Investigation of Specific Cutting Energy at low speed turning of Al 6061 T6

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February 2019

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A thesis submitted in partial fulfillment of the requirements for the degree of

MS Design and Manufacturing Engineering

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February 2019

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Acknowledgements

I am thankful to my Creator Allah Subhana-Watala to have guided me throughout this work at every step and for every new thought which you setup in my mind to improve it. Indeed, I could have done nothing without your priceless help and guidance. Whosoever helped me throughout the course of my thesis, whether my parents or any other individual was your will, so indeed none be worthy of praise but you.

I am profusely thankful to my beloved parents who raised me when I was not capable of walking and continued to support me throughout in every department of my life.

I would like to express special thanks to my supervisor Dr. Hussain Imran for his guidance and help throughout my research work.

I would also like to pay special thanks to Assistant Professor Salman Warsi for his tremendous support and cooperation. Without his help, I wouldn't have been able to complete my thesis.

I am also thankful to Nadeem Mughal, Shahrukh Khan, Saad Ali and Asad Ali for their motivation and cooperation.

Finally, I would like to express my gratitude to all the individuals who have rendered valuable assistance to my study.

Dedicated to my parents, adored siblings and friends whose tremendous support and cooperation led me to accomplish this work.

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ABSTRACT

Machine tools are accountable for environmental influence owing to their energy consumption. It is also a challenge for modern manufacturing how to reduce the environmental impacts related to machining processes. The environmental study about machine tool that used in machining reveals that more than 99% of environmental impacts are due to the consumption of electrical energy.

This research presents the energy consumption map at low cutting speed of Aluminum alloy Al 6061-T6. The constructed energy map tells about different energy consumption regions at different machining parameters (feed and speed) during single point cutting of Al 6061-T6 alloy. In this thesis, less energy consumption observes at cutting speed (in the ranges of 500-1000 m/min) and at higher feed (in the ranges 0.3-0.45). Designs of experiments were done with the help of full factorial. Aluminum alloy 6061-T6 used as a work-piece material and it is widely used materials in automobiles, aerospace, defense and bio-medical industries.

All these experiments were performed by using fresh cutting inserts, that’s why the effect of tool wear was not considered for power and energy measurements. The main purpose of this research is to investigate the energy consumption and developed the energy map. The presented map can be used for selection of the parameters which are efficient for SCE.

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Chapter 1

Introduction

The growth of a country depends upon the demand of energy. If this demand is not fulfilled then it will ruin the economic growth. Pakistan is such a country where industries increase day by day, so the requirement of energy will be increased which will affect the economic growth. Oil production reached to peak in the 2004 to 2012[1].As a result different energy efficient techniques are used.

The introductory survey of environment related to machining of machine tools has shown that more than 99% of environmental influences are due to electrical energy consumption. The consumption is due to use of machine tools in material removal process for turning, milling etc. if some reduction occurs in consumption of electrical energy, it not only benefits for manufacturer's but also enhances the environmental performance[2].

The aim of manufacturing companies has always been efficiency of time, costs & quality. Due to increases demand and price of energy, it also becomes an extra goal for manufacturers. So reduction in energy consumption is important for cost saving and environment friendly [3].

To improve the energy efficiency of manufacturing processes, it is necessary to understand the relationship among energy consumption, machine tools and cutting process. Turning is most commonly used process in manufacturing. A lot of work has been done by optimizing this process based on cost & productivity but no one has given appropriate attention by optimizing turning process on basis of energy consumption [2].

Specific energy consumption (SEC) is the machine tools energy that consumed for removing per cubic centimeter of material. It value is different for different material removal process. A complete investigation of SEC breaks down it into four different components according to consumption of input energy, such as specific fixed energy, operational energy, tool tip energy and un-productive energy. It has been manifest that input energy not only used to detach the material, but also make sure the machine readiness, spindle rotation and change energy into heat because of friction.

