MARMARA UNIVERSITY
INSTITUTE FOR GRADUATE STUDIES
IN PURE AND APPLIED SCIENCES

# SUSTAINABLE MACHINING OF THE MAGNESIUM ALLOY MATERIALS IN THE CNC LATHE MACHINE AND OPTIMIZATION OF THE CUTTING CONDITIONS

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**Ph.D. THESIS**
Department of Mechanical Engineering

**ADVISOR**

Assoc.Prof. Dr. Bülent EKİCİ

ISTANBUL, 2013

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Beril EKER GÜMÜŞ, a Doctor of Philosophy student of Marmara University Institute for Graduate Studies in Pure and Applied Sciences, defended her thesis entitled "**Sustainable Machining of the Magnesium Alloy Materials in the CNC Lathe Machine and Optimization of the Cutting Conditions**", on Dec 27, 2013 and has been found to be satisfactory by the jury members .

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## APPROVAL

Marmara University Institute for Graduate Studies in Pure and Applied Sciences Executive Committee approves that Beril EKER GÜMÜŞ be granted the degree of Doctor of Philosophy in Department of Mechanical Engineering on 17.01.2014................ (Resolution no: (2014/01-01)).

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**20.12.2013** Beril EKER GÜMÜŞ

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1990'ların ortalarından bu yana, sağlık ve çevre üzerindeki olumsuz etkileri nedeniyle kesme yağı kullanımını en aza indirmek veya ortadan kaldırmak için dünya çapında süregelen bir eğilim olmuştur. Maliyet, ekoloji ve insan sağlığı sorunları açısından bakıldığında, kesme sıvısının kullanılmadığı (dry turning) kuru tornalama ile kesme sıvısının en az ve yeterli şekilde kullanıldığı (Minimum Quantity Lubrication) MQL yöntemiyle tornalama potansiyel sürdürülebilir faydaları için ilgi kazanmıştır.

Bu çalışmada, minimum kesme sıvısı kullanılarak yapılan tornalama (MQL tornalama) performansı kuru koşullar ile karşılaştırılmıştır. Magnezyum alaşımlı malzeme ortogonal kesme uygulanarak şekillendirilmiştir. Her iki kesme işlemi için CNC torna tezgahı kullanılmıştır. Deney planı oluşturmak için Minitab 16 yazılımı kullanılmıştır. Bu çalışmada, iş parçası 230, 330 ve 430 m/dak kesme hızlarında, 0.20, 0.35 ve 0.50 mm/rev ilerleme oranlarında ve 1, 2, 3 mm kesme derinliklerinde tornalandı. Tornalama parametreleri Taguchi deneysel tasarım yöntemiyle tayin edildi. Taguchi Ortogonal dizinleri, sinyal gürültü oranı (S/N), varyans analizi (ANOVA), kesme hızı, ilerleme oranı, kesme derinliği seviyelerinin ve bunların kesme kuvvetleri, yüzey pürüzlülüğü, kesme sıcaklığı ve sertlik üzerindeki etkilerini kesme sıvısının kullanılmadığı (dry turning) kuru tornalama ile kesme sıvısının en az ve yeterli şekilde kullanıldığı Minimum Quantity Lubrication MQL yöntemiyle tornalama süresince analiz etmek için uygulanmıştır. Doğrulama testleri ile işleme parametrelerinin optimum seviyeleri Taguchi Optimizasyon yönteminin etkinliğini göstermek için yapılmıştır.


**Aralık, 2013** **Beril EKER GÜMÜŞ**

# ABSTRACT

## SUSTAINABLE MACHINING OF THE MAGNESIUM ALLOY MATERIALS IN THE CNC LATHE MACHINE AND OPTIMIZATION OF THE CUTTING CONDITIONS

Since the mid-1990s, there has been a continuing worldwide trend to minimize or eliminate the use of cutting fluids due to their adverse effects on health and the environment. From the viewpoint of cost, ecology and human health issues, dry and MQL turning have gained interest for their potential sustainable benefits.

In this study, MQL turning performance was compared to dry conditions. The magnesium based material was formed by applying the orthogonal cutting. The CNC Lathe was used for both cutting processes. The experiment used MINITAB 16 software to establish the experiment plan. In this study, workpiece was turned at cutting speeds of 230, 330 and 430 m/min, feed rates of 0.20, 0.35 and 0.50 mm/rev and cutting depth of 1, 2 and 3 mm. The settings of turning parameters were determined by using Taguchi experimental design method. Orthogonal arrays of Taguchi, the signal-to-noise (S/N) ratio, the analysis of variance (ANOVA) were carried out to determine the optimal levels and to analyze the effect of turning parameters such as cutting speed, feed rate, cutting depth on hardness, surface roughness, cutting temperature and cutting forces during dry and MQL turning. Confirmation tests with the optimal levels of machining parameters were performed to illustrate the effectiveness of Taguchi optimization method.

**December, 2013** **Beril EKER GÜMÜŞ**

# CLAIM FOR ORIGINALITY

## SUSTAINABLE MACHINING OF THE MAGNESIUM ALLOY MATERIALS IN THE CNC LATHE MACHINE AND OPTIMIZATION OF THE CUTTING CONDITIONS

Magnesium is in the strategic material category and has a large reserve in our country. Magnesium is a sustainable metal due to the following benefits. It's perfectly recyclable. The energy needed for the process of magnesium recycling is much lower than every other material. Magnesium is the lightest of all design metals. Magnesium automobile parts reduce the weight of trucks and cars which makes for less use of oil and less air pollution.The machining of magnesium material in an economic way, and without giving any harm to the environment is significant. Most machining of magnesium alloys can be done dry and it is also a suitable material for minimum quantity lubrication

Cutting conditions in a machining operation consist of cutting speed, feed rate, depth of cut, and cutting fluid supply strategies. Turning is greatly influenced by cutting conditions. These cutting conditions have significant effects on the quality of the machined parts. It is very important to investigate the influence of the cutting conditions on the mechanical characteristics of turned parts and for sustainable production . In recent years, the application of cutting fluids in machining operations has attracted immense scrutiny due to their adverse effects on health and the environment. In this study, sustainable machining processes such as Minimum Quantity lubrication and dry turning are chosen.

In spite of all their economic and environmental benefits, to make an informed decision, a direct comparison is needed between dry and MQL turning in terms of the quality of turned parts. There have not been any studies reporting a direct comparison between dry and MQL turning for magnesium material in terms of machining performance characteristics such as cutting force, cutting temperature and the quality characteristics of turned parts such as surface roughness, hardness. The purpose of this research is to study the effects of minimum quantity lubrication condition on the cutting performance of magnesium alloy, as compared to completely dry cutting.

**December, 2013 Assoc. Prof. Dr. Bülent EKİCİ Beril EKER GÜMÜŞ**

# LIST OF SYMBOLS

| | |
|---|---|
| $\bar{y}$ | : Signal factors |
| **ρ** | : Density |
| $\mu_a$ | : Average friction coefficient on the rake face |
| **ϕc** | : Shear angle |
| **b** | : Width of cut |
| **c** | : Specific heat |
| **d** | : Depth of cut |
| $D_f$ | : Final diameter |
| $D_o$ | : Original diameter of the part |
| $F_f$ | : Feed force |
| $F_n$ | : The normal force acting on the shear plane |
| **fr** | : Feed rate |
| $F_s$ | : Shear force |
| $F_t$ | : Tangential cutting force |
| $F_u$ | : Friction force |
| $F_v$ | : Normal force |
| **G** | : Generatrices |
| **k** | : heat conductivity |
| **L** | : Length of the cylindirical workpart |
| **N** | : Rotational speed |
| **r** | : Nose radius of the used tool |
| $R_a$ | : Arithmetic mean value of roughness |
| **S/N** | : Signal To Noise Ratio |
| $s^2$ | : Noise factors |
| $T_m$ | : Machining time |
| **V** | : Cutting velocity |

## ABBREVIATIONS

| | |
|---|---|
| **AA** | : Arithmetic Average |
| **ANOVA** | : Analysis of Variance |
| **BUE** | : Build up edge |
| **CI** | : Confidence Interval |
| **DOE** | : Design of Experiments |
| **DOF** | : Degree of Freedom |
| **DPH** | : Diamond Pyramid Hardness |
| **HV** | : Vickers Pyramid Number |
| **LIT** | : Lawrence Institute of Technology |
| **MQL** | : Minimum Quantity Lubrication |
| **MSD** | : Mean standard deviation |
| **NIST** | : National Institute of Science and Technology of the United States |
| **OA** | : Orthogonal Array |
| **RMR** | : Material removal rate |
| **SPC** | : Statistical Process Control |
| **TM** | : Taguchi Methods |
| **VW Beetle** | : Volkswagen Beetle |

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# CHAPTER 1

# INTRODUCTION

The idea of sustainability emerged in a series of meetings and reports in the 1970s and 1980s, and was largely spurred by environmental incidents and disasters, as well as fears about chemical contaminations and resource depletion.

The U.S. Department of Commerce (DOC) defines sustainable manufacturing as :

The creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound.

A technical version of the sustainable manufacturing definition is as follows:

"Sustainable manufacturing is a systems approach for the creation and distribution (supply chain) of innovative products and services that: minimizes resources (inputs such as materials, energy, water, and land); eliminates toxic substances; and produces zero waste that in effect reduces green house gases, e.g., carbon intensity, across the entire life cycle of products and services."

Based on the early work by Wanigarathne et al., Jawahir and Dillon proposed six major elements as significantly affecting the sustainability of manufacturing processes, as shown in Figure 1.1. Among these, manufacturing cost, energy consumption, and waste management can be considered as deterministic elements, while environmental impact, personnel health, and operator safety may not be readily or uniquely established by manufacturing system parameters.

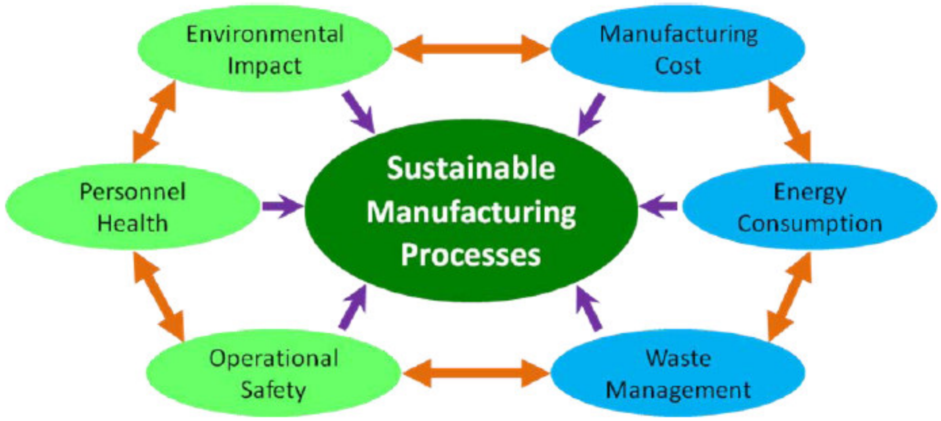


**Figure 1.1** Six elements of sustainable manufacturing processes[1]

The global environmental problems caused by the consumption of natural resources and the pollution resulting from the life of technical products have led to increasing political pressure and stronger regulations being applied to both the manufacturers and users of such products. The industries involved in production are additionally under economic pressure, and are attempting to compensate for increasing costs and create added value for their products. The adoption of sustainable development in production offers industry a cost effective route to improving economic, environmental, and social performance.

