices and machine standby state during the machining process.

CHAPTER 3: DESIGN OF EXPERIMENT

3.1 Introduction

3.1.1 In order to establish the impact of variation in parameters on energy consumption in a milling operation, it was necessary that the parameters with apparently the maximum significance on power consumption in a milling process be identified. The parameters after identification were required to be distributed in levels as to establish the results of experiment over a wide parametrial range. The different levels will then be required to put in combinations as to get the desired, reliable and authentic results in the minimum number of experiments.

3.1.2 While considering the fact that milling operation is not a continuous but an instantaneous operation, it is understood that with the engagement and disengagement of the cutting edges, the power consumption of the machine is likely to vary during the milling operation. In order to cater for the same, a power analyser capable of recording more reading in a second was required so the variation of power consumption during the milling operation can be well recorded and analysed.

3.1.3 The selection of the machine, tool, material and machining environment was required to be made in order to replicate the real time industrial scenarios. The 3-axis CNC vertical milling machine while being considered the most commonly used industrial milling machine was to be identified with wide variation in operational parameters as to provide flexibility in finalizing the parameter levels for milling operations.

3.2 Resource Selection

3.2.1 While considering the highest utilization in an aviation manufacturing facility, a 3-axis CNC vertical milling machine of Hyundai make with model No. SPT-V1000 as shown at Figure 3.1 was selected. A consideration was also made to evaluate the machine for wide range of operational parameters during milling process. The critical features of the machine reviewed for this purpose were motor torque, table travel in all 3-axis, tool compatibility, maximum operating feed and speed, etc.. While selecting the machine, the parameters of the machine were also reviewed in order to make it able to perform the wide range of experiments with variation in parameters and machine was observed to satisfy the requirements.

Figure.3.1: Hyundai CNC 3-axis Vertical Milling Machine SPT-V1000

3.2.2 The material selection was also a point of concern as to analyse the experimental results as close to the real time experiments as possible. While considering the extensive utilization of Aluminium alloy 6061 in various industries including automobile and aviation industry, the material for the work piece was selected to be Aluminium alloy 6061-T6. The selection of temper condition was made as T6 for evaluation of machining on the alloy with further treatments so as in to relate it to the real time industrial practices while milling in a significantly variable machining regime. Although the material was finalized but selection of material dimensions required for experimentation was completely dependent on the machining parameters of the experiment. A sample run was later done to identify the minimum dimensions of the work piece required for the experiments in order to achieve sufficient results for analysis without material wastage.

3.2.3 The selection of the machining process and the machining environment were also an area of concern. Although the previous research has revealed that symmetrical milling is the most economical milling mode in terms of the power consumption[10]; however, down milling was selected while considering its less power consumption as compared to the up milling as the symmetrical milling was either way not possible due to variation in the width of cut. The previous research also revealed that auxiliary/ peripheral systems like cooling pumps, etc in a milling operation are the largest contributors of power consumption[3]. In light of the same, it was decided that the experiments will be performed with all auxiliary/ peripheral systems switched off so as to measure the precise impact of machining on power consumption.

3.2.4 The power analyser available for analysing the power consumption during a milling operation was Yokogawa clamp-on power analyzer CW 240-F as shown in Figure 3.2. The power analyser used three clamp-on for measuring of voltage and three crocodile plugs for measuring of current on the main bus bar of the machine. The fourth crocodile was a neutral; however, the combination of these clamp-on and crocodiles required the understanding of the power analyser. The power analyser was found to be taking a reading at every one-tenth of a second. A sample run of a milling operation was done in order to ascertain the efficacy of the result with the mentioned capability of the power analyser.

Figure.3.2: Yokogawa Clamp-on Power Analyzer CW 240-F

3.2.5 Selection of the tool was made on the basis of the requirement to have a variation in width of cut. A face shell milling cutter 90 degrees with 8 flutes and diameter of 125 mm as shown in Figure 3.3 was selected in order to maintain a reasonable variation in the width of cut for identification of suitable levels. The variation in width of cut using the same tool can only be achieved while performing the operation of shoulder milling. The face shell milling cutter was mounted with eight uncoated carbide inserts (APGT 160408 PDER-ALU-LT05) manufactured by Lamina Technologies as shown in Figure 3.4 which were identified on the basis of material used, machining process and operational parameter range. The preferable operational parameter ranges for selected insert as stated by the Manufacturer (Lamina Technologies) are indicated in Figure 3.6. The face shell milling cutter was capable of mounting eight inserts and all eight inserts were installed in light of the fact that power consumption for a milling operation is most efficient with the increase in number of inserts. [10]

Figure.3.3: Face Shell Milling Cutter

Figure.3.4: Face Shell Milling Cutter Mounted with Uncoated Carbide Inserts

APGT 160408 PDER-ALU - LT 05

	Material Group	Gr.N°	VDI Group	Material Examples	Hardness	D.O.C [mm]		Feed [mm/rev]		V_c [m/min]		Suggested Starting Parameters		
						min	max	min	max	min	max	D.O.C	Feed	V_c
N F	Al (<8%Si)	13	21,22	Si < 4%	60 HB	0.5	15.0	0.15	0.32	400	1200	4.0	0.16	500
			23,24	4% < Si < 8%	100 HB	0.5	15.0	0.13	0.29	250	600	4.0	0.16	400
	Copper Alloys	14	26,27,28	CuZn30	100 HB	0.5	15.0	0.13	0.29	100	800	4.0	0.16	300
	Non-Metallic	15	29	Fiber Plastics	-	0.5	15.0	0.15	0.32	80	500	4.0	0.14	200
			30	Hard Rubber	-	0.5	15.0	0.15	0.32	80	300	4.0	0.14	150
			-	Graphite	-	0.5	15.0	0.15	0.32	100	200	4.0	0.14	150
H.T.A	Ti Based Alloys	10	36	Ti 1	-	0.5	15.0	0.10	0.32	35	60	4.0	0.14	45
			37	TiAl 6 V4	-	0.5	15.0	0.10	0.24	28	45	4.0	0.14	35

Figure.3.5: Operational Parameters (APGT 160408 PDER-ALU-LT05)

3.3 Parameter Selection

3.3.1 The parameters have a critical machining role as they not only impact the efficiency of the machining operation but also affect the finishing, preciseness, accuracy, machining time and other mechanical and physical properties of the final produce. The parameters have various impacts on various indicators the most of which have already been studied, analysed and discussed in various researches made on the subject in the past; however, the impact of these parameters on energy consumption has not been much reviewed which is being done in this research as already stated in the literature review..

3.3.2 The most significant parameters likely of having an apparent impact on energy consumption of a machining process in milling operations were required to be identified while considering their possibility of variation in relation to the output. While considering the likely significant impact on energy consumption, the parameters like feed, speed, depth of cut, number of inserts, width of cut and mode of milling were identified. A consideration for review of these parameters in light of their impact onz product with variation in these parameters was also made.

3.3.3 The factors like number of inserts and machining mode had already been analysed in previous researches[10]; however, the remaining four parameters were not reviewed for their impact on power consumption during milling operation. While considering the four parameters i.e. feed, speed, depth of cut and width of cut, it was considered appropriate to observe the impact of each parameter at three different levels closest to the actual milling operations in the industrial practices. In order to perform the experiments for four identified parameters at three different levels, a total number of 81 experiments were involved which was extremely expensive while considering the tool and material consumed along with the time period for machine engagement in an active production facility.

3.3.4 In order to reduce the number of experiments, Taguchi L9 Orthogonal Array was used and design of experiment was reduced to nine experiments. The three levels for each of the four parameters were established as shown in Table 3.1. The section of the levels was primarily made while considering the most common industrial practices and resource limitations like machine capacity, tool limitation, etc. The design of experiment finalized with Taguchi L9 orthogonal array for nine experiments is shown in Table 3.2.

Parameters / Levels	Speed (m/min)	Feed (mm/rev)	Depth of Cut (mm)	Width of Cut (mm)
Level 1	250	0.1	1	80
Level 2	500	0.2	2	100
Level 3	750	0.3	4	120

Table 3.1: Milling Parameters Identified for Experimentation

S No	Speed (m/min)	Feed (mm/rev)	Depth of Cut (mm)	Width of Cut (mm)
1	250	0.1	1	80
2	250	0.2	2	100
3	250	0.3	4	120
4	500	0.1	2	120
5	500	0.2	4	80
6	500	0.3	1	100
7	750	0.1	4	100
8	750	0.2	1	120
9	750	0.3	2	80

Table 3.2: Taguchi L9 Orthogonal Array DOE

3.4 Experimental Design

3.4.1 The nine experiments were undertaken on the 3-axis CNC machine as stated above. The experiments were designed on two-cycle approach in which the experiments were divided into two stages and each of the stage was repeated twice for verification of the results. The methodology was already deployed by Li and Kara[12] and Warsi et al[6] in their similar experiments of power analysis for turning operation. The first stage was running of the machine in the desired profile without any work piece. This was to provide the details of power consumption during the air cut. The same cutting profile was repeated with work piece, thus, giving the power consumption for an actual cut. The difference of both the cutting powers as shown in Equation 3.1 was calculated to establish the actual power required for the cutting of material during milling operation after eliminating the power required for tool positioning, energy in tool consumption and other factors not contributing towards the actual cutting operation.