Al is the 3rd most abundant of all elements after silicon and oxygen. It consists of face centered cubic structure. It has relatively low melting temperature as compared to other metals. Aluminum alloys are the most commonly used lightweight metallic material since it provides many various attractive mechanical and thermal properties. They can easily be used for shape making process. Aluminum alloys show maximum level of machining with respect to other materials that are lightweight such as magnesium and titanium alloys. Machinability express the performance of machining and it can also be checked by different criteria such as surface roughness, material removal rate and machine tool power etc. [4].

Research Aims:

The aim of this research is to develop the energy consumption map. In this research a single point cutting methodology is used for machining of aluminum alloy. Many modeling techniques and optimizing techniques are used for reducing energy consumption. Here is the use of energy map for reducing energy consumption on aluminum alloy.

Research Objectives:

The objectives of research work are followings:

- Literature review on energy consumption of machine tools.
- Through literature review to check the effect of cutting parameters on energy consumption of machine tools.
- In literature review to examine the behavior of surface roughness by varying the level of cutting parameters.
- Selection of cutting parameters.
- Preparation of experimental design.
- Power of air cut cycle and actual cut cycle recorded through energy analyzer.
- Measurement of cutting power and SCE through proper calculations.
- Developed the energy consumption map.
- Comparison of different regions of energy.

Chapter 2

Literature review:

Literature survey:

For reducing the energy consumption various techniques were used.