Turning operations can be classified into different types, such as dry turning , turning with minimum quantity lubrication (MQL), flood turning, and cryogenic turning. Of these, flood turning is the most traditional technique and by far the most widely used in industry. The process is characterized by the application of a large quantity of liquid, known as cutting fluid, at the cutting tool and workpiece interface. In machining operations, cutting fluid is applied for a number of reasons, such as to reduce the cutting temperature, to lengthen the tool life, to produce a better surface finish, to improve dimensional accuracy, and to facilitate chip disposal. However, the cutting fluids cause several negative effects of ecological, environmental and economical aspects. When cutting fluids inappropriately discharged, they may damage water and soil resources.On the shop floor, the workers may have respiratory and skin problems.This in turn means more economic problems for manufacturing companies.  It has been reported that 15%

of the total machining costs are due to the use of cutting fluids emulsions, while percentage of tool costs is a lot lower; around 4%. Typical flow rates are 5 to 50 ml/hr for MQL, compared to typical flood cooling where around 10 l/min can typically be dispensed. With simply avoiding the cutting fluids usage and applying dry machining alternatives, with new high performance coated cutting tools, there would be a huge process gain from sustainability point of view [2-3].

### 1.1 Aim of the Thesis

This study presents methods for achieving production sustainability on a machining technology level. In this study, sustainable machining processes such as Minimum Quantity lubrication and dry turning are chosen. CNC lathe was used for sustainable machining. Towards smart and competitive sustainable machining, CNC lathe will be used to optimize the machining process, where the raw material could be saved through First Part Correct technology, the energy could be saved through cutting speed optimization, and used parts could be saved by remanufacturing. In order to maximize sustainability performance, magnesium is selected as a workpiece material.

Magnesium is a sustainable metal due to the following benefits. It's perfectly recyclable. The energy needed for the process of magnesium recycling is much lower than every other material.The low density of magnesium(1.74 g/cm$^3$), which is approximately two-thirds that of aluminum (2.70 g/cm3) and one-fifth of iron (7.87 g/cm3), makes it attractive for applications where weight reduction is critical, for example, in the automotive, aerospace, and other industries. North American automotive manufactures have been constantly seeking new ways of increasing fuel efficiency of their vehicles by reducing the mass of the vehicles. Substitute steel or cast iron with magnesium alloys brings significant reduction in weight due to the lower density. Considering the large number of vehicles around, this weight saving could lead to a significant reduction of carbon dioxide released to the atmosphere. For this reason, automotive companies have been interested in replacing steel or cast iron components with those made of Mg wherever possible. Nowadays, most of the engine components such as block engine, upper valve components and some chassis parts are made out of different magnesium alloys. Magnesium alloys offer good strength-to-weight ratio, machinability, and corrosion resistance. The machinability of magnesium alloys has been reported to be good and characterized by low cutting force and well broken chips. Nevertheless, dry machining is exceedingly difficult because the reaction between magnesium and atmospheric air causes ignition of fine particles .

The purpose of this research is to study the effects of minimum quantity lubrication condition on the cutting performance of magnesium alloy, as compared to completely dry cutting. In the study, the minimum quantity lubrication is provided with a spray of air and mineral oil. During each test, cutting temperature, hardness, cutting forces and surface roughness are measured and compared.

The aim of this part is to provide a general perspective on the sustainable machining of the magnesium alloy materials in the CNC lathe machine and optimization of the cutting conditions. In order to accomplish this task, first, the general backround of the cutting conditions in turning, the fundamentals of cutting mechanics and magnesium as a workpiece material has been given. This chapter also presents a literature survey about Taguchi Methods and its application to several problems.

Chapter 2 of the thesis presents experimental set up, the procedure and the solution of the thesis problem in detail.

Chapter 3 presents the results obtained in this research. In this chapter, results obtained are also discussed and evaluated.

Conclusion and future recommendation are presented in Chapter 4.

Existing research works utilized in the thesis are listed in the References.

## 1.2 Literature Review

Papers relating to minimum quantity lubrication and dry turning of the magnesium material are limited and have appeared in technical literature only recently. Most documented studies thus far concerning MQL are built upon experimental observations with individual and separate treatment of machining performance measures such as cutting force, cutting temperature, tool wear progress, chip formation, surface roughness, or air quality [4].

M. Villeta et al.[5-10] reported that the process parameter with the greatest influence on the surface finish was feed rate. In fact, feed rate had a contribution to the variability of the surface roughness of around 84%. Lower feed rates led to better surface finish on the magnesium workpieces. The process parameters of tool coating, cutting speed, and the interaction of cutting speed with tool coating were also influential but to a lesser extent, tools for steels (TP200 and TK2000) were better than tools for non-ferrous alloys (HX), which is useful when considering inserts. The remaining interactions considered (feed rate with cutting speed and feed rate with tool coating) had no significant influence on the surface roughness. The combinations of cutting parameter levels and tool coatings that achieved the optimal surface finish were as follows: 0.05 mm/rev-150m/min-HX, 0.05 mm/rev- 225m/min-HX, 0.05 mm/rev-150 m/min-TP200, and 0.05 mm/rev-225 m/min-TK2000. The best dry turning process was obtained with these combinations, which seem to have insignificant statistical differences from each other . The optimal combinations of cutting conditions led to an expected optimal value for the average roughness Ra between 0.306 µm and 0.406 µm with 95% confidence.Moreover, the variation of the surfaceroughness depending on the length mechanized (L) and the generatrices (G), it does not present significant variations.Interaction between the tool and the length of mechanized is not meaningful as suggesting other preliminary work. However, before generalising these results, it will be necessary to prove that this occurs, as well, for other bigger depths of cut and lengths of pieces. Magnesium presents problems with the heat generated in the machining process, since it has a tendency to be flammable. In process of machining pieces of magnesium and in particular in pieces with inserts of steel or stainless steel is especially critical due to both the heat generated during the machining process that can make the magnesium burn, and the sparks generated in the machining of steels at cutting speeds up to 200-300m/min that can cause the ignition of chips or dust of the magnesium.

The widespread expression to estimate the surface roughness in turning processes using tools with round nose comes represented by the following equation.

$$Ra_{ideal} = 0.032\, f^2 / r \qquad (1.1)$$

$Ra_{ideal}$ is the surface roughness ideal, f is the feed and r is the nose radius of the used tool in the mechanized.

The cutting properties of magnesium alloy AZ91D when dry turning with kentanium cutting tools are presented by Xuhong Guo and the others.They reported that the cutting depth was the main influence factor on cutting force, followed by feed rate f and cutting speed v . The main form of tool wear showed to be diffusive wear and adhesive wear. The feed rate f had the main influence on chip form and the workpiece surface roughness, cutting speed v was less effective, the cutting depth was the least [11].

Magnesium is usually easy to machine; cutting forces are about 50% lower compared to the turning of aluminium. Tool wear for this reason can hardly be observed; magnesium shows the prerequisite for high-speed machining. However, if the cutting speed exceeds a critical value, adhesive effects between cutting tool material and workpiece material are observed for certain tool material-workpiece combinations in dry machining.The formation of flank build-up leads to unsteady machining forces and an inferior surface quality. Due to its high thermal expansion coefficient, dry machining also leads to a loss of shape accuracy of the machined part. Friemuth and Winkler reported that DP cutting tools show a superior behavior in dry machining magnesium alloys compared to uncoated and TiN-coated cemented carbide tools. Adhesion between cutting tool and workpiece material, as well as material build-up, can best be avoided if diamond coatings are used. Because machining forces are low when using DP tools, the chip temperature and therefore the danger of chip ignition can be reduced. When machining magnesium-based MMC, DP-tipped tools are preferred because they have the best resistance against abrasion.[14-18]

According to researchers [17-21] the cutting performance of MQL machining is better than that of dry cutting for steels. MQL reduced cutting force significantly because of reduced cutting temperature due to improved tool-chip interaction. Minimum quantity lubrication enabled favorable change in the chip–tool and work–tool interactions, which helped in reducing friction, built-up edge formation, thermal distortion of the work, wear of the cutting tool, surface roughness and dimensional deviation. Dimensional accuracy also substantially improved mainly due to significant reduction of wear and damage at the tool tip by the application of MQL. Surface finish of the turned piece was also improved with MQL cutting compared to dry cutting. The analysis of chip morphology reveals that cutting temperature was lower while cutting with MQL compared to dry cutting. Therefore, it appears that MQL, if properly employed, not only provides environment friendliness but can also improve the machinability characteristics.

Sreejith P.S. studied turning of 6061 aluminium alloy under different conditions of dry, MQL and flooded coolant/lubricant using diamond-coated carbide inserts. It was seen that the application of coolant does not necessarily reduce tool wear since at MQL conditions the tool wear was found to be lower, but the amount of coolant determines the material adhesion on the tool surface. The cutting forces were found to be dependent on the coolant system. For improving the quality of the work-piece surface, coolant is necessary [22].

### 1.3 General Backround

#### 1.3.1 Cutting Conditions In Turning

One of the practical problems in machining is selecting the proper cutting conditions for a given operation. Given the work material and tooling, the selection of these conditions is very influential in determining the success of a machining operation.

Cutting conditions in a machining operation consist of speed, feed, depth of cut, and cutting fluid (whether a cutting fluid is to be used and, if so, what type of cutting fluid) A cutting fluid is often applied to the machining operation to cool and lubricate the cutting tool . Determining whether a cutting fluid should be used, and, if so, choosing the proper cutting fluid, is usually included within the scope of cutting conditions. Tooling considerations are usually the dominant factor in decisions about cutting fluids.

The feed of a cutting tool in a lathe work is the tool advances for each revolution of the work. Feed is expressed in millimetre per revolution. Increased feed reduces cutting time. The depth of cut is the perpendicular distance measured from the machined surface to the uncut surface of the work piece. Cutting speed (v) of the tool is the speed at which the metal is removed by the tool from work piece.

Depth of cut is often predetermined by workpiece geometry and operation sequence. Many jobs require a series of roughing operations followed by a final finishing operation. In the roughing operations followed by a final finishing operation. In the roughing operations, depth is made as large as possible within the limitations of available horsepower, machine tool and setup rigidity, strength of the cutting tool, and so on. In the finishing cut, depth is set to achieve the final dimensions for the part. The problem then reduces to selection of feed and speed. In general, values of these parameters should be decided in the order: feed first, speed second. Determining the appropriate feed rate for a given machining operation depends on the following factors:

- Tooling. What type of tooling will be used? Harder tool materials (e.g. cemented carbides, ceramics, etc.) tend to fracture more readily than high speed steel. These tools are normally used at lower feed rates. HSS can toleratebhigher feeds because of its greater toughness.
- Roughing or finishing. Roughing operations involve high speeds, typically 0.5 to 1.25 mm/rev for turning, finishing operations involve low feeds, tpically 0.125 to 0.4 mm/rev for turning.
- Constraints on feed in roughing. If the operation is roughing, how high can the feed rate be set? To maximize metal removal rate, feed should be set as high as possible. Upper limits on feed are imposed by cutting forces, setup rigidity, and sometimes horsepower.
- Surface finish requirements in finishing. If the operation is finishing, what is the desired surface finish? Feed is an important factor in surface finish, and computations can be used to estimate the feed that will produce a desired surface roughness.