$$P_{cut} = P_{actual} - P_{air}$$ [6] Equation 3.1

3.4.2 In order to normalize the results of all experiments being performed and make them comparable, the specific cutting energy was utilized for comparative analysis. The specific cutting energy is the energy required for removing the unit volume of the work piece. The Material removal rate was ascertained while using the Equation 3.2 where w is the width of cut, d is the depth of cut and f_r is the feed rate which can be calculated while using the Equation 3.3. In Equation 3.3, the f is feed, N is Revolutions per minute and N is number of inserts. The Revolutions per minute (N) for Equation 3.3 was obtained by using the Equation 3.4 where v is the speed in m/min and d is the tool diameter.

$$MRR = w.d.f_r$$ [14] Equation 3.2

$$f_r = f.N.n$$ [14] Equation 3.3

$$N = v/(\pi.d)$$ [14] Equation 3.4

3.4.3 The material removal rate indicating the volume of material removed in terms of time was calculated for each experiment while using the Equation 3.2; however, the material removal rate of each experiment was also different from each other indicating that recorded power consumption of each of the experiment will be responsible for different volume of material removed. In order to make the results normalized and comparable, the cutting energy obtained for each of the experiment was divided by the material removal rate, thus, giving the specific cutting energy as shown in Equation 3.5. The specific cutting energy is the energy required for unit volume removal of material and the experimental results for various power consumption experiments could now be comparatively analyzed.

$$SCE = P_{cut}/ MRR$$ [14] Equation 3.5

3.4.4 The power consumption for each experimental scenario was to be recorded twice for both the air and the dry cut with repetition of each experiment to establish the authenticity and correctness of the results. To study the response of a milling operation on a power consumption, a sample run was made in order to review the impact of result on the design of experiment. The sample run revealed that a tooth type response was received for a milling cut and response of the power analyzer with respect to time was ascertained in order to establish the minimum length of the cut. The graph response for power consumption over time was observed to be tooth type curve with an initial repeated curve followed by an increased tooth response at the time of tool engagement. At the time of work piece disengagement, the power curve faced an abrupt drop which is further dropped at the machine halt. The graph depicting the response on the power analyzer is shown at Figure 3.6.

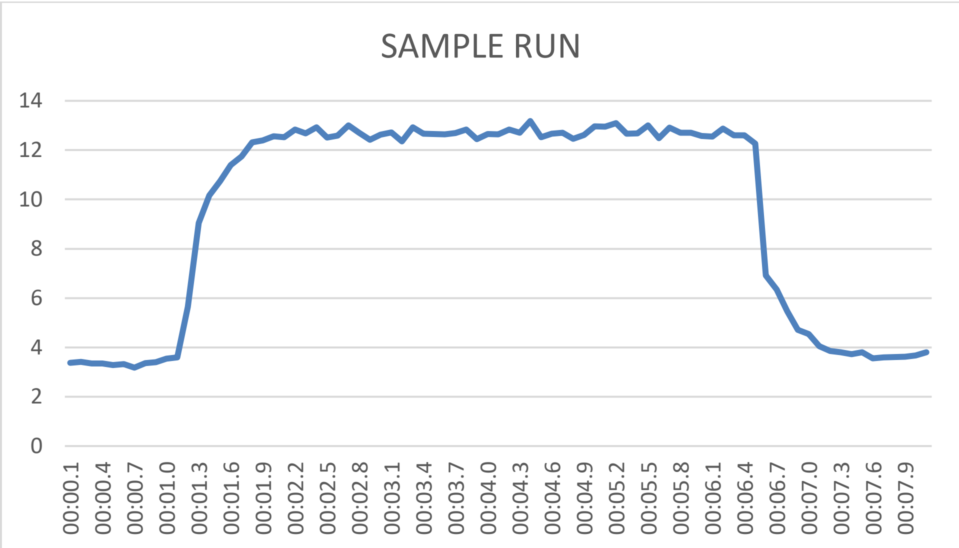


Figure.3.6: Graph Response of Power versus Time for Milling Operation

3.4.5 The tooth type curve for power consumption was averaged in a stable region by dividing the summation of all the available readings with the total number of readings in a stable region indicating the average power utilized for each operation. The measure of power in a stabilized region was only considered to exclude the impact of acceleration, deceleration and rapid movement of the tool. A similar methodology was also observed to be used in earlier research made on energy consumption in milling operation [10]. The value of cutting power achieved through the power analyzer for each experiment was utilized after being averaged which was to provide with two values for power consumed in each air cut and actual cut against each experiment thus providing two values of cutting power for each of the experiment. The calculated cutting powers were to be used for calculation of two values of specific cutting energy for each experiment while using the equation 3.5. In totality, two responses in terms of specific cutting energies were to be established for all experiments with four input variables i.e. speed, feed, depth of cut and width of cut. The detailed design of experiment is shown in Table 3.3.

S No	No. of Inserts	Speed (m/min)	Feed (mm/rev)	Depth of Cut (mm)	Width of Cut (mm)	RPM	Feed Rate (mm/min)	MRR (cm^3/ sec)
1	8	250	0.1	1	80	636.36	509.09	0.68
2	8	250	0.2	2	100	636.36	1018.18	3.39
3	8	250	0.3	4	120	636.36	1527.27	12.22
4	8	500	0.1	2	120	1272.73	1018.18	4.07
5	8	500	0.2	4	80	1272.73	2036.36	10.86
6	8	500	0.3	1	100	1272.73	3054.55	5.09
7	8	750	0.1	4	100	1909.09	1527.27	10.18
8	8	750	0.2	1	120	1909.09	3054.55	6.11
9	8	750	0.3	2	80	1909.09	4581.82	12.22

Table 3.3: Final Design of Experiment

3.4.6 The experimental values after putting into calculations will be analyzed through ANOVA technique on Minitab application in order to ascertain the factor with most significant and least significant impact on power consumption during a milling operation. The percentage contribution of each variable input on power consumption will also be identified so the effort can be taken into industrial use to draw balance between the inputs and desired results for reduction in the production cost and conservation of the global energy and environment. A regression equation was also to be presented for predicting of specific cutting energy for other machining scenarios with variation in speed, feed, depth of cut and width of cut.

CHAPTER 4: EXPERIMENTAL PROCEDURE

4.1 Introduction

4.1.1 In order to establish the cutting energy required for unit volume of material removal, the power consumption for air cut and actual cut was required to be established. The experiments were to be conducted as per the design of experiment as already stated but a significant effort was required to setup the equipment. The power analyzer was to be well understood along with the machine circuitry for correct installation and configuration of both to achieve the authentic and correct results. A methodology for data retrieval from the machine with correct tagging was also required to have the results in a sorted, defined and workable format.

4.1.2 The workpiece block having the size of 400 mm x 220 mm x 90 mm as established by the results of sample experimental run was ordered in aluminium alloy 6061 at temper condition T6. The block was procured from a reliable facility along with the qualitative spectrometric analysis as shown in Table 4.1 and mechanical properties as indicated in Table 4.2.

Element	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**	**Others**	**Al**
Wt %	0.44-0.56	0.38 (max)	0.16-0.30	0.11 (max)	0.84-1.00	0.13-0.26	0.01 (max)	0.01	<0.15	Bal.

Table 4.1: Chemical Composition of Aluminum Alloy 6061-T6

Tensile Strength (MPa)	**Yield Strength (MPa)**	**% Elongation GL-50 mm**	**Hardness (HV)**
320-330	290-300	7.4-8.8	105-110

Table 4.2: Mechanical Properties of Aluminum Alloy 6061-T6

4.1.3 The tool was checked for the engagement and effectiveness of inserts after engagement. The total weight of the tool with inserts was reviewed in light of the machine capacity and tool engagement in the machine. The machining parameters as selected above were tested through an experiment at the extreme machining conditions on the desired machine for smooth operation of machine and conduct of complete experiments. The availability of relevant power sources near the machine was also ensured for smooth setup of experiment.

4.2 Experimental Setup and Actual Experiments

4.2.1 The power analyzer was reviewed for its connecting points. It was observed that power analyzer had an adopter port, three clamp-on terminals and four crocodile terminals as shown in Figure 4.1. The study of the Yokogawa Clamp-on Power Analyzer CW 240-F manual revealed that the adopter port was to be connected with the 220 V power source whereas the three clamp-on terminals were to be installed on the 3-phase main bus bar of the machine for voltage measurement. The three out of four crocodile terminals were to be connected on the main bus bar end points for measurement of the current; however, the configuration of the clamp-on and crocodile terminals was to be maintained as such to keep the readings measurable which could be confirmed through a wiring self-check which was an inherent function of the machine.

Figure 4.1: Connecting Points of Power Analyzer CW 240-F

4.2.2 A thorough study of the manual was made and a combination of both the clamp-on and crocodile terminals was identified for passing the wiring check of the circuitry. The setting of the power analyzer was shifted to 3P3W3I and three clamp-on wires and three crocodile wires were connected to the main bus bar of the machine as shown in Figure 4.2. The arrangement of wires was followed by a wiring self-check on the power analyzer and wirings were arranged such that the wiring self-test of the power analyzer yielded satisfactory results after being put on in idle as shown in Figure 4.3.