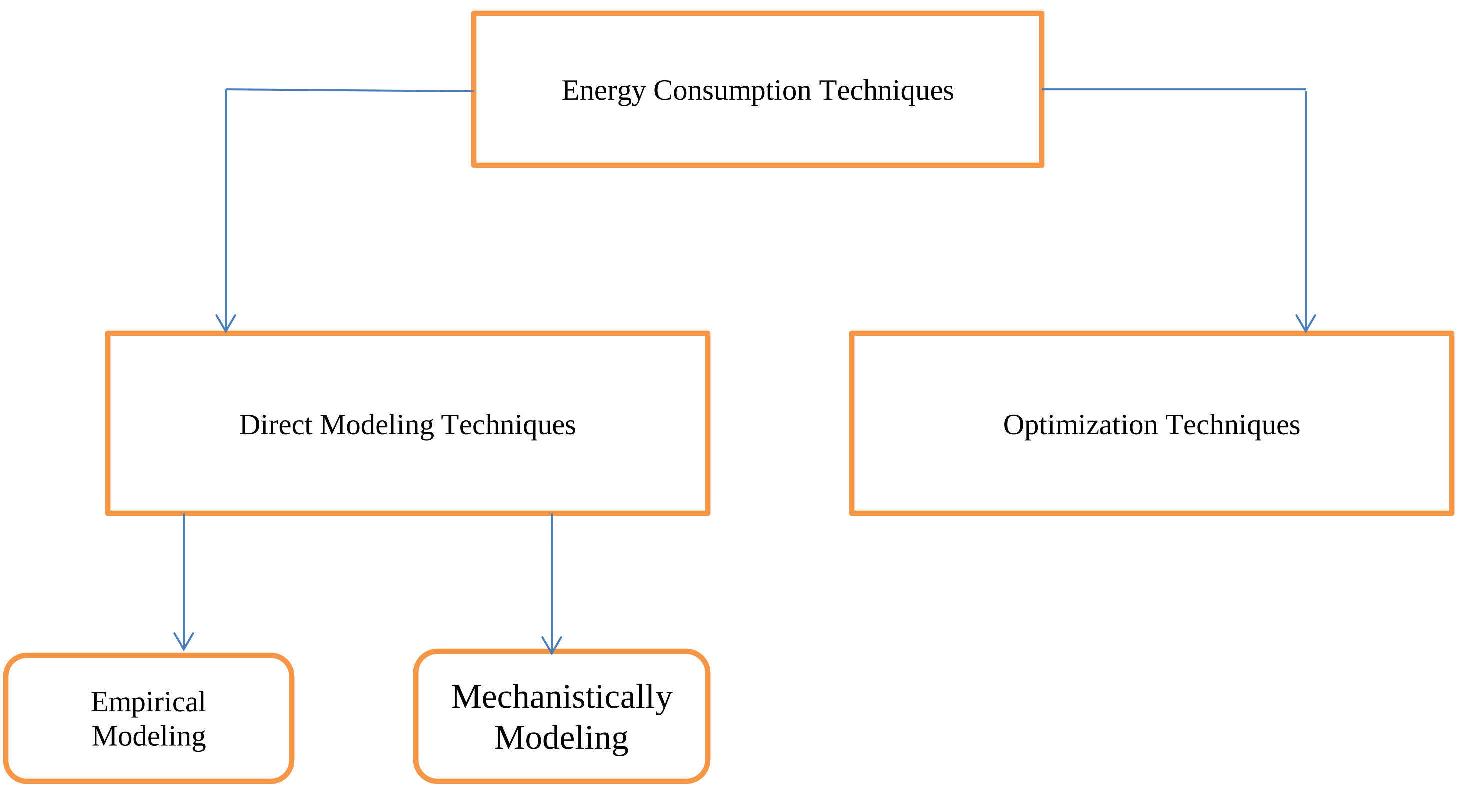

Figure 1 Flow chart of energy consumption techniques study in literature

Direct Energy Modeling

Direct energy modeling is done both empirically and mechanistically [5].

Empirical Modeling

Draganescu et al.[6] 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.[7] 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.

Mechanistically Modeling

Gutowski et al.[8] 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.[9] 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.[10] 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 [9][10] 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[11] 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[12] 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 1cm3 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 [13] gives an energy consumption model that defines 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.

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[14], a methodology has been presented which incorporates both energy usage and roughness of surface for optimizing the cutting variables.

Campatelli[15] 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[16] 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[17] 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 CO2 emission has largely increased. There are a lot of studies which are done to evaluate reduced power usage by machines. This article [18] 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 [19] 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[20] 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.

In the work of C. Camposeco-Negrete [2], response variables were energy consumption and surface roughness. Energy was calculated by multiplying time with power value. Power was measured with the help of LabVIEW interface during machining process and power meter was attached to the main supply of lathe machine. Each experiment was carried out three times to calculate the average value of power. In this research paper power is divided into two categories such as machining power and cutting power. Machining power was measured when there is no contact between work piece and cutting tool but when physically tool contact with work piece material then power meter used to measure cutting power. Other response variable was surface roughness; it was measured with the help of roughness meter Mitutoya. Analysis of variance (ANOVA), main effects plot and S/N ratio were employed to analyse the effect of cutting parameters for response variables such as machining power and machining energy, cutting power and cutting energy and surface roughness.

We studied many modeling and optimizing techniques for reducing the energy consumption used in manufacturing processes. But here both techniques will not be used. There is the use of energy mapping approach.

Warsi et al [21] used energy mapping approach to investigate specific cutting energy consumption at different cutting parameters. This approach was used on orthogonal cutting of Al 6061-T6 alloy.
Here is the use of same approach but this approach will be used on single point turning of Al 6061-T6.

Aluminum Alloy

Aluminum is available both in pure and alloyed shapes. It is soft and weak material. Commercially aluminum is accessible up to 99.8 percent pure. Both at low and high temperature, aluminum show a weak strength. The main supremacy of aluminum is its small density, excellent strength to weight ratio, good workability, weldability & ductility, resistance to corrosion, 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 [22].

Aluminium alloy is basically a chemical composition of different elements in pure aluminum. These elements are added to enhance the properties of pure aluminum specially its strength. That's why aluminum alloy remarkably shows high strength as compared to pure aluminum. The following elements consist of silicon, manganese, magnesium, iron, copper & zinc and added up to 5% by weight in pure aluminum. Aluminium alloys have broadly used in aircraft and automobiles industries. The 2000 and 6000 series of aluminum alloys have regularly used for design applications [22].