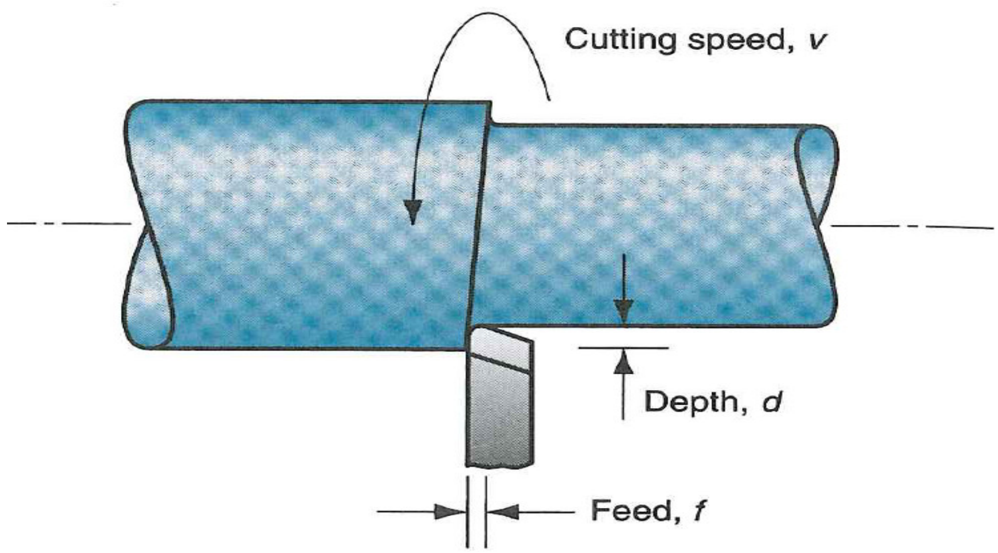


**Figure 1.2** Cutting speed, feed and depth of cut for a turning operation

Selecting of cutting speed is based on making the best use of the cutting tool, which normally means choosing a speed that provides a high metal removal rate yet suitably long tool life. Mathematical formulas have been derived to determine optimal cutting speed for a machining operation, given that the various time and cost components of the operation are known. The original derivation of these machining economics equations is credited to W. Gilbert. The formulas allow the optimal cutting speed to be calculated for either of two objectives (1) maximum production rate or (2) minimum unit cost. Both objectives seek to achieve a balance between material removal rate and tool life. The formulas are based on the Taylor tool life equation that applies to the tool used in the operation, as well as feed, depth of cut, and work material.

Turning is a machining process in which a single-point tool removes material from the surface of a rotating workpiece. The tool is fed linearly in a direction parallel to the axis of rotation to generate a cylindrical geometry. Turning is traditionally carried out on a machine tool called a lathe, which provides power to turn the part at a given rotational speed and to feed the tool at a specified rate and depth of cut.

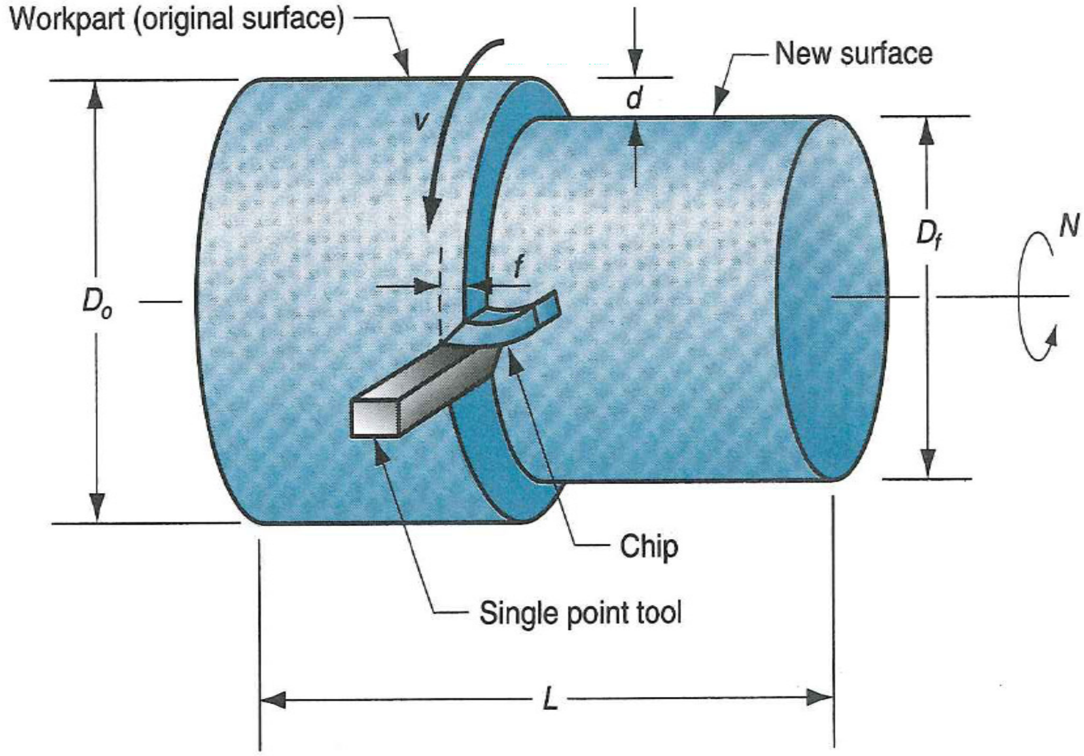


**Figure 1.3** Turning Operation

The rotational speed in turning is related to the desired cutting speed at the surface of the cylindrical workpiece by the equation:

$$N = \frac{v}{\pi D_0} \quad (1.2)$$

where N =rotational speed, rev/min; v =cutting speed, rn/rnin; and Do= original diameter of the part, m.

The turning operation reduces the diameter of the work from its original diameter $D_o$ to a final diameter $D_f$, as determined by the depth of cut d:

$$D_f = Do - 2d \quad (1.3)$$

The feed in turning is generally expressed in mm/rev. This feed can be converted to a linear travel rate in mm/min by the formula:

$$f_r = Nf \quad (1.4)$$

where fr = feed rate, mm/min; and f = feed, mm/rev.

The time to machine from one end of a cylindrical workpart to the other is given by:

$$T_m = \frac{L}{f_r} \quad (1.5)$$

Where $T_m$ = machining time, min, and L= length of the cylindirical workpart, mm. A more direct computation of the machining time is provided by the following equation:

$$T_m = \frac{\pi D_0 L}{f v} \quad (1.6)$$

Where $D_0$= work diameter, mm, L= work part length, mm, f=feed, mm/rev, and v= cutting speed, mm/min. As a practical matter, a small distance is usually added to the work part length at the beginning and end of the piece to allow for approach and over travel of the tool. Thus, the duration of the feed motion past the work will be longer than $T_m$.

Speed, feed, and depth of cut can be used to calculate the material removal rate for the process:

$$RMR = vfd \quad (1.7)$$

where RMR =material removal rate, $mm^3/min$ , v =cutting speed, m/min , which must be converted to mm/s ; f = feed, mm/min ; and d = d depth of cut, mm. In using this equation, the units for f are expressed simply as mm, in effect neglecting the rotational character of turning [23-26].

### 1.3.2 The Fundamentals of Cutting Mechanics

#### 1.3.2.1 Mechanics of Metal Cutting

Machining is found in every engineering workpiece. Every workpiece should be machinable to certain degree. Machining creates geometric shapes, tolerances and surface finish unobtainable by other techniques. Machining is to generate the shape of the workpiece from a solid body or to improve the tolerances and surface finish of previously formed workpiece, by removing excess material in the form of chip. The machining operations can be classified under two major categories: cutting and grinding processes. The cutting operations are used to remove material from the blank. The subsequent grinding operations provide a good surface finish and precision dimensions to the part. The most common cutting operations are turning, milling, and drilling followed by special operations such as boring, broaching, hobing, shaping, and form cutting. However, all metal cutting operations share the same principles of mechanics, but their geometry and kinematics may differ from each other. Shortly, metal cutting is the process of removing excess material from a workpiece by a harder tool through a process of extensive plastic deformation or controlled fracture. Machinability refers the ease a workpiece can be machined. Machinability is related to tool life, surface finish, forces and power, and type of chip.

#### 1.3.2.2 Mechanics Of Orthogonal Cutting

The simple case of two-dimensional orthogonal cutting is used to explain the general mechanics of metal removal. In orthogonal cutting, the material is removed by a cutting edge that is perpendicular to the direction of relative tool-workpiece motion.

Schematic representation of orthogonal cutting process is shown in Figure 1.4 . The orthogonal cutting resembles a shaping process with a straight tool whose cutting edge is perpendicular to the cutting velocity (V). A metal chip with a width of cut (b) and depth of cut (h) is sheared away from the workpiece. In orthogonal cutting, the cutting is assumed to be uniform along the cutting edge; therefore it is a two-dimensional plane strain deformation process without side spreading of the material. Hence, the cutting forces are exerted only in the directions of velocity and uncut chip thickness, which are called tangential ($F_t$) and feed forces ($F_f$).

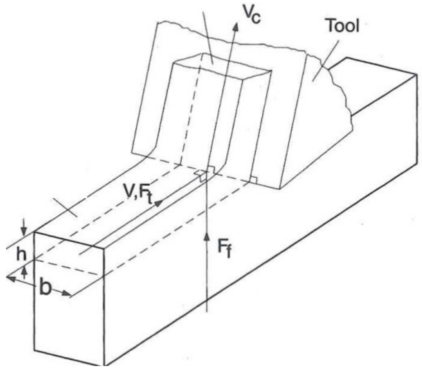


**Figure 1.4** Orthogonal cutting geometry

There are three deformation zones in the cutting process. As the edge of the tool penetrates into the workpiece, the material ahead of the tool is sheared over the primary shear zone to form a chip. The sheared material, the chip, partially deforms and moves along the rake face of the tool, which is called the secondary deformation zone. The friction area, where the flank of the tool rubs the newly machined surface, is called the tertiary zone. The chip initially sticks to the rake face of the tool, which is called the sticking region. The friction stress is approximately equal to the yield shear stress of the material at the sticking zone where the chip moves over a material stuck on the rake face of the tool. The chip stops sticking and starts sliding over the rake face with a constant sliding friction coefficient. The chip leaves the tool, losing contact with the rake face of the tool. The length of the contact zone depends on the cutting speed, tool geometry, and material properties. There are basically two types of assumptions in the analysis of the primary shear zone. Merchant developed an orthogonal cutting model by assuming the shear zone to be a thin plane. Others, such as Lee and Shaffer and Palmer and Oxley based their analysis on a thick shear deformation zone, proposing "shear angle prediction" models in accordance with the laws of plasticity.In this text, the primary shear deformation zone is assumed to be a thin zone for simplification.

The cutting forces are shown on the cross-sectional view of the orthogonal cutting process (see Figure 1.5). It is assumed that the cutting edge is sharp without a chamfer or radius and that the deformation takes place at the infinitely thin shear plane. The shear angle $\phi_c$ is defined as the angle between the direction of the cutting speed (V) and the shear plane. The resultant force (F) on the chip, applied at the shear plane, is in equilibrium to the force (F) applied to the tool over the chip-tool contact zone on the rake face; an average constant friction is assumed over the chip-rake face contact zone. From the force equlibrium, the resultant force F is formed from the feed $F_f$ and tangential $F_t$ cutting forces.

$$F = \sqrt{F_t^2 + F_f^2} \tag{1.8}$$

The feed force (or thrust force) is in the direction of uncut chip thickness and the tangential cutting force (or power force) is in the direction of cutting velocity. The cutting forces acting on the tool will have equal amplitude but opposite directions with respect to the forces acting on the chip.