Figure 4.2: Arrangement of Power Analyzer Terminals on Main Bus Bar

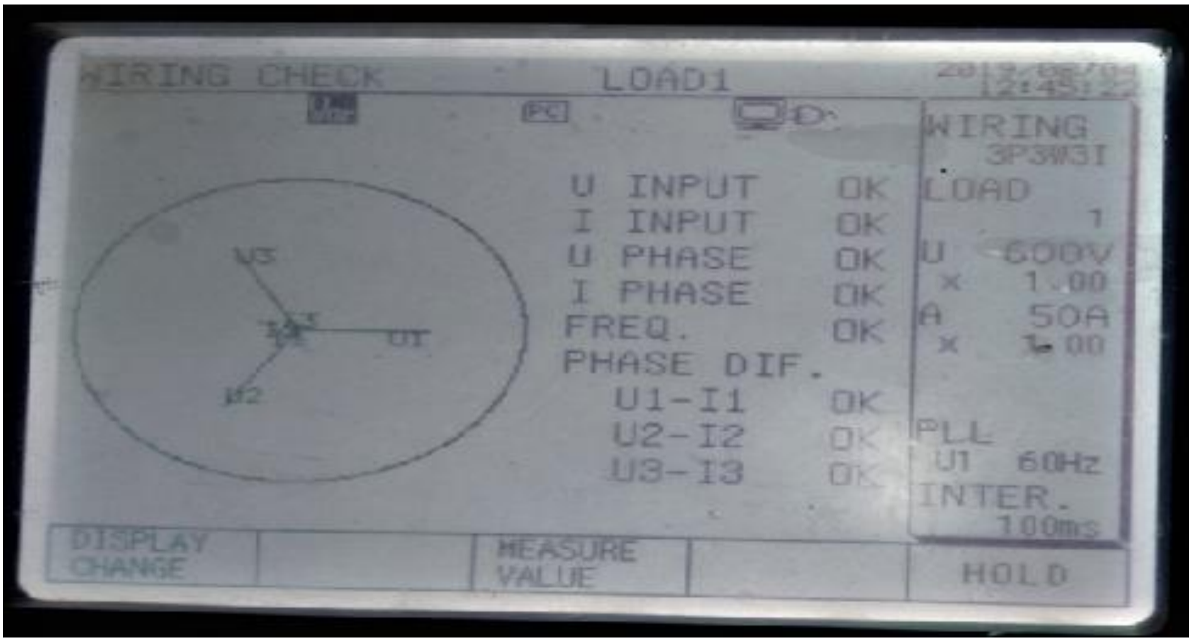


Figure 4.3: Wiring Self-test on Power Analyzer

4.2.3 After achieving the satisfactory results of wiring check self-test on the power analyzer, the CNC machine was mounted with the work piece. The work piece was mounted and secured with the machine table followed by tool adjustment to zero position. The program was run for travel of tool over the work piece without engaging the work piece with parameters as mentioned in the design of experiment at Table 3.3, thus, resulting in an air cut clear over the surface of the work piece as shown in Figure 4.4. The power analyzer record switch was pressed with the start of the machine run for recording the power consumption readings. The recording process was stopped at the completion of the run and file was saved with a specific name for identification at retrieval and analysis stage.

Figure 4.4: Air Cut during the Experiment

4.2.4 After completion of the run, machine tool was sent back to the starting position and another run was made for air cut with recording of the power consumption values. The second experimental run was also given a separate name for identification at analysis stage. After the two runs of air cut for one set of parameters, two runs of actual cut with tool and work piece engagement as shown in the figure 4.5 were made.at the similar machining parameters and power for both the runs was recorded with different and unique names for identification at later stage. Same four set of experiments consisting of two air cuts and two actual cuts experiments were done for all set of parameters as per the design of experiment. A total of thirty-six files for thirty-six runs were stored on the power analyzer as per the details shown in Table 4.3.

Figure 4.5: Actual Cut during the Experiment

S No	Speed (m/min)	Feed (mm/rev)	Depth of Cut (mm)	Width of Cut (mm)	Air Cut 1st Run	Air Cut 2nd Run	Actual Cut 1st Run	Actual Cut 2nd Run
1	250	0.1	1	80	25	26	27	28
2	250	0.2	2	100	13	14	15	16
3	250	0.3	4	120	1	2	3	4
4	500	0.1	2	120	5	6	7	8
5	500	0.2	4	80	29	30	31	32
6	500	0.3	1	100	17	18	19	20
7	750	0.1	4	100	21	22	23	24
8	750	0.2	1	120	9	10	11	12
9	750	0.3	2	80	33	34	35	36

Table 4.3: File Identification Numbers for Each Experimental Run

4.2.4 The data stored in the machine for above stated experiments was copied through an industrial card reader into a computer. The data was in thirty six files with separate file for each experiment. All the files were in .BIN format and were accessed using a software AP140/240E as shown in Figure 4.6. The data was registered and read using the software as shown in Figure 4.7; however, all the files were converted to .CSV format using the same software for ease of processing and analysis.