Table 1: Mechanical and Physical properties of Aluminium alloy 6061

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

Series of Aluminum Alloy:

Alloys are given four digits' number; the 1st number represents the general class of alloying elements. Some alloys series of aluminum are followings.

The series 1xxx composed of 99 percent pure aluminum and this series represent some eminent properties such as corrosion resistance, greater thermal and electrical conductivity. It is frequently used for transmission purposes. Copper is major alloying element in 2xxx series. 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.

Magnesium is very effective alloying element used in 5xxx series and it is extensively used with aluminum. 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 7xxx series. 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. [23]

Table 2 : Major alloying elements in different series of Aluminium alloys.

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Series	Major Alloying Elements	Secondary Alloying Elements
1xxx	Commercially Pure 99%	**None**
2xxx	Copper (Cu)	Mg, Mn,Si
3xxx	Manganese (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 [23].

Table 3: Chemical composition of Aluminum alloy 6061

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		0.04		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		__	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 mechanical and physical properties of Aluminum alloy 6061-T6 with other work-piece materials

Property	Material						
	Al 6061-T6	Al 2011-T3	Al 7075-T6	AISI 1117	AISI 4140	SS 416	Inconel 718
Density(g/cm^3)	2.7	2.83	2.81	7.87	7.85	7..75	8.22
Hardness(HB)	95 HB	95 HB	7 HRC	130 HB	197 HB	262 HB	42 HRC
UTS(MPa)	310	379.2	572	450	1590	517	1350
Yield Strength (MPA)	275	296.5	503	310	1460	276	1170
Modulusof Elasticity(GPA)	69	70.3	71.7	200	207	300	200
Ductility (%)	Dec-14	15	11	20	12.5	30	16
Thermal Conductivity (W/Mk)	167	226	130	51.9	35.8	26.8	11.4

Metal cutting process:

In machining material of work-piece is removed in the form of chips. It is called metal cutting process when the work-piece material is metallic. The nomenclature and geometry of wedge shaped cutting tool is basically an intricate matter. It is hard to understand that single point cutting tool has different angles and also tough to determine the slope of the tool face. In machining philosophy, the wedge shaped tool is used to detach the material from the work piece in the form of chips (continuous or dis-continuous). The geometry of wedge shape cutting edge is obtained when two surface of cutting tool bisect with each other's. This surface consists of two faces, the first one is rake face and the other is flank face. The surface through which chips remove is known as rake face and the other which contact with machined work piece surface is called flank face [24]. The machining processes are divided into two categories.

1. Orthogonal cutting
2. Oblique cutting

Orthogonal cutting process:

It is the most common cutting operation that takes place when the single point cutting tool moves in the direction that is normal to the cutting chips of the tool. In this process, the cutting force of the tool is at 90 degree to the line of action of the tool and tool with a constant velocity.

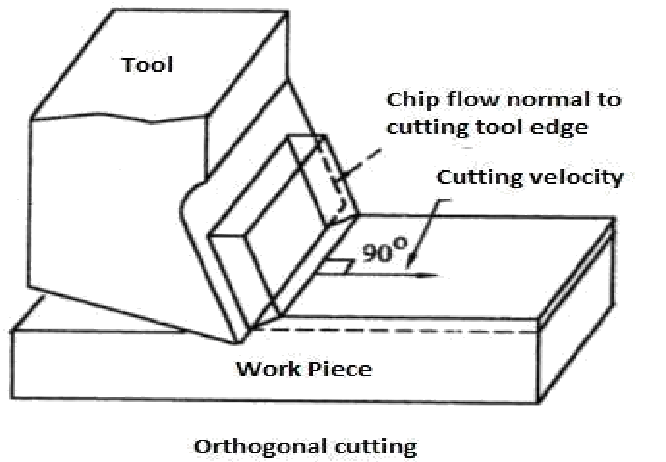

Figure 2 Orthogonal cutting

In cutting process, some sections of plastic deformation occur in the work piece. This sections of deformation basically occurred between the chips and the elastically deformed material. The deformation zones which are produced due to the generation of chips are listed into primary and secondary shear zones. Primary zone is generated when material is squeezed both by elastically and plastically while secondary zone is produced where chips are generated. This is due to the presence of friction between chips and rake face. The shape of plastically deformed section depends on the cutting speed conditions. The value of deformed section is large at low cutting conditions but it decreases in size at comparatively high cutting conditions [24].