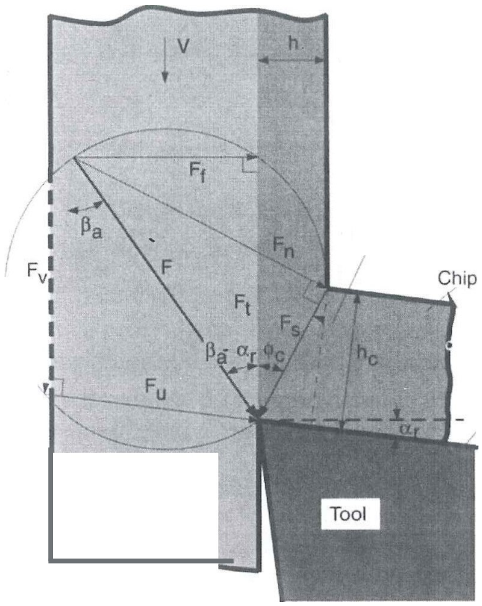


**Figure 1.5** Cutting force diagram

The shear force can be expressed as a function of the feed and tangential cutting forces:

$F_s = F_t \cos\phi_c - F_f \sin\phi_c$ (1.9)

Similarly, the normal force acting on the shear plane is found to be

$F_n = F_t \sin\phi_c + F_f \cos\phi_c$ (1.10)

There are two components of the cutting force acting on the rake face of the tool, the normal force $F_v$

$F_v = F_t \cos\alpha_r - F_f \sin\alpha_r$ (1.11)

and the friction force $F_u$ on the rake face,

$F_u = F_t \sin\alpha_r + F_f \cos\alpha_r$ (1.12)

In the orthogonal cutting analysis shown here, it is assumed that the chip is sliding on the tool with an average and constant friction coefficient of μa In reality, the chip sticks to the rake face for a short period and then slides over the rake face with a constant friction coefficient[27] . The average friction coefficient on the rake face is given as

$$\mu_a = \tan \beta_a = \frac{F_u}{F_v} \tag{1.13}$$

**1.3.2.3 Surface Quality**

Machining aims to create a part with required geometry, dimensions and dimensional tolerances. For proper function of part, surface finish is also prescribed. Surface must also be free of cracks, residual stresses and must not have undesirable metallurgical changes. With respect to Figure 1.6, surface roughness can be defined as the average of the vertical deviations from the nominal surface over a specified surface length. An arithmetic average (AA) is generally used, based on the absolute values of the deviations, and this roughness value is referred to by the name average roughness. In equation form,

$$R_a = \int_0^{L_m} \frac{|y|}{L_m} dx \tag{1.14}$$

Where Ra= arithmetic mean value of roughness, m (in), y = the vertical deviaton from nominal surface ( converted to absolute value), m((in), and $L_m$= the specified distance over which the surface deviations are measured. An approximation of Equation 1.14, perhaps easier to comprehend, is given by

$$R_a = \sum_{i=1}^{n} \frac{|y_i|}{n} \tag{1.15}$$

where Ra has the same meaning as above; yi = vertical deviations converted to absolute value and identified by the subscript i, m (in); and n =the number of deviations included in Lm. The units in these equations are meters and inches. In fact, the scale of the deviations is very small, so more appropriate unit is μm (μm= m x $10^{-6}$ = mm x $10^{-3}$). This is the unit commonly used to express surface roughness.

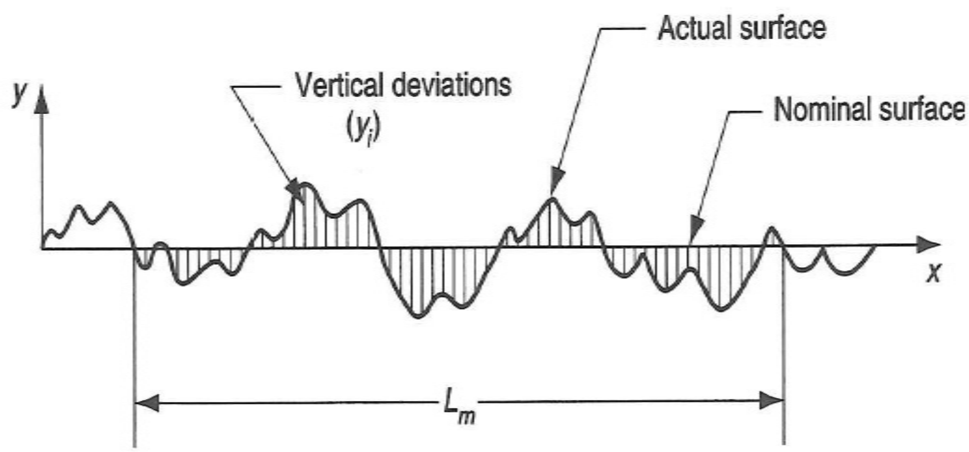


**Figure 1.6** Deviations from nominal surface used in the definition of surface roughness [23]

Surface roughness suffers the same kinds of deficiencies of any single measure used to assess a complex physical attribute. For example, it fails to account for the lay of the surface pattern; thus, surface roughness may vary significantly depending on the direction in which it is measured.

Another deficiency is that waviness can be included in the Ra computation. To deal with this problem, a parameter called the cutoff length is used as a filter that separates the waviness in a measured surface from the roughness deviations. In effect, the cutoff length is a sampling distance along the surface. A sampling distance shorter than the waviness width will eliminate the vertical deviations associated with waviness and only include those associated with roughness. The most common cutoff length used in practice is 0.8 mm . The measuring length Lm is normally set at about five times the cutoff length. The limitations of surface roughness have motivated the development of additional measures that more completely describe the topography of a given surface.

Surface Roughness when a tool of corner radius R moved over a surface with feed f, the ideal transverse roughness can be calculated as follows,

$$R_{max} = \frac{f^2}{8R} \quad (1.16)$$

$$R_a = \frac{R_{max}}{4} = \frac{f^2}{32R} \quad (1.17)$$

In longitudinal direction, ideal roughness is zero. In actual cutting, other roughness creating factors are intoduced into the workpiece

1. Cuttting in low speeds with discontinuous chips, cracks develop perpendicular to cutting direction
2. Cutting with Buid up Edge BUE, some particles are welded on the workpiece surface. Ceramic and diamond tools generally produce a better surface finish than other tools, largely because of their much lower tendency to form a BUE.
3. Cutting with no BUE and continuous chip comes close to ideal, but localized wear or chipping of tool edge causes roughness
4. Chatter introduces variations in surface geometry
5. Surface finish changes with wearing of tool.

A dull tool has a large radius along its edges, just as the tip of dull pencil or the cutting edge of a knife. Figure 1.7 illustrates the relationship between the radius of the cutting edge and the depth cut in orthogonal cutting. Note that at small depths of cut, the rake angle effectively can become negative and the tool simply may ride over the workpiece surface instead of cutting it and producing chip . This is a phenomenon similar to trying to scrape a thin layer from the surface of a stick of butter with a dull knife.

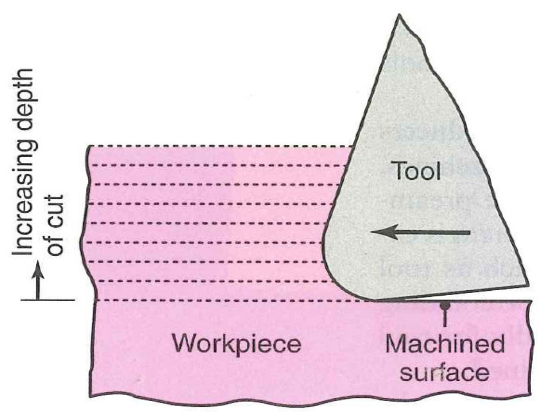


**Figure 1.7** Schematic illustration of a dull tool with respect to the depth of cut in orthogonal machining [25].

Note that the tool has a positive rake angle effectively can become negative. The tool then simply rides over the workpiece ( without cutting ) and burnishes its surface, this action raises the workpiece temperature and causes surface residual stresses.

If the tip radius of the tool is large in relation to the depth of cut, the tool simply will rub over the machined surface. Rubbing will generate heat and induce residual surface stresses, which in turn may cause surface damage, such as tearing and cracking. Consequently, the depth of cut should be greater than the radius on the cutting edge.

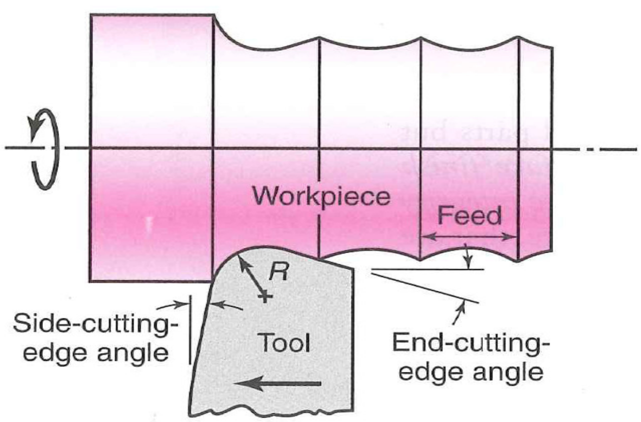


**Figure 1.8** Schematic illustration of feed marks on a surface being turned (exaggerated) [25].

In a turning operation, as in other cutting processes, the tool leaves a spiral profile (feed marks) on the machined surface as it moves across the workpiece, as shown in Figure 1.7 and Figure 1.8 . We can see that the higher the feed, f, and the smaller the tool nose radius, R, the more prominent these marks will be.

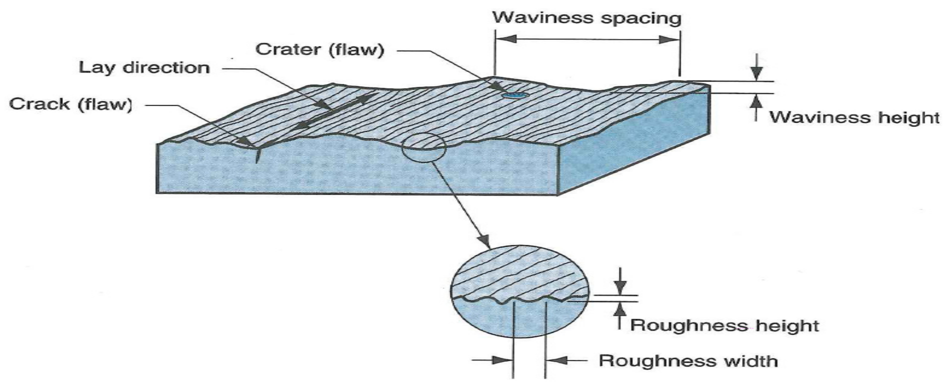


**Figure 1.9** Surface texture features [23]

Surface texture consists of the repetitive and/or random deviations from the nominal surface of an object; it is defined by four features: roughness, waviness, lay, and flaws, shown in Figure 1.9 . Roughness refers to the small, finely spaced deviations from the nominal surface that are determined by the material characteristics and the process that formed the surface. Waviness is defined as the deviations of much larger spacing; they occur because of work deflection, vibration, heat treatment, and similar factors. Roughness is superimposed on waviness. Lay is the predominant direction or pattern of the surface texture. It is determined by the manufacturing method used to create the surface, usually from the action of a cutting tool. Figure presents most of the possible lays a surface can take, together with the symbol used by a designer to specify them. Finally, flaws are irregularities that occur occasionally on the surface; these include cracks, scratches, inclusions, and similar defects in the surface. Although some of the flaws relate to surface texture, they also affect surface integrity .

Surface roughness is a measurable characteristic based on the roughness deviations defined above. Surface finish is a more subjective term denoting smoothness and general quality of a surface. In popular usage, surface finish is often used as a synonym for surface roughness.The most commonly used measure of surface texture is surface roughness. Surface roughness represents a key quality characteristic in machining processes and uses to be a technical requirement for products. The surface roughness formation process is of a complex nature and is affected by different factors; therefore, it is difficult to ensure that requirements will be satisfied[23-25]. Surface roughness is often affected by multiple factors, such as cutting speed, feed rate, depth of cut, workpiece material, workpiece length, tool nose radius, cutter geometry, cutter runout, flank, coolant, environmental temperature, and rake angle. Surface roughness refers to deviation from the nominal surface of the third up to sixth order. Order of deviation is defined in international standards.First and second order deviations refer to form, i.e. flatness, circularity, etc. and to waviness, respectively, and are due to machine tool errors, deformation of the workpiece, erroneous setups and clamping, vibration and workpiece material inhomogenities. Third and fourth order deviations refer to periodic grooves, and to cracks and dilapidations, which are connected to the shape and condition of the cutting edges, chip formation and process kinematics. Fifth- and sixth-order deviations refer to workpiece material structure, which is connected to physical–chemical mechanisms acting on a grain and lattice scale (slip, diffusion, oxidation, residual stress, etc.). Different order deviations are superimposed and form the surface roughness profile, see Figure 1.10[14].