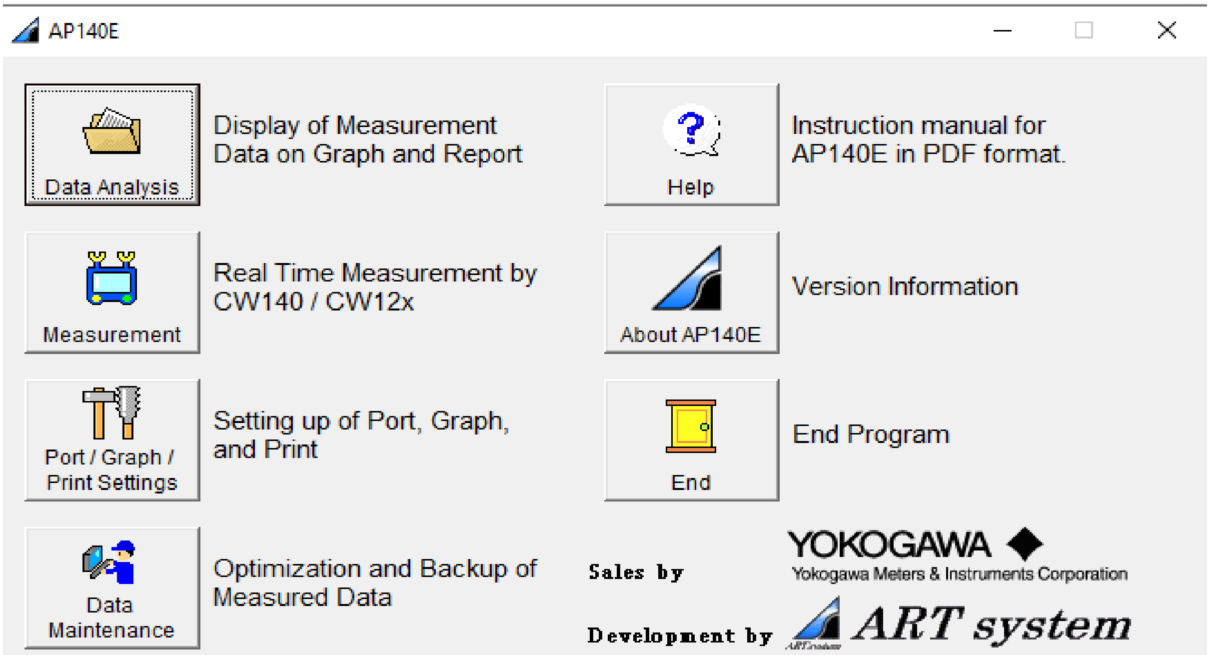


Figure 4.6: Software for Data Retrieval and Review

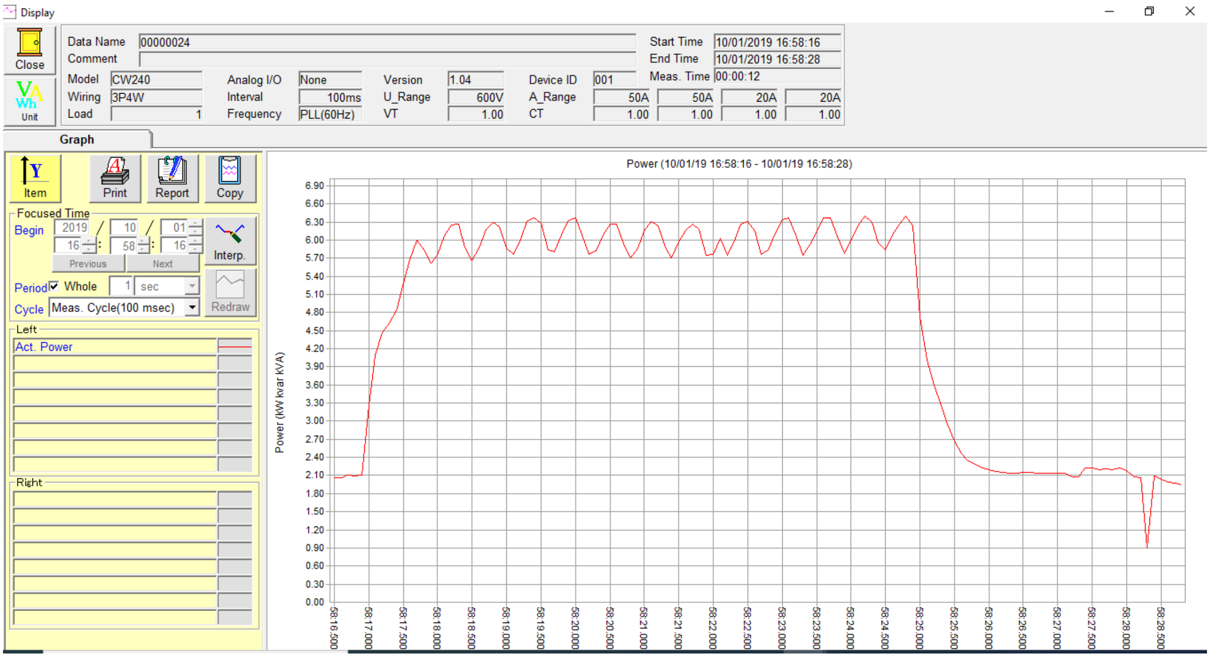


Figure 4.7: Data Review using the AP140/240E

4.2.5 In order to establish the machine tool independence of the experiment, a similar experiment was also performed on a different machine placed in SMME, NUST with different capacities and limitations; however, the results could not be achieved as the machine capacity to operate at the parameters as identified by the extreme conditions in the design of experiment was a problem. The run for extreme conditions was made thrice; however, every time, the machine got stuck with an error code at the start of the operations soon after the work piece tool engagement, therefore, the relationship for machine tool independence could not be established during the experiment.

CHAPTER 5: DATA COMPILATION AND PROCESSING

5.1 Introduction

5.1.1 The results collected for all the experiments required a very careful evaluation to get the meaningful information required for the analysis. The power consumption trend for each of the experiment was a tooth type graph which was required to be normalized while using a reasonable logic to make the assessment logical, meaningful and relevant. Moreover, because of the variation in speed and feed, the duration for all the experimental runs is not identical; therefor, same was also required to be standardized.

5.1.2 With the power analyzer capability to record a reading of power while measuring the voltage and current every tenth of a second left with a great number of values that was to be generalized prior to utilization. The results were then to be analyzed in a logical and meaningful manner in order to derive the most relevant and reasonable outcomes of the available information with relation and impact of the same in future operations.

5.2 Data Compilation

5.2.1 All the results received for thirty-six experimental runs were retrieved and reviewed. Out of the thirty-six data sets available, eighteen were for air cuts made at nine experimental scenarios as per the design of experiment with two runs for each scenario where as the remaining eighteen were for the actual cuts made at the similar machining scenarios. The data analysis revealed that a significant difference was observed in the readings of an air cut and its comparative actual cut; however, the variation between the two varied between the nine parametric scenarios as defined in the design of the experiment.

5.2.2 While reviewing the results for the air run, it was identified that an initial increased power consumption was observed at the start of the operation which later settles down and variates in a tooth type graph as shown in Figure 5.1. The variation between the minimum and maximum is limited thus indicating little variance in power consumption. The curve continues to variate in a tooth like pattern and eventually drops immensely at machine tool halting. It later stabilizes without any tool movement at a value of power consumed for working of a machine without moving of the tool.

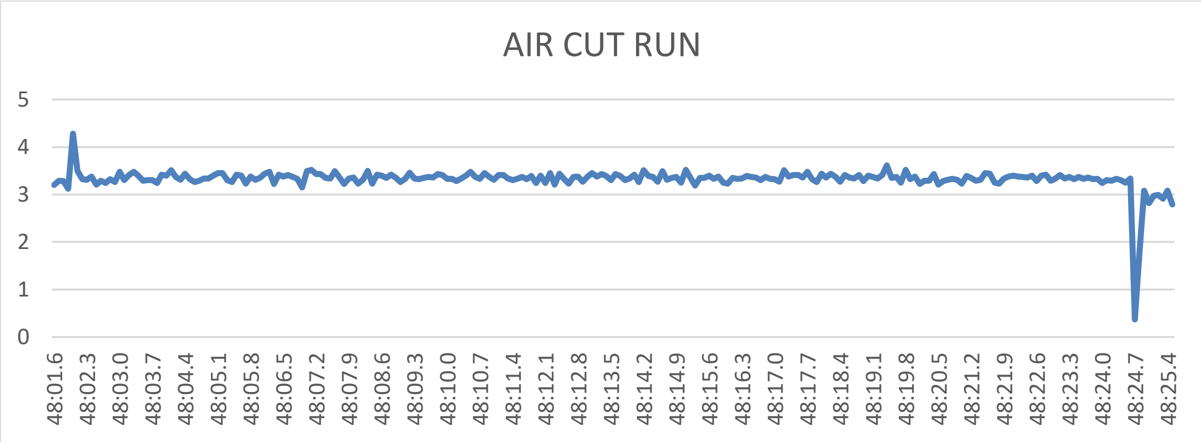


Figure 5.1: Graph for Air Cut Run

5.2.3 As it can be seen in the graph at Figure 5.1 that during an air cut, the initial part of the graph is at nominal indicating that the machine is in ON state; however, the operation has yet not begun. An instantaneous upward spike at the initial part of the graph is an indication of the beginning of operations, that is the start of the tool movement, thus, consuming a greater amount of start-up power. The power is then stabilized over a longer duration of time that is for the operation. Tooth type graph is formed due to slight variations which are to be ignored. The magnitude for these tooth type variations is less for air cut but same in likely to enhance prominently for actual cut while considering the engagement and disengagement of inserts with the work piece as the tool rotates and moves ahead. In the end, it can be observed that as the tool rotation comes to a halt, an instantaneous downward spike is observed and then the curve is stabilized at a value as it was before the start of the tool rotation.

5.2.4 While reviewing the results for the actual run, it was identified that an initial increased power consumption was observed at the start of the operation which later settles down and variates in a tooth type graph as shown in Figure 5.2. The variation between the minimum and maximum is high as compared to the air cut run thus indicating great variance in power consumption. The increased variance is due to the engagement and disengagement of the inserts along with the rotary and linear motion of the tool into the work piece. The curve continues to variate in a tooth like pattern and eventually drops abruptly at the machine tool halting.

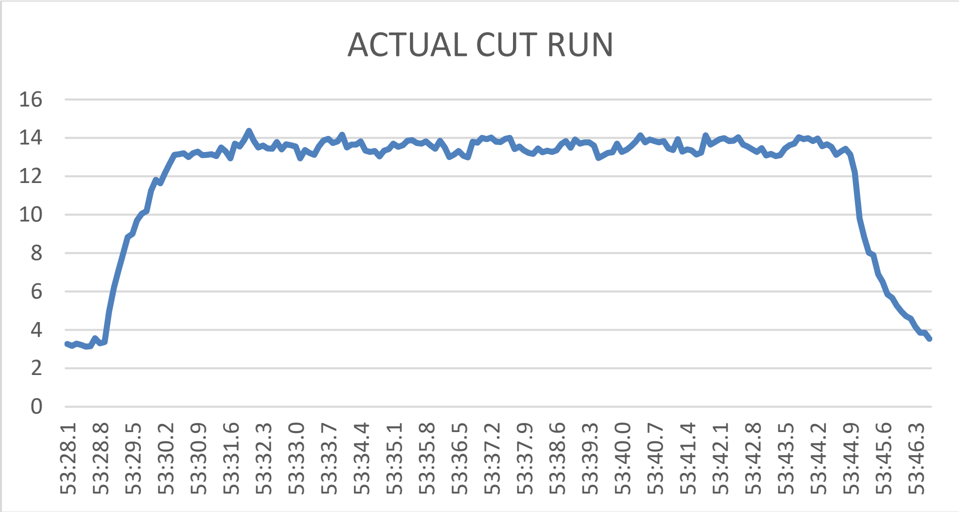


Figure 5.2: Graph for Actual Cut Run

5.2.5 As it can be seen in the graph at Figure 5.2 that during an actual cut, the initial part of the graph is at nominal power indicating that the machine is in ON state; however, the operation has yet not begun. An instantaneous upward spike at the initial part of the graph is an indication of the beginning of operations, that is the start of the tool movement, thus, consuming a greater amount of start-up power. The power is then stabilized at a value more than the air cut over a longer duration of time that is for the operation. Tooth type graph is formed due to high grade variations which are due to the engagement and disengagement of inserts as the tool move horizontally and in rotation. The trend of the stable region is repetitive over a period of time which indicates that the curve is repeated for every time a rotation cycle of a tool is completed. The significant enhancement in the variation between the tooth extremes as compared to the air cut is attributed to the change in number of inserts at an instant. In the end, it can be observed that as the tool rotation comes to a halt, an instantaneous downward spike is observed.