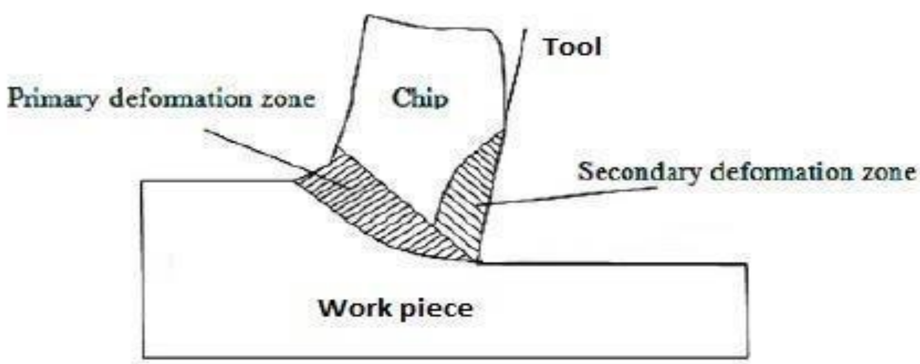

Figure 3 Deformed primary and secondary zone

Oblique cutting process:

It is a type of metal cutting process in which cutting edge of wedge shaped tool is not normal to the direction of flow of chips. Orthogonal is a specific case of oblique cutting. Oblique is basically a 3-dimensional cutting while orthogonal is a 2-dimensional.

There are very limited investigations at the subject of oblique cutting because the procedure of it is much more difficult comparatively to orthogonal cutting. In oblique cutting, chip passes through rake face but the direction of chip is not perpendicular to the cutting edge. It is removed at some angle which is less than 90^0[24].

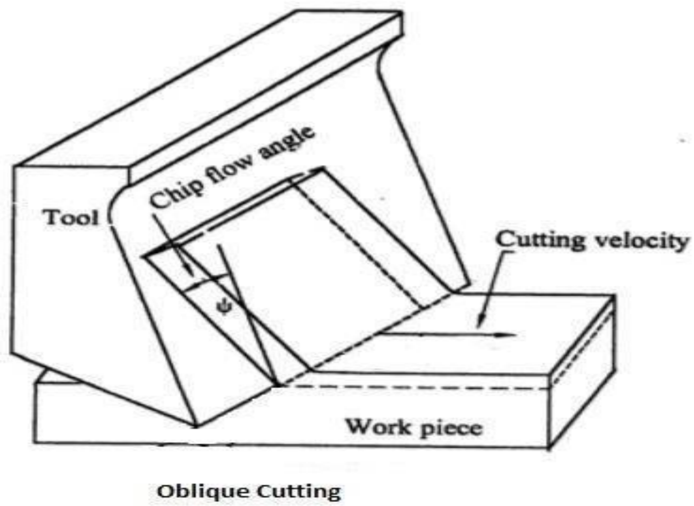

Figure 4 Oblique Cutting

Comparison of orthogonal and oblique cutting:

Orthogonal cutting:

5. It is two dimensional (2-D) cutting process. In this process two components of forces are involved, feed or thrust force and cutting force. So that's it is called as 2-D cutting process.
6. The cutting edge of single point cutting tool is normal to the direction of tool travel or tool feed.
7. Cutting edge is also at right angle to orientation of chip moves.
8. The heat produced because of friction per unit area is greater as compared to oblique cutting.
9. Tool life is lower than oblique cutting. (at identical cutting conditions)
10. In orthogonal cutting process, smaller amount of material is removed.