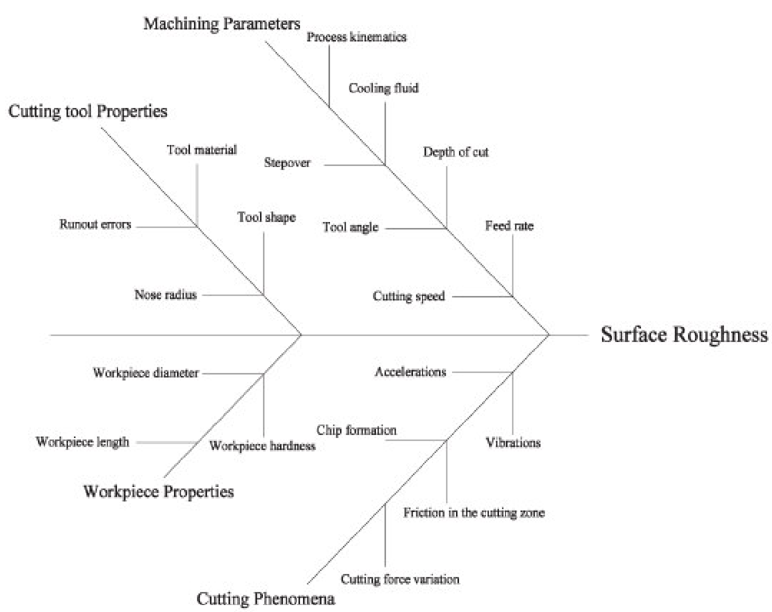


**Figure 1.10** Fishbone diagram with the parameters that affect surface roughness [14].

Finally, the set of parameters that are thought to influence surface roughness and thus have been investigated by the researchers, is diagrammatically displayed in Figure 1.10.

#### 1.3.2.4 Hardness

The Metals Handbook defines hardness as "Resistance of metal to plastic deformation, usually by indentation. However, the term may also refer to stiffness or temper, or to resistance to scratching, abrasion, or cutting. It is the property of a metal, which gives it the ability to resist being permanently, deformed (bent, broken, or have its shape changed), when a load is applied. The greater the hardness of the metal, the greater resistance it has to deformation.

In mineralogy the property of matter commonly described as the resistance of a substance to being scratched by another substance. In metallurgy hardness is defined as the ability of a material to resist plastic deformation.

The dictionary of Metallurgy defines the indentation hardness as the resistance of a material to indentation. This is the usual type of hardness test, in which a pointed or rounded indenter is pressed into a surface under a substantially static load.

There are three types of tests used with accuracy by the metals industry; they are the Brinell hardness test, the Rockwell hardness test, and the Vickers hardness test. Since the definitions of metallurgic ultimate strength and hardness are rather similar, it can generally be assumed that a strong metal is also a hard metal. The way the three of these hardness tests measure a metal's hardness is to determine the metal's resistance to the penetration of a non-deformable ball or cone. The tests determine the depth which such a ball or cone will sink into the metal, under a given load, within a specific period of time. The followings are the most common hardness test methods used in today`s technology:

Rockwell hardness test

Brinell hardness

Vickers

Knoop hardness

Shore

Vickers Hardness Test

It is the standard method for measuring the hardness of metals, particularly those with extremely hard surfaces: the surface is subjected to a standard pressure for a standard length of time by means of a pyramid-shaped diamond. The diagonal of the resulting indention is measured under a microscope and the Vickers Hardness value read from a conversion table .

The Vickers hardness test was developed in 1921 by Robert L. Smith and George E. Sandland at Vickers Ltd as an alternative to the Brinell method to measure the hardness of materials. The Vickers test is often easier to use than other hardness tests since the required calculations are independent of the size of the indenter, and the indenter can be used for all materials irrespective of hardness. The basic principle, as with all common measures of hardness, is to observe the questioned material's ability to resist plastic deformation from a standard source. The Vickers test can be used for all metals and has one of the widest scales among hardness tests. The unit of hardness given by the test is known as the Vickers Pyramid Number (HV) or Diamond Pyramid Hardness (DPH). The hardness number can be converted into units of pascals, but should not be confused with a pressure, which also has units of pascals. The hardness number is determined by the load over the surface area of the indentation and not the area normal to the force, and is therefore not a pressure.

The hardness number is not really a true property of the material and is an empirical value that should be seen in conjunction with the experimental methods and hardness scale used.

The indenter employed in the Vickers test is a square-based pyramid whose opposite sides meet at the apex at an angle of 136º. The diamond is pressed into the surface of the material at loads ranging up to approximately 120 kilograms-force, and the size of the impression (usually no more than 0.5 mm) is measured with the aid of a calibrated microscope. The Vickers number (HV) is calculated using the following formula:

$$HV = \frac{1.854\,F}{D^2} \tag{1.18}$$

with F being the applied load (measured in kilograms-force) and $D^2$ the area of the indentation (measured in square millimetres). The applied load is usually specified when HV is cited. The Vickers test can be used for all metals and has one of the widest scales among hardness tests.

#### 1.3.2.4 Residual Stresses

In almost all manufacturing processes, residual stresses are present in semi-finished products and machine components. According to Figure 1.11, all the causes of residual stresses can be classified under the following three main groups: material, manufacturing, loading by service conditions [28].

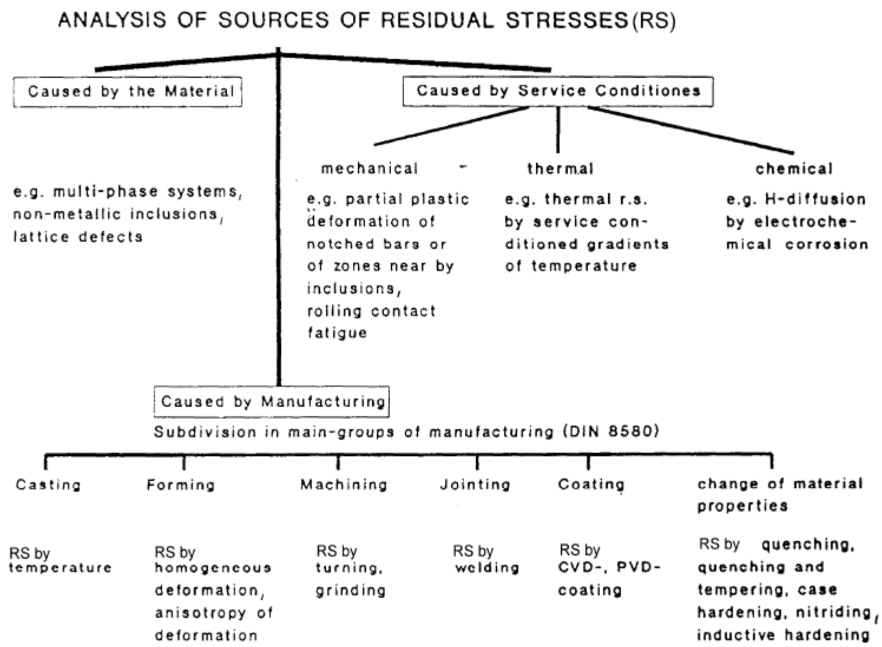


**Figure 1.11** All the causes of residual stresses can be classified under the following three main groups: material, manufacturing, loading by service conditions [28]

Internal stresses in the material, called residual stresses, have an effect similiar to an applied mean stress. Hence, compressive residual stresses are beneficial. Smoother surfaces that result from more careful machining in general improve resistance to fatigue, although some machining procedures are harmful, as they introduce tensile residual stresses. Various surface treatments may alter the microstructure, chemical composition, or residual stress of the surface and therefore affect the fatigue resistance [29].

Residual stresses in the surface layer may be caused by the following phenomena:

• plastic deformation due to mechanical influences;

• plastic deformation due to thermal gradient;

• phase transformation.

The total resulting residual stress depends on the balance between these three

factors.

In the past, the residual stresses resulting from machining have been investigated, and sufficient data is currently available. Earlier works reveal that the residual stress is very sensitive to material properties, especially hardness of the work-material. For example, when machining AISI 4340 steel, it was found that the surface residual stress is tensile at low hardness values and becomes more compressive as hardness increases.

Wu W. D., Matsumoto Y reported that shear angle is found to increase with material hardness. Large shear angles tend to make residual stress on the machined surface more compressive. The average stress ratio in the primary deformation zone decreases as hardness increases. This effect produces a more tensile residual stress on work-material. Temperature rise, although insensitive to hardness, causes the residual stress to become more tensile. As hardness increases, an increasing yield point results in a more tensile residual stress. These effects compete with each other and govern residual stress formation. From the experimental evidence presented in the paper, it is inferred that residual stress pattern is correlated most strongly to the shear angle effect. It therefore concludes that for machining various hardness of work-material the change in residual stress pattern is mainly caused by the change of the shear angle in the chip formation process [30-31].

An important factor related to the workpiece surface alteration occurring during machining is the residual stress distribution. Indeed, it can greatly affect the material's properties and its ability to withstand severe loading conditions (stress corrosion cracking, fatigue, . . .). The nature of residual stresses depends not only on machining parameters such as the cutting speed, feed rate, depth of cut, but also on the tool geometry and the lubrication conditions. Residual stresses resulting from metal removal processes have been studied for several decades. Henriksen attributed residual stresses mainly to mechanical effects caused by the forces acting on the tool during the cutting process, deeming thermal stresses due to heat generation to be negligible. However, another study performed by Okushima and Kakino showed that tensile residual stresses were caused by thermal effects and compressive residual stresses by mechanical effects related to the machining operation. The later results obtained by Liu and Barash tend to validate Henriksen's conclusions.

Recent works on carbon steel have also shown that the nature of the residual stresses produced on a machined surface is related to the material properties, especially its hardness. Matsumoto et al. showed that the residual stresses obtained from the machining of AISI 4340 steel are tensile for low hardness levels but become compressive as hardness increases. For the same material, Wu and Matsumoto showed that the residual stress pattern is linked to the orientation of the primary shear deformation zone in metal cutting. In most cases, a tensile residual stress state is found on the machined surface. Brinksmeier and Scholtes showed that the tensile residual stresses and the depth of the stressed region tend to increase with feed rate. Schreiber and Schlicht and Brinksmeier found that residual stresses increase with cutting speed. The use of a coolant at low cutting speeds reduces the maximum residual stress and the depth of the stressed region, when compared with the results obtained with dry cutting. Lubrication does not seem to have any significant influence on the residual stress distribution, when the cutting speed increases [32].

Fatigue life is an important dynamic property and it is strongly affected by the surface condition produced during machining. The fatigue crack, in general, nucleates at the surface of the part, and then propagates into the bulk. As the crack extends the resistant section is reduced, and when the residual section can no longer withstand the applied load component fatigue occurs. Consequently, it is the state of stress at the surface, where the crack nucleates, that is of paramount importance. This state is the sum of the stress due to the applied load and of the residual stresses (or self stresses) generated during machining. Residual stress is the result of various mechanical and thermal events, which occur in the surface region during machining. It is usually found that the absolute value of the residual stress close to surface it high and decreases continuously with an increase in depth beneath the machined surface eventually vanishing. Residual stress may be tensile or compressive and the stressed layer may be shallow or deep, depending upon the cutting conditions, work material, and tool geometry. It has been shown that residual stresses may be compressive at the surface and tensile just below the surface or vice versa. Compressive residual stresses are generally improve component performance and life because they reduce service (working) tensile stresses and inhibit crack nucleation. On the other hand, tensile residual stresses can significantly increase service (working) stresses which can lead to premature failure of components . The maximum residual stresses always occur beneath the machined surface rather than on the nearest layer to the machined surface [32].