5.2.6 If we draw a comparison between the two graphs at Figure 5.1 for air cut and Figure 5.2 for actual cut, it can be observed that a significant increase in the stable region of operations can be observed in actual cut as compared to the air cut, thus, indicating the excessive consumption of power during the cutting operation due to tool interaction with the work piece. It is also noticed that the variation in the maximum and minimum of the power consumption in the stable tooth type graphical region has been increased in the actual cut as compared to the air cut. The variation in the air cut is very limited and primarily because of the reading error and machine limitation; however, the same is further enhanced and clearly visible in actual cut because of the addition of the insert interaction. The number of inserts engaged at a particular time in a machining operation is changing continuously and repeatedly which results in the increased variation in case of actual cut as compared to the air cut. The overlap of both the graphs shown at Figure 5.1 and Figure 5.2 is shown at Figure 5.3 which indicates the Power for cut as a result of differential of both the actual cut and the air cut.

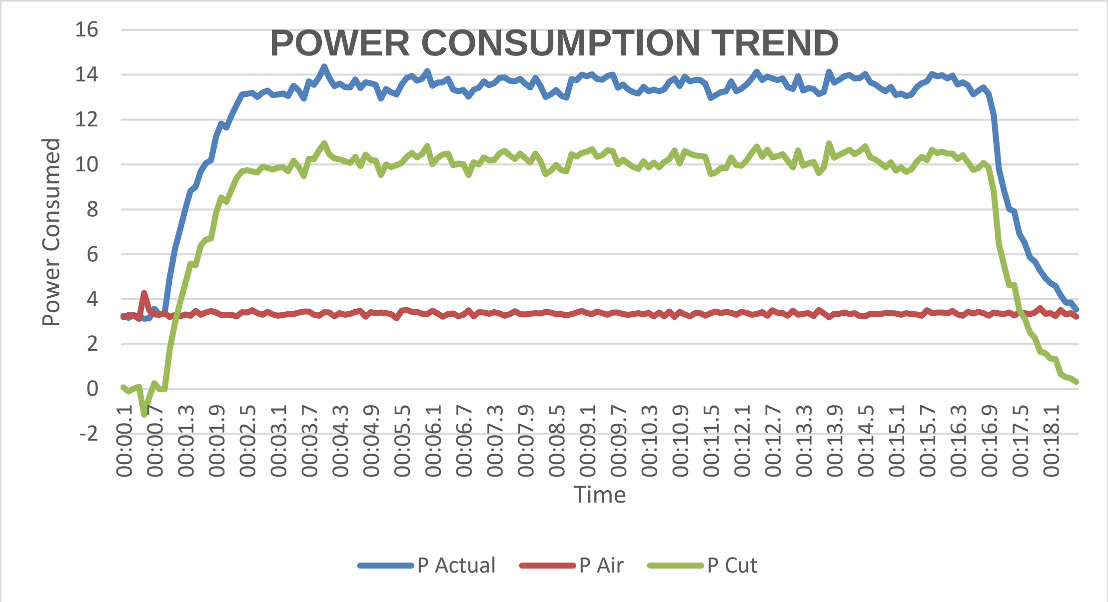


Figure 5.3: Overlapping Graph for Power Consumption Trends

5.2.7 As it can be seen in the figure that the power for actual cut is maximum where as that of the air cut is minimum. The differential of both these powers has provided the cutting power which is the exact power required for removal of the material at certain operational parameters. The tooth type stable graph region was taken in to consideration for establishing the value for data analysis as it was the actual value indicating the power consumption. The mean for all the data values in a tooth type stable region were considered for establishing a single value. It was done while considering a similar practice in a previous research made for power analysis in milling operations[10]. A singular value for all thirty six experiments for power consumption was obtained while using the average of all the values in a tooth type stable region for each of the thirty six experiments. The obtained values were then put into a tabular form as shown in Table 5.1 for further processing and analysis.

S No	Speed (m/min)	Feed (mm/rev)	Depth of Cut (mm)	Width of Cut (mm)	Power (1st Run)		Power (2nd Run)	
					Air Cut	Actual Cut	Air Cut	Actual Cut
1	250	0.1	1	80	3.25	4.03	3.27	4.05
2	250	0.2	2	100	3.29	6.33	3.29	6.39
3	250	0.3	4	120	3.35	13.56	3.36	13.56
4	500	0.1	2	120	3.82	7.79	3.85	7.85
5	500	0.2	4	80	3.81	12.29	3.82	12.38
6	500	0.3	1	100	3.83	7.89	4.24	7.94
7	750	0.1	4	100	3.45	12.02	3.46	12.14
8	750	0.2	1	120	3.93	8.88	3.50	8.92
9	750	0.3	2	80	3.95	12.71	3.56	13.19

Table 5.1: Power Consumption during Experimentation

5.3 Data Processing

5.3.1 The results were obtained in form of power consumption for each of the two air cut and two actual cut experiments at all of the nine parametric conditions as per Taguchi L9 Orthogonal Design of Experiment. The achieved results were then utilized for obtaining the cutting power required for each of the nine parametric scenarios for both the first and second run thus leaving us with eighteen active result values to work upon. The data for cutting power of first and second run of all nine parametric conditions is shown at Table 5.2.

S No	Speed (m/min)	Feed (mm/rev)	Depth of Cut (mm)	Width of Cut (mm)	P_C (1st Run)	P_C (2nd Run)
1	250	0.1	1	80	0.78	0.77
2	250	0.2	2	100	3.04	3.10
3	250	0.3	4	120	10.21	10.20
4	500	0.1	2	120	3.97	4.00
5	500	0.2	4	80	8.48	8.56
6	500	0.3	1	100	4.06	3.70
7	750	0.1	4	100	8.57	8.68
8	750	0.2	1	120	4.95	5.42
9	750	0.3	2	80	8.76	9.63

Table 5.2: Power Consumption for Cutting Operations

5.3.2 The data for cutting power was further processed to make it comparable between all the nine experiments. While considering the fact that material removal for each of the experiment was different due to variation in speed, feed, depth of cut and width of cut, therefore, all the values were tailored for unit material removal rate. It was achieved by measuring the Material removal rate for each of the experiment in accordance with the equation 3.2 and then dividing each of the cutting power with the material removal rate to obtain the specific cutting energy. The specific cutting energy is the energy required to remove a unit volume of material for each of the experiment which makes the results competitive and comparable for analysis. The details of Material Removal Rate and Specific Cutting energy for each of the experiments is shown in Table 5.3.

S No	Speed (m/min)	Feed (mm/rev)	Depth of Cut (mm)	Width of Cut (mm)	MRR (cm^3/sec)	SCE (1st Run)	SCE (2nd Run)
1	250	0.1	1	80	0.68	1.15	1.14
2	250	0.2	2	100	3.39	0.89	0.91
3	250	0.3	4	120	12.22	0.84	0.83
4	500	0.1	2	120	4.07	0.97	0.98
5	500	0.2	4	80	10.86	0.78	0.79
6	500	0.3	1	100	5.09	0.80	0.73
7	750	0.1	4	100	10.18	0.84	0.85
8	750	0.2	1	120	6.11	0.81	0.89
9	750	0.3	2	80	12.22	0.72	0.79

Table 5.3: MRR and SCE for all the Experiments

5.3.3 It can be observed from the Table 5.3 that the specific cutting energy from first run and second run are almost same with very slight variation having a maximum value of 0.08 for experimental run at serial number 8. The slight variation in both the values can be caused due to power analyzer or machine limitations like tool vibrations, etc.; however, the closeness of the values for both the first and second run indicate the authenticity of the experimental results. The results also indicate that the first experimental run has the maximum specific cutting energy for the minimum values of speed, feed, depth of cut and width of cut; however, the minimum value of specific cutting energy can be observed for the last experiment as per Table 5.3 which was being operated at maximum speed, maximum feed, minimum width of cut and medium depth of cut. The result indicates that the relation between all four parameters in combination and the specific cutting energy is not direct which means that increase or decrease in all four parameters will not result in a definitive increase or decrease in the specific cutting energy.

5.3.4 The values of specific cutting energy obtained in Table 5.3 were to be analyzed while using Analysis of Variance (ANOVA) technique on a Minitab software. The analysis was to be done in order to ascertain the significance and contribution of all the four variables i.e. speed, feed, depth of cut and width of cut on the response i.e. the specific cutting energy. The analysis is aimed at establishing the impact of each of the variable on the response, their significance on the response and percentage contribution of each of the factor on the response. A predictive model for predicting the specific cutting energy for any values of speed, feed, depth of cut and width of cut is also to be established.