Oblique cutting:

1. It is three dimensional (3-D) cutting process. In this case three sections of forces are involved, cutting force, feed or thrust force and radial force. So it is referred as 3D cutting process.
2. The cutting edge of the tool is inclined at an angle which is less 90^0, to the direction of tool feed.
3. The direction of chip flows is not perpendicular to the cutting edge.
4. The amount of heat that is produced in this process per unit area is less.
5. Hence, tool has longer life comparatively to orthogonal cutting.
6. In oblique cutting process, much rapid and larger amount of material is removed.
7. Cutting edge of the tool may be smaller than the tool width.

Chapter 3

Research Methodology

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. It is commonly used as a light weight metallic material and having good mechanical and thermal properties. It shows maximum level of machinability comparatively other materials [21].

All the experiments were done at two different CNC turning machines. These machines have a special feature of turret center. The total power capacity of CNC machine is 26kw. The power capacity of spindle motor is 3500 rpm/min. Some specifications of these machines are listed below.

Table 5: Specifications of machine tools.

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

Requirements for power measurement:

Consumption of energy in machining processes depends upon the factors i.e. constant factors and variable factors. Constant factors do not depend upon the type of machining and utilized fixed amount of energy. These factors have following units such as control system power supply, lighting system for cutting, motor drive and so on. These components consume continuous supply of energy regardless of machining. But another side variable factor utilized variable amount of energy and also utilized more energy as compared to constant factors. Mostly variable factors consist of drive units of machine tool and they are load-dependent. Variable amount of energy was consumed due to different types of machining processes. Drive units provide motion to machine tool components and drive system includes following units: [25]

[1] Feed drive units
[2] Spindle drive units
[3] Tool altering & fixing units
[4] Work-piece altering & fixing units

Standby mode or idle power of machine is a constant amount of power that requires for machine and its supplementary components such as control unit, fans, motors and pumps etc. The purpose of these components in active mode is to show that machine is in ready state [26].

The actual power that required for material removal is incorporate both normal cutting and air cutting. W. Li & S. Kara [17] have been used two cycle approach, so a same type of methodology was used in this research. In air cycle there is no contact between tool and work piece. Cutting tool moves along the length of work piece just to check the correctness of program and to ensure that machine components such as rotation of spindle and tool moves accordance to numeric control program. This is also called non-productive approach. Due to these requisite there is a need of extra power comparatively to idle power or fixed power. So the power measured in this cycle was indicated as P_{air}.

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 [27].

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.

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 [28].

The design of experiments was done through full factorial. We have to measure specific cutting energy under four levels of cutting speed at four different values of feed. Both parameters are shown below.

Table 6 Different cutting speeds and feeds.

Machine Parameters	Level 1	Level 2	Level 3	Level4
Cutting Speed (m/min)	250	500	750	1000
Feed (mm/rev)	0.1	0.2	0.3	0.4

There was repetition of three times of each experiment and fresh insert used in each experiment for energy consumption measurement without the effect of tool wear.

Actual power and air cut power are measured through Yokogawa Power Analyzer (CW-240). It was clamped on main bus of CNC machine.

Figure 5 Yokogawa Power Analyzer CW-240

Figure 6 Power Analyzer clamped with main bus of CNC machine

When tool moves along cutting length then there is a physical contact between cutting tool and work piece. Material was removed in this cycle and it is also called productive approach. So the power recorded in actual machining was indicated as Pactual. The power difference between actual cut and air cut is basically an energy that was used for material removal from work piece. It was indicated as Pcut and calculated by following equation.

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

The power measured through this formula was the actual power that consumed in the duration at which cutting tool and work piece are in contact with each other.

Material removal rate mm3/sec was calculated through following formula;

$$MRR = vbf$$

Where

v=cutting speed,m/min
f=feed,mm/rev
b=width of cut,

Specific cutting energy (SCE) was calculated by dividing the average cut power of machine tool by material removal rate (MRR). It is generally measured in N-m/mm³ or J/mm³.

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

Table 7 Experimental results of SCE under different cutting speeds and feeds.