S.Agrawal and S.S. Joshi developed an analytical model to predict the residual stresses in orthogonal machining of AISI4340 steel.The model incorporates (i) stresses in three contact regions viz. shear, toolnose- work piece and tool flank and machined surface regions, (ii) machining temperature, (iii) strain, strain rate and temperature dependent work material properties, (iv) plastic stresses evaluation by two algorithms, S-J and hybrid, (v) relaxation procedure and (iv) cutting conditions. The model benchmarking with the experimental results show that the predicted values of the residual stresses are in good (86–88%) agreement with the experimental values in the X- and Y-directions. In general, the machining induced residual stresses are tensile on the machined surface and are compressive beneath the machined surface. The residual stress is greatly affected by the process parameters such as feed, cutting speed, machining temperature and tool design parameters, such as edge radius. These parameters affect the model results and show that: The tensile residual stresses on the machined surface decrease with an increase in the edge radius. However, the compressive residual stresses below the machined surface increase with an increase the edge radius. The tensile residual stresses on machined surface increase with an increase in the cutting speed. It is observed that the tensile residual stresses on the machined surface increase when thermal aspects of machining are considered. As the depth of cut increases, the tensile residual stresses on the machined surface reduce. Comparison of model results with that a model from the literature shows that the proposed model with hybrid algorithm predicts the residual stresses more accurately at the lower feed rate. However, the model with S-J algorithm gives better prediction at the higher feed rate. All the predictions are closer to the experimental values than those predicted by the model in the literature. Nevertheless, the gaps in the experimental and predicted values point to the opportunity for the future work. The gap may be reduced by better definition of the physical phenomena at tool chip, tool-work and tool edge radius interfaces in a machining process [33-36].

**1.3.2.6 Cutting Temperature**

Of the total energy consumed in machining, nearly all of it ( ~98%) is converted into heat. This heat can cause temperatures to be very high at the tool chip interface over 600 $^{o}$C is not unusual. The remaining energy (~ 2%) is retained as elastic energy in the chip.

Temperature rise is a very important factor in machining because of its major adverse effects, such as the following:

- Reduce tool life: Excessive temperature lowers the strength, hardness, stiffness, and wear resistance of the cutting tool; tools also may soften and undergo plastic deformation; thus, tool shape is altered.
- Increased heat causes uneven dimensional changes in the part being machined making it difficult to control its dimensional accuracy and tolerances.
- An excessive temperature rise can induce thermal damage and metallurgicaI changes in the machined surface, adversely affecting its properties.
- Produce hot chips that pose safety hazards to the machine operator.

The main sources of heat in machining are: (a) the work done in shearing in the primary shear zone, (b) energy diss: pated as friction at the tool-chip interface, and (c) heat generated as the tool rub against the machined surface, especially for dull or worn tools. Detailed calculations show that the maximum temperature is developed at the rake face some distance away from the tool nose but before the chip lifts away.

A rough estimate of temperatures may be obtained by dimensional analysis, assuming that all energy E is converted into heat. Then the mean tool face temperature $T_T$ is

$$T_T = E\left(\frac{vh}{k\rho c}\right)^{1/2} \qquad (1.19)$$

where E is elasticity modulus, k is heat conductivity, ρ density, and c specific heat (heat content per unit volume) of the workpiece material.

Cutting stronger materials increases $T_T$

Cutting low heat conducting materials increases $T_T$

Cutting at high speeds increases $T_T$

An expression for the mean temperature in turning on a lathe is given by

$$T_{mean} \alpha V^a f^b \qquad (1.20)$$

where Vis the cutting speed and f is the feed of the tool.

It has been estimated that 90 % of the energy is removed by the chip during a typical machining operation, with the rest by the tool and the workpiece[25-26].

**1.3.3 Workpiece Material**

In today's machining industries, it is important to achieve maximum productivity and high quality with minimum cost of production. Therefore, in the machining field, it is necessary to select the optimum cutting conditions regarding cutting speed, feed rate, depth of cut, etc. The optimization of these conditions is deeply related to the machinability of work materials. Therefore, it is essential to know the machinability, chemical composition, and mechanical property of a work material for efficient machining. In this study, magnesium is selected as a workpiece material.

**1.3.3.1 Magnesium and Magnesium Alloys**

Perhaps the most outstanding characteristic of magnesium is its density, 1.7 g/cm3 , which is the lowest of all the structural metals; therefore, its alloys are used where light weight is an important consideration. Magnesium is 33% lighter than aluminum. It is light in weight just like a plastic material and also tough like a metal [37].

Magnesium has an hexagonal close-packed crystal structure, is relatively soft, and has a low elastic modulus 45 x 103 MPa.

Magnesium is the eighth most abundant element in the earth's crust (average magnesium content, 2.1%) by weight. Magnesium does not occur in nature in elemental form but in the form of compounds in seawater, minerals, brines and rocks. Canada (50%), Russia (19%), China (13%), and Israel (9%) were the primary sources of magnesium and magnesium alloys in 2002. Of the total magnesium imports in 2002, 48% was alloy and 34% was pure metal.

This silvery white metal is most commonly produced in cast form, but is also extruded, forged and rolled. At room temperature magnesium and its alloys are difficult to deform; in fact, only small degrees of cold work may be imposed without annealing. Most fabrication is by casting or hot working at temperatures between 200 and 350°C. Magnesium, like aluminum, has a moderately low melting temperature (651 °C). Consequently, it is to be expected that there will be problems preventing creep in stressed components. Alloys containing Thorium, show at 623K the highest service temperatures of magnesium alloys and, incidentally, compared to melting point, the highest of any material[38-41].

**Table 1.1** Properties and Uses for Selected Engineering Metals and their Alloys

Notes: The values of Tm, ρ and E are only moderately sensitive to alloying. Ranges for σu and uses include alloys based on these metals. Properties ρ, E, and σu are at room temperature, except σu is at 1650 °C for tungsten [29].

| Metal | Melting Temp. | Density | Elastic Modulus | Typical Strength | Uses, Comments |
|---|---|---|---|---|---|
| | Tm °C | ρ g/cm$^3$ | E GPa | MPa | |
| Iron (Fe) and steel | 1538 | 7.87 | 212 | 200 to 2500 | Diverse: structures, machine and vehicle parts, tools. Most widely used engineering metal |
| Aluminum (Al) | 660 | 2.70 | 70 | 140 to 550 | Aircraft and other lightweight structure and parts |

| | | | | | |
|---|---|---|---|---|---|
| Magnesium (Mg) | 650 | 1.74 | 45 | 170 to 340 | Parts for high speed machinery, aerospace parts |
| Titanium (Ti) | 1670 | 4.51 | 120 | 340 to 1200 | Aircraft structure and engines, industrial machine parts, surgical implants |
| Copper (Cu) | 1085 | 8.93 | 130 | 170 to 1400 | Electrical conductors, corrosion resistant parts,valves, pipes. Alloyed to make bronze and brass. |
| Nickel (Ni) | 1455 | 8.90 | 210 | 340 to 1400 | Jet engine parts, alloying addition for steels. |
| Cobalt (Co) | 1495 | 8.83 | 211 | 650 to 2000 | Jet engine parts, wear resistant coatings, surgical implants |
| Tungsten (W) | 3422 | 19.3 | 411 | 120 to 650 | Electrodes, light bulb filaments, flywheels, gyroscopes |
| Lead (Pb) | 328 | 11.3 | 16 | 12 to 80 | Corrosion resistant piping, weights, shot. Alloyed with tin in solders |

Magnesium alloys do have very good damping capacity and castings have found application in high vibration environments. Aluminum, zinc, manganese and some of the rare earths are the major alloying elements.However, magnesium occupies the highest anodic position on the galvanic series, and, as such, there is always the strong potential for corrosion.

Its high specific toughness and rigidity, good machinability, castability and weldability with known methods make it attractive for automotive. Magnesium automobile parts reduce the weight of trucks and cars which makes for less use of oil and less air pollution. Resistivity of magnesium is $4.5 \times 10^{-8}$ Ω-m.

#### 1.3.3.2 Designation

A standard system of alloy and temper designations, adopted in 1948, is explained in Table 1.2. As an example of how the system works, consider magnesium alloy AZ91E-T6, The first part of the designation, AZ, signifies that aluminum and zinc are the two principal alloying elements. The second part of the designation, 91, gives the rounded-off percentages of aluminum and zinc (9 and 1, respectively). The third part, E, indicates that this is the fifth alloy standardized with 9% Al and 1% Zn as the principal alloying additions. The fourth part, T6, denotes that the alloy is solution treated and artificially aged [42].

**Table 1.2.** Designations. Standard four-part ASTM system of alloy and temper designations for magnesium alloys [44].

| First Part | Second Part | Third Part | Fourth Part |
|---|---|---|---|
| Indicates the two principal alloying elements | Indicates the amount of the two principal alloying elements | Distinguishes between different alloys with the same percentages of the two principal alloying elements | Indicates condition (temper) |

| | | | |
|---|---|---|---|
| Consists of two code letters representing the two main alloying elements arranged in order of decreasing percentage or alphebetically if percentages are equal | Consists of two numbers corresponding to rounded off percentages of the two main alloying elements and arranged in same order as alloy designations in first part | Consists of a letter of the alphabet assigned in order as compositions become standard | Consists of a letter followed by a number (seperated from the third part of the designationby a hypen) |
| A-- aluminum<br>B– bismuth<br>C– copper<br>D—cadmium<br>E—rare earth<br>F–- iron<br>G–- magnesium<br>H—thorium<br>K—zirconium<br>L–- lithium<br>M—manganese<br>N—nickel<br>P—lead<br>Q—silver<br>R—chromium<br>S—silicon<br>T—tin | Whole numbers | Letters of alphabet except I and O | F—as fabricated<br>O—annealed<br>H10 and H11 – slightly strain hardaned<br>H23, H24 and H26-strain hardened and partially annealed<br>T4—solution heat treated<br>T5– artificially aged only<br>T6—solution heat treated and artificially aged<br>T8—solution heat treated, cold worked, artificially aged |

W—yttrium

Y—antimony

Z--zinc

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#### 1.3.3.3 Raw Materials for Magnesium Production

There are six sources of raw materials for the production of magnesium: magnesite, dolomite, bischofite, carnallite, serpentine and sea water. These sources differ in the magnesium content, in production methods, and in their origin. Some are mined from mines, some in open mining, others originated in various processes carried out on sea water and salt lakes, and another material originates from the waste of the asbestos production process.

**Table 1.3.** Raw materials and their molecular formula

| Material | Chemical formula |
|---|---|
| Magnesite | $MgCO_3$ |
| Dolomite | $MgCO_3*CaCO_3$ |
| Bischofite | $MgCl_2*6H_2O$ |
| Carnallite | $MgCl_2*KCl*6H_2O$ |
| Serpentine | $3MgO*2SiO_2*2H_2O$ |
| Sea Water | $Mg^{+2}(aq)$ |

Magnesium is produced from seawater, brines and magnesium-bearing minerals which gives it a virtually unlimited supply of ore reserves, for example, it has been estimated that at current world use levels there is enough magnesium in the Dead Sea for at least 22,000 years. The availability of magnesium in seawater at about %0,13 percent [43].

#### 1.3.3.4 Historical Aspects

Both of the world's most plentiful and most useful light metals were discovered at about the same time magnesium in 1808 and aluminium in 1807. Serious industrial production of both metals started in the late 1880's, using relatively simple processes which are inexpensive when a plentiful supply of cheap power is available. Both metals are derived from sources which occur widely and in immense quantities [44].