CHAPTER 6: ANALYSIS, DISCUSSION AND CONCLUSION

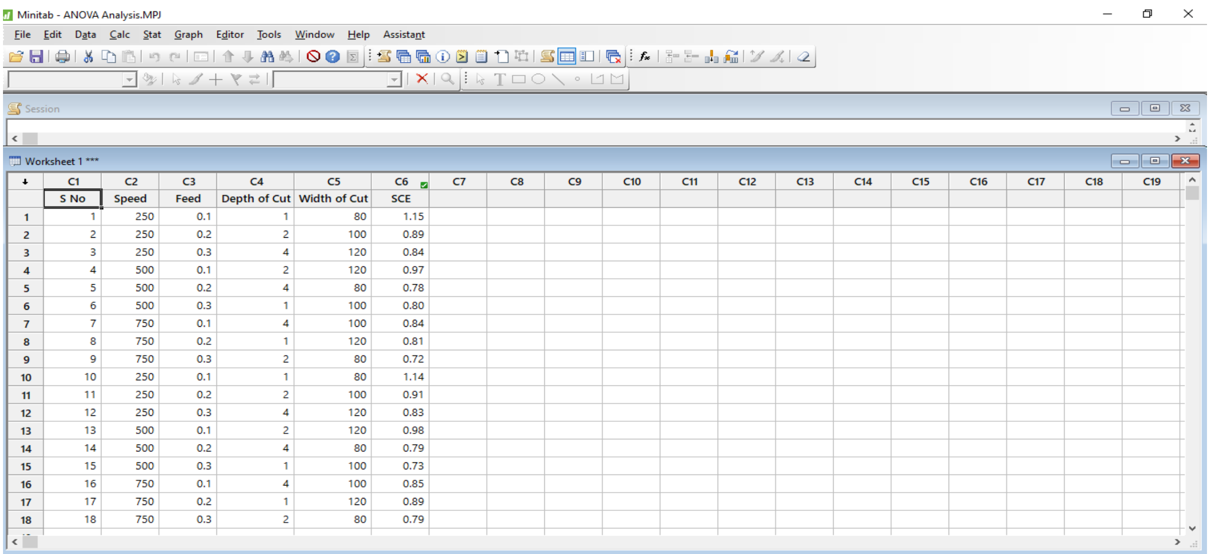
6.1 Introduction

6.1.1 The Analysis of Variance (ANOVA) was performed through Minitab software for establishing the impact of each of the variable on the response, their significance on the response, percentage contribution of each of the factor on the response and predictive model. The data set as per Table 5.3 excluding the material removal rate was imported on the Minitab for analysis. The results obtained from the analysis were reviewed for inferring the impacts of factors on the responses.

6.1.2 The results of the ANOVA will reveal the impact of each of the factor on the response, their significance on the response, percentage contribution of each of the factor and regression model for predicting the specific cutting energies for any set of values of speed, feed, depth of cut and width of cut. The graphical model of the impact factor, percentage contribution and regression equation were to be drawn out of the analysis.

6.2 Analysis

6.2.1 ANOVA is the analysis of variance which is used for predicting a model of a system, validating the responses, ascertaining the impact of factors and their contributions on the response and evaluating various other things on the basis of variation in the response with changing factors. The ANOVA model was performed on Minitab software for ease of calculations; however, both the responses were studied together to evaluate the various elements of the system. A total of eighteen entries with four factors and one response against each set of four factors was added in the Minitab software as shown in Figure 6.1.



	C1	C2	C3	C4	C5	C6
	S No	Speed	Feed	Depth of Cut	Width of Cut	SCE
1	1	250	0.1	1	80	1.15
2	2	250	0.2	2	100	0.89
3	3	250	0.3	4	120	0.84
4	4	500	0.1	2	120	0.97
5	5	500	0.2	4	80	0.78
6	6	500	0.3	1	100	0.80
7	7	750	0.1	4	100	0.84
8	8	750	0.2	1	120	0.81
9	9	750	0.3	2	80	0.72
10	10	250	0.1	1	80	1.14
11	11	250	0.2	2	100	0.91
12	12	250	0.3	4	120	0.83
13	13	500	0.1	2	120	0.98
14	14	500	0.2	4	80	0.79
15	15	500	0.3	1	100	0.73
16	16	750	0.1	4	100	0.85
17	17	750	0.2	1	120	0.89
18	18	750	0.3	2	80	0.79

Figure 6.1: Importing of Data in Minitab for ANOVA

6.2.2 The General Linear model of the ANOVA under the statistical techniques of the Minitab was applied to the data as shown in Figure 6.1. The model was applied on the data while including the Specific Cutting Energy in the Response and speed, feed, depth of cut and width of cut in the factors fields as shown in the Figure 6.2. In addition to this, the display of results under the display option in a General Linear Model was shifted Expanded tables as shown in Figure 6.3 to have a complete visibility of the results.

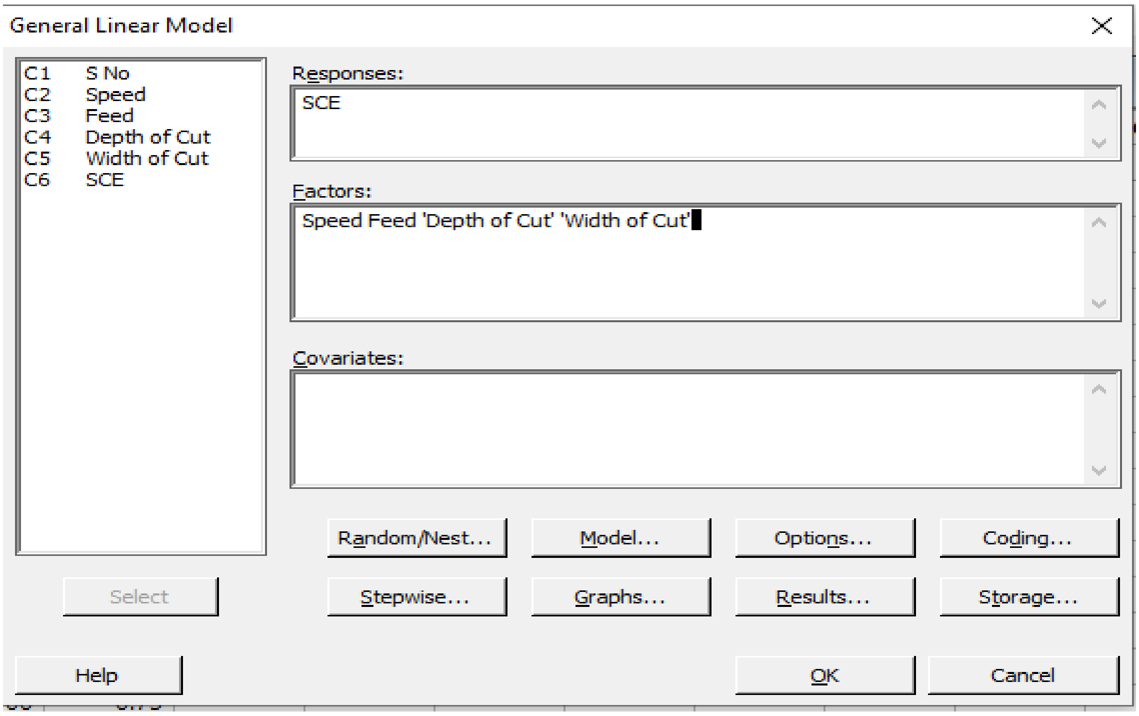


Figure 6.2: Inclusion of Data in Responses and Factors

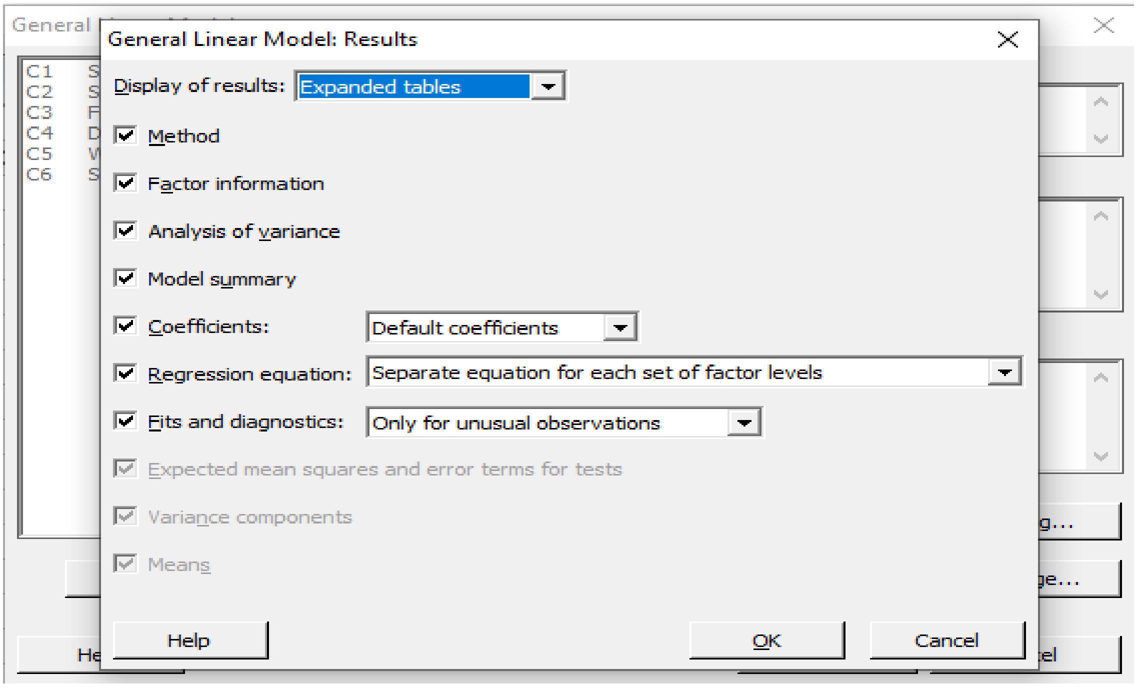


Figure 6.3: Display of Results in Extended Tables

6.2.3 On running the analysis, factor information, model summary, analysis of variance, coefficients and regression equation were retrieved as the analysis output. The output was thoroughly reviewed to get the meaningful results of the output. The analysis of variance is shown at Table 6.1. The Main Effect Plot for all the four factors on the response was also plotted through ANOVA on Minitab as shown in Figure 6.4.