Sr. No.	**Cutting Speed (m/min)**	**Feed (mm/rev)**	**MRR (mm^3/sec)**	**SCE (J/mm^3)**
1	250	0.1	0.42	0.82
2	250	0.15	0.62	0.74
3	250	0.2	0.83	0.70
4	250	0.25	1.04	0.67
5	250	0.30	1.25	0.66
6	250	0.35	1.46	0.62
7	250	0.4	1.67	0.61
8	350	0.1	0.64	0.80
9	350	0.15	0.81	0.69
10	350	0.25	0.90	0.66
11	500	0.1	0.83	0.77
12	500	0.15	1.25	0.68
13	500	0.2	1.67	0.67
14	500	0.25	2.08	0.64
15	500	0.3	2.50	0.62
16	500	0.35	2.92	0.60
17	500	0.40	3.33	0.60
18	600	0.1	0.90	0.76
19	600	0.15	1.50	0.67
20	600	0.30	3.10	0.62
21	750	0.1	1.25	0.73
22	750	0.15	1.87	0.70
23	750	0.20	2.50	0.66
24	750	0.25	3.12	0.64
25	750	0.30	3.75	0.61
26	750	0.35	4.37	0.59
27	750	0.40	5.00	0.59
28	900	0.05	1.25	0.69
29	900	0.25	3.60	0.63
30	900	0.30	4.40	0.61
31	1000	0.1	1.67	0.67
32	1000	0.15	2.50	0.66

33	1000	0.20	3.33	0.65
34	1000	0.25	4.17	0.62
35	1000	0.30	5.00	0.61
36	1000	0.35	5.83	0.59
37	1000	0.40	6.66	0.58

Chapter 4

Results and discussion

In this research energy map is constructed for single point turning of Al 606.1-T6 alloys using H13A inserts. The method used to make this energy consumption map is totally experimental. Forty experiments have to be done for constructing this map. The SCE is calculated on different parameters of cutting speed and feed and draw on a feed–speed grid. The values of SCE which are plotted gave different regions of energy consumption.