In 1808 sir Humphry Davy found that magnesium oxide was the oxide of a previously unknown metal. He also was the first to isolate a small quantity of magnesium from magnesium oxide.
However, in 1828, Antoine Bussy, who received the credit for discovering magnesium, managed to obtain pure and large amounts of the metal. He fused magnesium chloride with metallic potassium vapor to get the metallic form.
In 1833 Michael Faraday electrolyzed dehydrated liquid magnesium chloride to form liquid magnesium and chlorine gas.

In 1852 Robert Bunsen, a German, constructed a small laboratory cell for electrolysis of the fused chloride. This led to the commencement of magnesium commercial production in 1886 in Germany. In 1940 Lloyd Montgomery Pidgeon pioneered the first industrial metallothermic magnesium extraction plant in Canada; it was based on early German patents, in which dolomite was reduced with ferrosilicon under vacuum.

In the past, magnesium was used extensively in World War I and again in World War II but apart from use in niche applications in the nuclear industry, metal and military aircraft, interest subsequently waned. The most significant application was its use in the VW beetle but even this petered out when higher performance was required. The requirement to reduce the weight of car components as a result in part of the introduction of legislation limiting emission has triggered renewed interest in magnesium.

**Figure 1.12** Volkswagen (VW Beetle) from 1938 until 2003

Racing cars use magnesium in 1920's, but magnesium castings were not exstensively used in commercial vehicles until 1936 when the Volkswagen Beetle was introduced. The car contained around 20 kg of magnesium in the powertrain and during its peak production in 1971 consumption of magnesium reached 42,000 tonnes per annum.

It might be of interest, that in 1940 the first airplane, almost completely designed for magnesium, had been constructed, the Northrop XP-56.

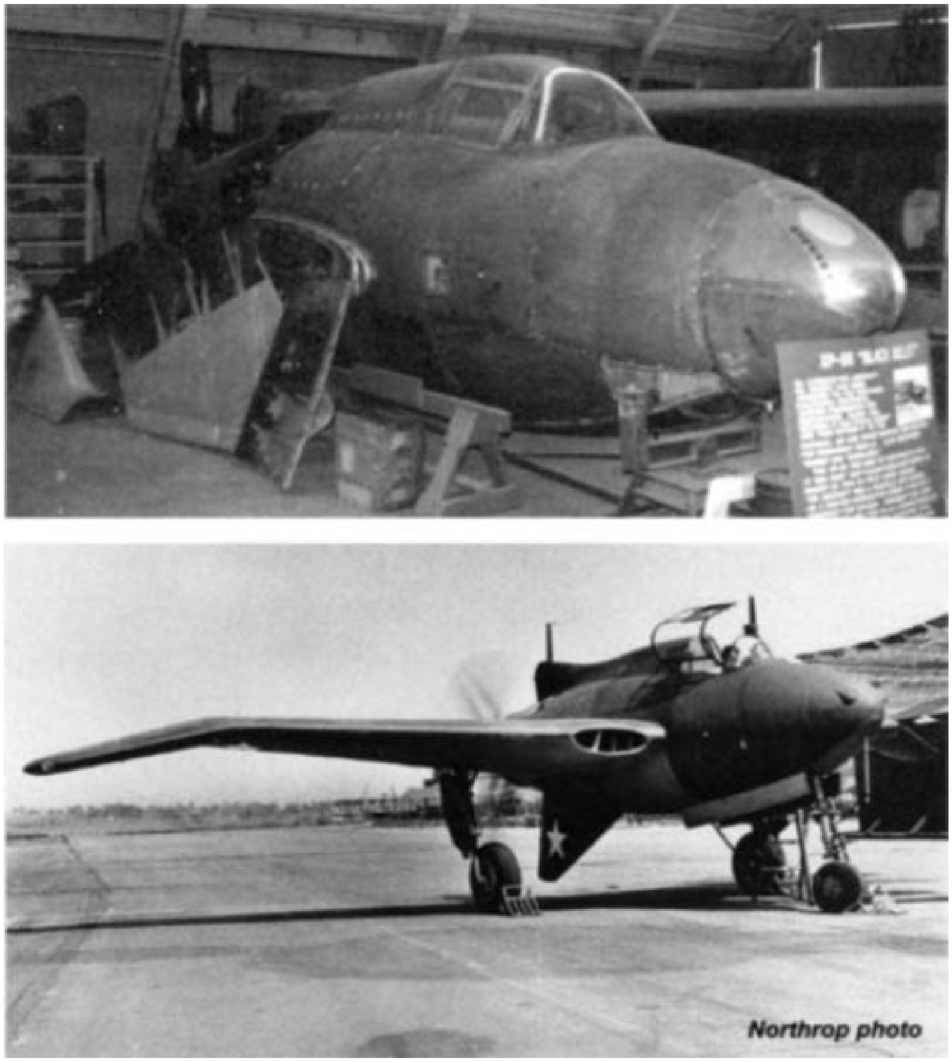



**Figure 1.13 Northrop XP-56** First airplane nearly completely designed with magnesium-Northrop XP-56.

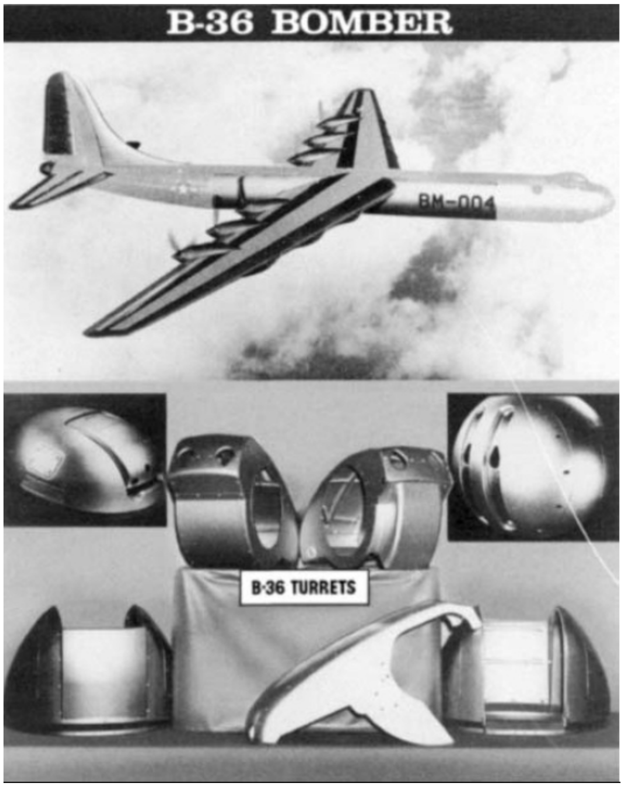



**Figure 1.14** B-36 World's largest bomber contained 8618 kg of magnesium. Service experience in B-36, in all environments, proved magnesium's ability to withstand all requirements as satisfactory aircraft structural material.

**1.3.3.5 The Advantages of Magnesium and Magnesium Alloys**

- lowest density of all metallic constructional materials;
- high specific strength;
- good castability, suitable for high pressure diecasting
- can be turned:milled at high speed;
- good weldability under controlled atmosphere;
- much improved corrosion resistance using high purity magnesium; readily available;

*compared with polymeric materials*

- better mechanical properties;
- resistant to ageing;
- better electrical and thermal conductivity;

- recyclable.

#### 1.3.3.6 The disadvantages of magnesium

- low elastic modulus;
- limited cold workability and toughness;
- limited high strength and creep resistance at elevated temperatures;
- high degree of shrinkage on solidification;
- high chemical reactivity;
- in some applications limited corrosion resistance.

#### 1.3.3.7 Magnesium Alloys

Magnesıum alloys usually are heat treated either to improve mechanical properties or as a means of conditioning for specific fabricating operations. The type of heat treatment selected depends on alloy composition and form (cast or wrought), and on anticipated service conditions. Solution heat treatment improves strength and results in maximum toughness and shock resistance.

Alloying elements do not generally exceed 10% total for all additions, the most common being aluminum, manganase, zinc and zirconium. The highest strengths are about 60% as large, resulting in comparable strength to weight ratios. Aluminum and zinc are relatively soluble in solid magnesium, but their solubilities decrease at low temperatures. The solubility of aluminum is 12.7% by weight at 437 °C and 3.0% at 93 °C ; solubility of zinc is 6.2% at 340 °C and 2.8% at 204 °C, solubilities of manganese, zirconium, and cerium are less than 1.0% by weight at 482 °C.

At the eutectic temperature, 4.5% thorium is soluble in magnesium. Manganese is effective in improving the corrosion stability of magnesium alloys that contain aluminum and zinc. Several of these alloys, which employ manganese to control both the iron content and activity in the alloy, are available and have excellent corrosion resistance. Other alloys not containing aluminum and zinc, but containing yttrium, are also available and exhibit good corrosion resistance.

**Aluminum**

Aluminum has the most favorable effect on magnesium of any of the alloying elements. It improves strength and hardness, and it widens the freezing range, and makes the alloy easier to cast. When exceeding 6 wt%, the alloy becomes heat treatable, but commercial alloys rarely exceed 10 wt% aluminum. An aluminum content of 6 wt% yields the optimum combination of strength and ductility.

**Manganese**

Manganese does not affect tensile strength considerably, yet it slightly increases the yield strength. Its most important function is to improve saltwater resistance of Mg-Al and Mg-Al-Zn alloys by removing iron and other heavy-metal elements into relatively harmless intermetallic compounds, some of which separate out during melting. The amount of manganese that can be added is limited by its relatively low solubility in magnesium. Commercial alloys containing manganese rarely contain over 1.5 wt%, and in the presence of aluminum, the solid solubility of manganese is reduced to about 0.3 wt%.

**Zinc**

Zinc is next to aluminum in effectiveness, as an alloying ingredient in magnesium. It is often used in combination with aluminum to produce improvement in room-temperature strength; however, it increases hot shortness when added in amounts greater than 1 wt% to magnesium alloys containing 7-10 wt% aluminum. Zinc is also used in combination with zirconium, rare earths, or thorium to produce precipitation-hardenable magnesium alloys having good strength. Zinc also helps overcome the harmful corrosive effect of iron and nickel impurities that might be present in the magnesium alloy.

**Zirconium**

Zirconium has a powerful grain-refining effect on magnesium alloys. It is added to alloys containing zinc, rare earths, thorium, or a combination of these elements, where it serves as a grain refiner (up to its limit of solid solubility). However, it cannot be used in alloys containing aluminum or manganese because it forms stable compounds with these elements and is thus removed from solid solution. It also forms stable compounds with any iron, silicon, carbon, nitrogen, oxygen, and hydrogen present in the melt.

Because only the portion of the zirconium content available for grain refining is that which is in solid solution, the soluble zirconium content, rather than the total zirconium content, is the value important to the alloy.

**Yttrium**

Yttrium has a relatively high solid solubility in magnesium (12.4 wt%) and is added with other rare earths to promote creep resistance at temperatures up to 300 $^{o}$C. About 4-5% Zr is added to magnesium to form commercial alloys such as WE54 and WE43, where it imparts good elevated-temperature properties up to about 250 $^{o}$C.

**Iron**

Iron is one of the most harmful impurities in magnesium alloys due to considerable reduction of corrosion resistance even in present in small amounts.

In ordinary commercial-grade alloys, the iron content can average as high as 0.01-0.03 wt%. However, for maximum corrosion resistance, 0.005% is specified as the upper limit for iron content.

**Copper**

Copper adversely affects the corrosion resistance of magnesium if present in amounts exceeding 0.05 wt%. However, it improves high-temperature strength.