Analysis of Variance							
Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Speed	2	0.071740	28.23%	0.071740	0.035870	38.81	0.000
Feed	2	0.134666	52.98%	0.134666	0.067333	72.86	0.000
Depth of Cut	2	0.028035	11.03%	0.028035	0.014017	15.17	0.001
Width of Cut	2	0.011405	4.49%	0.011405	0.005703	6.17	0.021
Error	9	0.008317	3.27%	0.008317	0.000924		
Total	17	0.254164	100.00%				

Table 6.1: Analysis of Variance

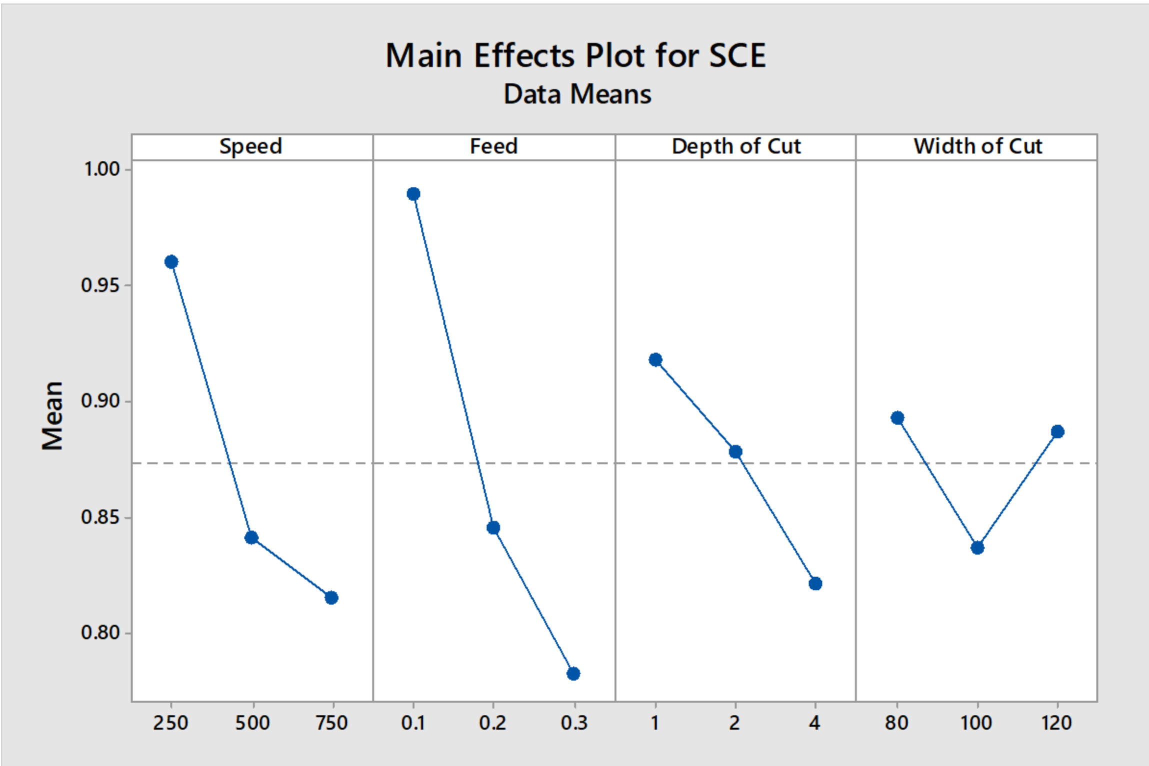


Figure 6.4: Main Effect Plot

6.3 Discussion

6.3.1 Based upon the study of Main Effect plot, it can be observed that with maximum variation over the three intervals, feed is the most significant factor affecting the specific cutting energy followed by speed, depth of cut and width of cut which can also be validated through the lo P-values for each of the factors in Table 6.1. The low P-values as shown in Table 6.1 also indicant the significance of all the four factors on the specific cutting energy. The trend for each of the factor cannot be reviewed independently as the experimental results have been established for review of all four factors together.

6.3.2 It is observed that the data has been plotted in Main Effect Plot at Figure 6.3 indicating the feed as the most significant factor effecting the Specific Cutting Energy. Similar results indicating feed as the most prominent factor for specific cutting energy have been achieved on a similar study made for turning operation on a lathe machine by Warsi et al[6]. An effort to draw a comparison of specific cutting energy between the results achieved by Warsi et al [6] during a turning operation and results drawn out of these experiments for a milling operation was also made. It is worth mentioning that although the machining dynamics of both the turning and milling are altogether different; however, comparison could be drawn for specific cutting energy as it is the energy required to remove a unit volume of the material irrespective of the machining process. Moreover, the methodology adopted by Warsi et al [6] for isolating the cutting power by subtracting the power for air cut out of the power for actual cut addresses the machine capacity issue and similar methodology has been followed here. A comparison of both the results is tabulated at Table 6.2.

S No	Speed (m/min)	Feed (mm/rev)	SCE (Turning Operation) Warsi et al.	SCE (Milling Operation) Usman Avg	% Difference
1	250	0.1	0.72	1.14	37.05%
2	250	0.2	0.62	0.90	31.38%
3	250	0.3	0.58	0.84	30.55%
4	500	0.1	0.61	0.98	37.66%
5	500	0.2	0.59	0.78	24.76%
6	500	0.3	0.55	0.76	27.81%
7	750	0.1	0.62	0.85	26.77%
8	750	0.2	0.59	0.85	30.49%
9	750	0.3	0.54	0.75	28.23%

Table 6.2: SCE Comparison for Turning and Milling Operation

6.3.3 The experiments performed by Warsi et al. [6] were performed with two variables involved i.e. speed and feed as width of cut is irrelevant in turning operation and depth of cut was taken as a constant; however, the experiments performed for milling were based upon four factor i.e. speed, feed, depth of cut and width of cut. While considering the fact that speed and feed are the most significant factors on Specific Cutting Energy in a milling operation and depth of cut and width of cut are comparatively insignificant, the depth of cut and width of cut have been omitted from the comparative analysis. An analysis has been drawn for equal values of speed and feed in both the turning and milling operation which indicates that milling operation consumes more energy for a unit volume of material removal as compared to a turning operation which is evident in Table 6.2. A milling operation is considered to consume around 30% more power as compared to a turning operation for each unit volume material removal. While considering the variation in depth of cut and width of cut, the analysis is crude for exact value; however, a trend for excessive power consumption in a milling operation as compared to a turning operation can be established the likely reason of which can be the engagement and disengagement of tool with the work piece which results in an energy consumption spike for every engagement whereas, in turning operation, the tool is continuously in contact with the work piece.

6.3.4 While comparing the result from another research made by Warsi et al [17] for study of specific cutting energy in a turning operation with variation in speed, feed and depth of cut, the ANOVA analysis and Main effect plot of both the experiments for turning and milling were compared. The ANOVA analysis performed on SCE results presented by Warsi et al [17] is shown in Table 6.3 and main effect plot for the said results is at Figure 6.5.

Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
V (m/min)	5	0.0032	4.16%	0.0032	0.0006	2.2	0.153
f (mm/rev)	2	0.0664	85.55%	0.0664	0.0332	113.31	0
d (mm)	2	0.0056	7.27%	0.0056	0.0028	9.63	0.007
Error	8	0.0023	3.02%	0.0023	0.0003		
Total	17	0.0776	100.00%				