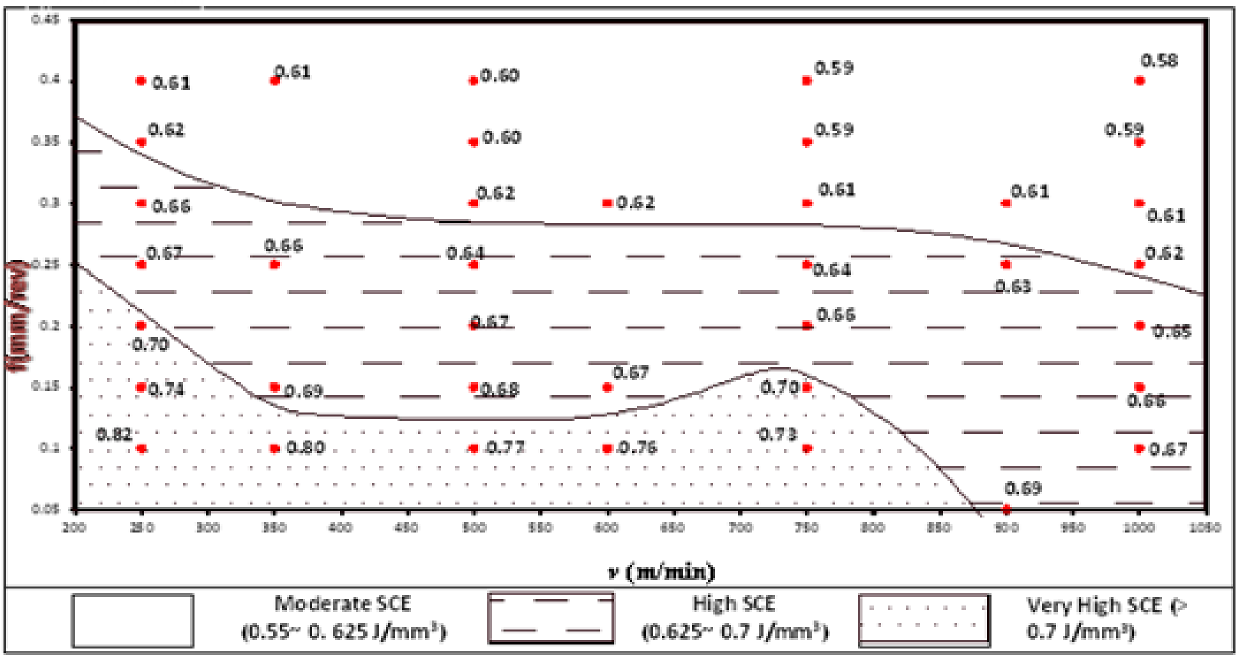

Figure 7, Developed map for energy consumption of Al 6061-T6 at low speed turning 250–1000 m/min and having 0.05–0.45 mm/rev

Following are the regions which are identified on the basis of SCE consumption values.

[19] Very High Specific Cutting Energy Region shown with white background with dotted lines having values > 0.7 J/ mm³

[38] High Specific Cutting Energy region shown white background with dashed lines having values 0.625 ~ 0.7 J/ mm^3

[39] Moderate Specific Cutting energy region shown with completely white background with dotted lines having values 0.55 ~ 0.625 J/ mm^3

These regions are selected by comparing experimental values that are present in literature (table 8).

Table 8 Specific energy values present in literature.

Source	**Specific energy (J/mm^3)**
Black and Kohser	0.46–0.85
Groover	0.7–0.8
Kalpakjian and Schmid	0.4-1
Present research	0.59-0.82

High values of SCE are observed at low feed. At low feed the material removal rate is reduced but electric power consumption is greater due to which there is increase in SCE. The region of low SCE consumption is observed at higher feed. The effect of feed and effect of cutting speed have been observed in this research. The SCE consumption is reduced with increasing feed. The reduction in SCE consumption is in the range of 11-25% when feed increases from 0.05 to 0.45. The SCE consumption is also reduced with increasing cutting speed but the effect of cutting speed is less. The reduction in SCE consumption in the range of 4-18% when cutting speed increases. In this research the effect of feed is greater on SCE while there is small effect of cutting speed on SCE for Al 6061 alloys at low cutting speed range. In different energy consumption region the SCE has been reduced by increasing the feed rate and cutting speed. Low SCE has been resulted by combining high feed and high cutting speed.

The first region which is characterized as very high SCE consumption region (.0.7 J/mm^3) has been observed at low feed. This region is noticed when the feed is up to 0.25mm/rev and the cutting speed is up to 850 m/min. As the cutting speed is increased from 850m/min and the feed is reduced to 0.05 it will gave the other region which is named as higher SCE consumption region. The SCE is higher in the region in which feed is 0.25 to 0.35mm/rev. The SCE consumption (0.55– 0.625 J/mm^3) is in the region in which feed is 0.35 to 0.45mm/rev. A trend of moderate SCE consumption region is same to high SCE consumption region.

Chapter 5

Conclusions:

This study presents the energy consumption map at 1mm depth of cut at cutting speed (up to 1000 m/min) during single point cutting. Al 6061-T6 used as work piece material for machining and uncoated cutting inserts H13A have been used for all the experiments. Following conclusions can be drawn from the experimental work.

- Feed has very important effect in SCE consumption. The SCE consumption is reduced with increasing feed. The reduction in SCE consumption is in the range of 11-25% when feed increases from 0.05 to 0.45.

- Cutting speed has small effect in SCE consumption. The SCE consumption is also reduced with increasing cutting speed but the effect of cutting speed is less. The reduction in SCE consumption in the range of 4-18% when cutting speed increases.

- The maximum values of specific cutting energy(SCE) is observed at lower feed 0.05-0.25 mm/rev and when cutting speed is up to 1000m/min.

- The SCE consumption is smaller when the feed is in range of 0.35 and 0.45 mm/rev and the cutting speeds are 500-1000 m/min.

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