Table 6.3: ANOVA Analysis of Turning Experiments performed by Warsi et al

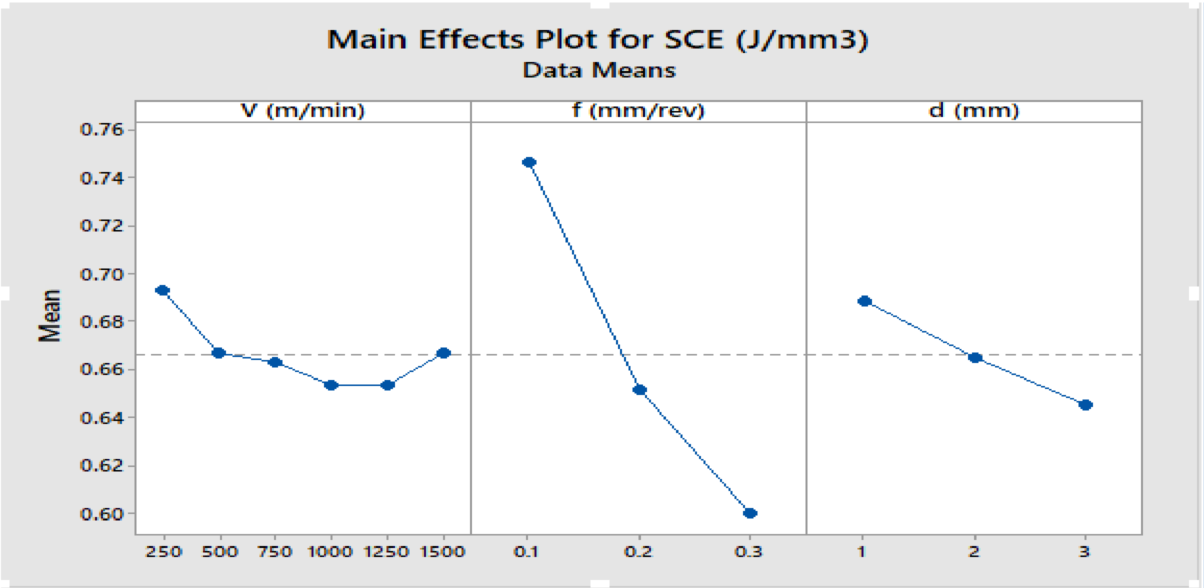


Figure 6.5: Main Effects Plot for Turning Experiments performed by Warsi et al

6.3.5 The results reveal that turning also depicts similar results as milling when discussing the impact of feed and depth of cut on the specific cutting energy. For both the turning and milling experiments, the specific cutting energy faces a decreasing trend with increase in feed and depth of cut; however, the speed depicts a peculiar initial decrease in specific cutting energy which tends to increase later when the speed is further increased. Moreover, unlike milling, the impact of speed on specific cutting energy is almost negligible in case of the turning operation. On the contrary, the feed is observed to have a very huge percentage contribution on the specific cutting energy when talking about the turning operation.

6.3.6 It is also observed from the main effects plot at Figure 6.4 that specific cutting energy shows a decreasing trend with increase in speed, feed and depth of cut; however, the width of cut indicates a peculiar trend in which the specific cutting energy first decreases with the increase in width of cut and later increases on further increase in the width of cut. The experiments performed for turning operations by Warsi et al [6] considered for two variables i.e. speed and feed; however, similar trends for both the parameters have also been observed for milling operations.

6.3.7 The percentage contribution of each of the factor i.e. speed, feed, depth of cut and width of cut on specific cutting energy has also been established during ANOVA. Although the main effects plot revealed feed to be the highest impacting factor followed by speed, depth of cut and width of cut; however, their exact contribution as established through Analysis of Variance at Table 6.1 is shown below in Table 6.4.

Source	Percentage Contribution
Speed	28.23%
Feed	52.98%
Depth of Cut	11.03%
Width of Cut	4.49%
Error	3.27%
Total	100.00%

Table 6.4: Percentage Contribution of each Factor

6.3.8 The table 6.4 reveals that feed contributed 52.98% in the Specific cutting energy of a milling operation, whereas, the percentage contribution for speed, depth of cut and width of cut is 28.23%, 11.03% and 4.49% respectively. A 3.27% of error has also been shown which is attributed to the rounding off of data, tool and work piece vibrations, measurement limitations or other uncontrollable factors. Data shows that variation in specific cutting energy with variation in width of cut is nominal whereas the change of feed can variate the specific cutting energy to a great extent.

6.3.9 A regression equation has also been established through ANOVA and is shown at Equation 6.1. It can be used for solving the Specific cutting energy for a combination of speed, feed, depth of cut and width of cut.

SCE = 0.87276 + 0.0881 Speed_250 - 0.0312 Speed_500 - 0.0568 Speed_750 + 0.1169 Feed_0.1 - 0.0273 Feed_0.2 - 0.0896 Feed_0.3 + 0.0454 Depth of Cut_1 + 0.0054 Depth of Cut_2 - 0.0508 Depth of Cut_4 + 0.0207 Width of Cut_80 - 0.0354 Width of Cut_100 + 0.0147 Width of Cut_120

(Equation 6.1)

6.3.10 The interaction plot for all the variables is also established through Minitab software and is shown at Figure 6.6. It can be observed that specific cutting energy does not follows a specific trend when studied with interaction of two variable; however, a general decrease in specific cutting energy is largely observed with increase in parameters value except few peculiar cases where a uniform trend is not followed by the specific cutting energy.

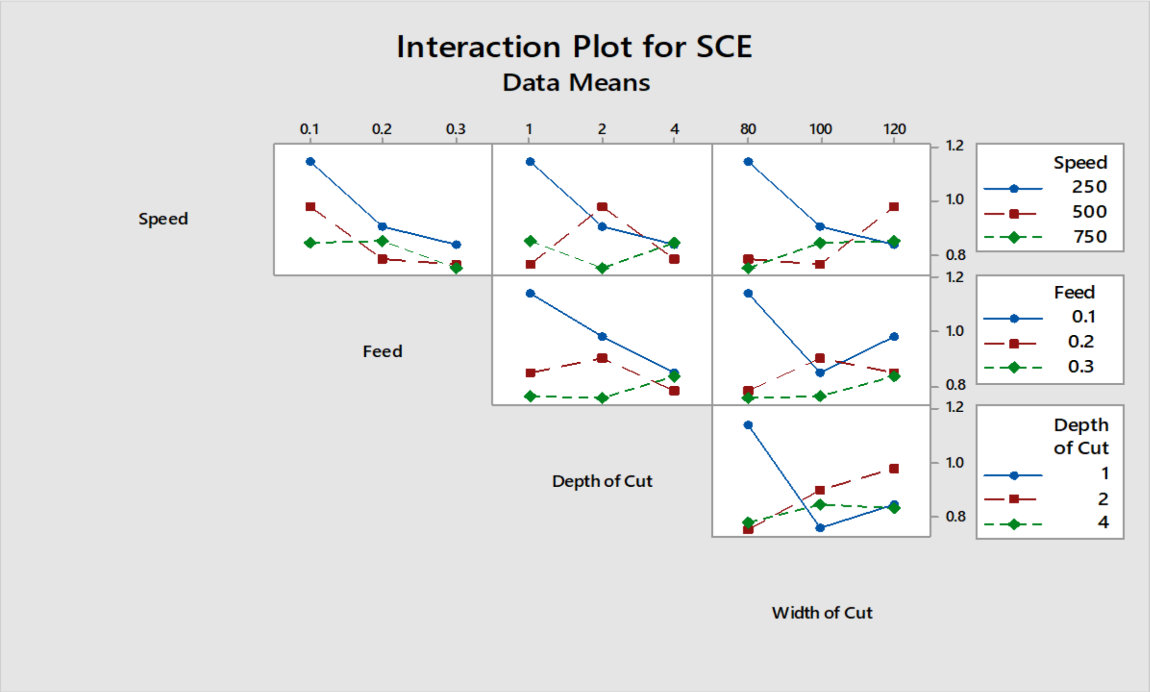


Figure 6.6: Interaction Plot

6.4 Conclusion

6.4.1 The parameters identified for variation during experimentation are based on their likelihood to influence the specific cutting energy during a milling operation. Speed, feed, depth of cut and width of cut were identified as the critical parameters with possible impact on specific cutting energy. Factors like number of inserts and milling mode were also given consideration but were dropped as had already been reviewed for their impact on power consumption in previous research. [10]

6.4.2 The experimental results for power consumption analysis with variation in critical parameters like speed, feed, depth of cut and width of cut during milling machining reveal a significant impact of these factors on the power consumption. Out of the mentioned factors, feed has the highest significance in specific cutting energy with percentage contribution of 52.98%. It is then followed by speed with percentage contribution of 28.23%, depth of cut with percentage contribution of 11.03% and width of cut with percentage contribution of 4.49%.

6.4.3 A uniform trend has been generally observed between these factors and specific cutting energy with an exception of width of cut. For speed, feed and depth of cut, the increase in parametrial value results in a decrease in specific cutting energy, whereas, for width of cut, the specific cutting energy is initially decreased with an increase in width of cut; however, the further increase in width of cut results in the increase in specific cutting energy.

6.4.4 The most significant contributory factor and impact of increase and decrease in speed and feed can also be validated by similar experiments performed during turning operations on a lathe machine by Warsi et al [6]. The impact of variation in depth of cut and width of cut were omitted to make the results comparable.

6.4.5 The comparison of the research done by Warsi et al [6] with present research reveals that milling operation consumes more power as compared to turning operation for a unit volume of material removal which can be attributed to power consumption spike made because of a discontinuous tool work piece interaction. In a milling operation, an instantaneous power spike is observed at every engagement of tool to the work piece whereas the tool work piece interaction in the turning operation is otherwise continuous.

6.1 Recommendations

6.5.1 The study requires to be validated with a different tool on a different machine while using a different material to authenticate the general applicability of results.

6.5.2 The study also suggests that while defining the manufacturing process, the process engineers should resort to higher values of speed, feed and depth of cut for reduced power consumption while keeping into consideration the other design limitations like tolerance, surface finish, etc.

6.5.3 The micro machining elements of milling machining like number of inserts engaged with tool at any point of time with their rate of change through predictive methodology needs to be studied for better understanding of machining dynamics and enhanced efficacy of milling operations.

6.5.4 The study reveals that in a milling operation, the tool and work piece interaction is required to be studied in depth and a methodology for milling with continuous tool and work piece interaction be adopted for reducing the power consumption in a milling operation after necessary validation.

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