**Rare earth metals**

Rare earth metals are added to magnesium alloys either as mischmetal or as didymium. Mischmetal is a natural mixture of rare earths containing about 50 wt% cerium, the remainder being mainly lanthanum and neodymium; didymium is a natural mixture of approximately 85% neodymium and 15% praseodymium. Additions of rare earths increase the strength of magnesium alloys at elevated temperatures. They also reduce weld cracking and porosity in casting because they narrow the freezing range of the alloys.

**1.3.3.8 Markets & Applications**

During the last few decades the world has seen a rapid growth of application of magnesium and its alloys almost in every field of today's industry.

- **Aerospace Industry** (*brake devices, gearboxes,wheels, turbine engines exct.*)

- **Automotive Industry** (*brakes, wheels, engine covers exct.*)
- **Defence** (*seawater batteries*)
- **Domestic and Outdoor Appliances** (*camping equipment, suitcases exct.*)
- **Electronics** ( *electric shavers, lamps exct.*)
- **Energetics** (*canning materials*)
- **Medicine and Pharmaceuticals** (*dental products, vitamins exct.*)
- **Miscellaneous Products** (*eyewear frames, snowshoes exct.*)
- **Processing Equipment** (*Furnaces exct.*)
- **Raw Material and Unfinished Products** (*ingots, plates, sheets, forgings, extrusions, wire, anodes,bars exct.*)
- **Sports** ( *bcycle parts and frames, tennis rackets exct.*)

The main use of magnesium by far is as an alloying addition to aluminum alloys. Other major utilization includes desulphurization of steel, the production of ductile iron and as a structural material in its own right

*Using Mg for light-weighting cars*

Considering its characteristics of low density, its extensive use in vehicles would obtain major reductions of weight and corresponding fuel savings. The data indicate that the overall weight savings could be of around 10%. In turn, this weight saving would lead to a fuel saving of the order of 20-30% without drastic changes in design. A new passenger car produces on average some 150 g/km exhaust gasses. With magnesium technology this value could be reduced to around 100-120g/km. Considering the large number of vehicles around, this weight saving could lead to a significant reduction of carbon dioxide released to the atmosphere, reducing the impact on global warming in agreement with the Kyoto treaty. Magnesium is now the center of attention for the United States Automotive Materials Partnership (USAMP). This USCAR initiative investigates ways to develop a family car that can attain 2.9 L/100 km. The $10 million project involves the U. S. government, automakers, suppliers, universities, and national laboratories [46,47].

*Magnesium Engine Blocks*

The engine block is the heaviest single component in a car, and the block made from magnesium alloy represents an example of light weighting heavier automobile components by direct substitution. While aluminium engine blocks have been slowly replacing cast iron blocks and saving around 66% in weight, magnesium equivalents takes this reduction further to around 75%. Other benefits of using magnesium can be its high shock and dent resistance and its greater ability than aluminium to dampen noise and vibration. The magnesium EB for V6 3.0 litre engine weighs 30 kg compared to 39 kg and 84.6 kg, respectively, for an aluminium and cast iron block. Australian Magnesium Company announced a strategic alliance with German-based VAW Aluminium, AG to assess the potential for the production of a magnesium engine block. The agreement aims to define an appropriate engine block alloy, to test prototypes and move to commercial production of a magnesium engine block. The annual demand for magnesium alloy in a typical mass-produced four-cylinder engine block is about 7000 t/a. AMC believes magnesium engine blocks will be used in a number of vehicles within the next 10 years.

#### 1.3.3.9 Machinability

Machining is a process of the removal of excess material from a component in order to impart to it the required dimension and finish. The importance of the machining process can be appreciated by the fact that machining found in every engineering workpiece. Machining creates geometric shapes, tolerances and surface finish unobtainable by other techniques. Every workpiece should be machinable to certain degree. Machinability refers the ease a workpiece can be machined.

Magnesium exhibits excellent machinability. Magnesium is an excellent material for machining dry. This is because of the low cutting pressures, free machining characteristics and the high thermal conductivity which allows heat to dissipate quickly through the part. Machining magnesium can usually be performed up to ten times faster than steel and twice as fast as aluminium. Machining magnesium is normally limited by the speed and power of the machine rather than the tool. The power required to remove a given amount of metal is lower for magnesium than for any other commonly machined metal. Based on the volume of metal removed per minute, the comparative power requirements of various metals are:

**Table 1.4.** Relative Power & Comparative Machinability of Metals

| Metal | Relative power | AISI-B1112 Machinability Index (%) |
|---|---|---|
| Magnesium alloys | 1.0 | 500 |
| Aluminum alloys | 1.8 | 300 |
| Mild Steel | 6.3 | 50 |
| Titanium Alloys | 7.6 | 20 |
| Cast iron | 3.5 | |
| Brass | 2.3 | |
| Nickel alloys | 10.0 | |

*Advantages of machining magnesium*

- Low power required- approximately 55% of that required for Al.
- Fast machining- employing the use of high cutting speeds, large feed rates and greater depths of cut.
- Excellent surface finish- extremely fine & smooth surface achieved.
- Well broken chips- due to the free cutting qualities of magnesium
- Reduced tool wear- leading to increased tool life

Because of the free cutting characteristic of magnesium, chips produced in machining are well broken. Dimensional tolerances of about ±0.1 mm can be obtained using standard operations. Tool wear is also reduced when machining magnesium because of the high thermal conductivity of the metal, which allows rapid dissipation of heat, and the low cutting pressures required. Ordinary carbon steel tools can be used in machining magnesium, but high-speed tools and carbide tipped tools can be used for high production rate jobs.

An outstanding machining characteristic of magnesium alloys is their ability to acquire an extremely fine finish. Often, it is unnecessary to grind and polish magnesium to obtain a smooth finished surface. Surface smoothness readings of about 0.1 μm have been reported for machined magnesium and are attainable at both high and low speeds, with or without cutting fluids.

*Cutting Fluids (Coolants)*

Cutting fluids are used to reduce the negative effects of the heat and friction on both tool and workpiece. The cutting fluids produce three positive effects in the process

Heat removal elimination (*cooling*)

Lubrication on the chip-tool interface

*Easy chip removal*

However, the advantages caused by the cutting fluids have been questioned lately, due to the several negative effects they have caused in the environment and worker health. When inappropriately discharged, cutting fluids may damage soil and water resources, causing serious environmental impacts. On the shop floor, the machine operators may be affected by the negative effects of cutting fluids, such as skin and respiratory problems.

**Figure 1.15** Cutting fluids & coolants

These problems result in a large number of ecological problems and in a climate of increasingly strict work safety and environmental legislation. This in turn means more economic problems for manufacturing companies. Economic pressure on industries due to waste disposal is increasing progressively. Today, costs of cutting fluids can reach 20% of production costs [48].

In order to make machining process more ecological, the Minimal Quantity Lubrication has been accepted as a successsful near-dry applications because of its environmentally friendly characteristics.

Most machining of magnesium alloys is done dry, but cutting fluids sometimes are used for cooling the work.

Although less heat is generated during machining of magnesium alloys than during machining of other metals, higher cutting speeds and the low heat capacity and relatively high thermal expansion characteristics of magnesium may make it necessary to dissipate the small amount of heat that is generated.

Heat generation can be minimized by the use of correct tooling and machining techniques, but cutting fluids are sometimes needed to reduce the possibilities of distortion of the work and ignition of fine chips. Because they are used primarily to dissipate heat, cutting fluids are referred to as coolants when used in the machining of magnesium alloys.

Numerous mineral oil cutting fluids of relatively low viscosity are satisfactory for use as coolants in the machining of magnesium. Suitable coolants represent a compromise between cooling power and flash point. Additives designed to increase wetting power are usually beneficial. Only mineral oils should be used as coolants; animal and vegetable oils are not recommended.

Water-soluble oils, oil-water emulsions, or water solutions of any kind should not be used on magnesium. Water reduces the scrap value of magnesium turnings and introduces potential fire hazards during shipment and storage of machine shop scrap.

The possibility of chips or turnings catching fire must be considered when magnesium is to be machined. Chips must be heated close to their melting point before ignition can occur. Roughing cuts and medium finishing cuts produce chips too large to be readily ignited during machining. Fine finishing cuts, however, produce fine chips that can be ignited by a spark. Stopping the feed and letting the tool dwell before disengagement, and letting the tool or tool holder rub on the work, produce extremely fine chips and should be avoided.

Factors that increase the probability of chip ignition are:

- Extremely fine feeds
- Dull or chipped tools
- Improperly designed tools
- Improper machining techniques
- Sparks caused by tools hitting iron or steel inserts

Feeds less than 0.02 mm per revolution and cutting speeds higher than 5 m/s increase the risk of fire. Even under the most adverse conditions--with dull tools and fine feeds--chip fires are very unlikely at cutting speeds below 3.5 m/s. Any fire hazard connected with machining of magnesium is easy to control, and large quantities of magnesium are machined without difficulty.

Following these rules will reduce the fire hazard:

- Keep all cutting tools sharp and ground with adequate relief and clearance angles
- Use heavy feeds to produce thick chips
- Use mineral oil coolants (15 to 19 L/min, or 4 to 5 gal/min) whenever possible; when not possible,avoid fine cuts
- Do not allow chips to accumulate on machines or on the clothing of operators. Remove dust and chips at frequent intervals and store in clean, plainly labeled, covered metal cans
- Keep an adequate supply of a recommended magnesium fire extinguisher within reach of operators If dry chips are ignited, they will burn with a brilliant white light, but the fire will not flare up unless disturbed. Burning chips should be extinguished as follows:
- Scatter a generous layer of clean, dry cast iron chips or metal extinguishing powder over the burning magnesium
- Cover actively burning fires on combustible surfaces like wood floors with a layer of the extinguishant, then shovel the entire mass into an iron container or onto a piece of iron plate
- Do not use water or any of the common liquid or foam-type extinguishers, which intensify magnesium chip fires

Distortion of magnesium parts during machining occurs rarely and usually can be attributed to excessive heating or improper chucking or clamping. Heating of the work is increased by use of dull or improperly designed tools, extremely high machining feeds and speeds, or very fine cuts. Because magnesium has a relatively high coefficient of thermal expansion, such excessive heating results in substantial increases in dimension particularly in thin sections, where heating causes relatively large increases in temperature.

Use of sharp, properly designed tools; mineral oil coolants; and relatively coarse feeds and depths of cut reduces excessive heating. Wide variations in room temperature during machining can also cause sufficient dimensional change to affect machining tolerances.

Clamping should always be done on heavier sections of magnesium castings, and clamping pressures should not be high enough to cause distortion. Special care should be taken with light parts that could be distorted easily by the chuck or by use of heavy cuts. Distortion of magnesium parts is seldom caused by stresses during casting, forging, or extruding, but it may result from stresses caused by straightening or welding.

Such stresses can be relieved prior to machining by heating at 260 °C for 2 h and slowly cooling. If distortion of part is observed after rough machining, the cutting tool should be inspected to ensure that it is sharp and properly ground. If so, the size of cut should be decreased. With complex parts or parts machined to extremely close tolerances, it may be advisable to stress relieve or, if time permits, to store parts for 2 or 3 days between rough machining and finishing.

#### 1.3.3.10 Machining Process Variables

**Machining Processes input and output parameters**

**Machining process input variables**

(process independent variables)

1) machine tool (rigidity, capacity, accuracy, etc.)
2) cutting tool (material, coating, geometry, nature of engagement with the work material, tool rigidity etc.)
3) cutting conditions (speed,feed and the depth of cut)
4) work material properties (hardness, tensile strength, chemical composition, micro structure, method of production, thermal conductivity, ductility, shape and dimensions of the job, work piece rigidity etc.)
5) cutting fluid properties and characteristics

**Machining Process output variables**

(process dependent variables)

1) cutting tool life/ tool wear/ tool wear rate
2) cutting forces/ specific cutting forces
3) power consumption/ specific power consumption
4) processed surface finish
5) processed dimensional accuracy
6) material removal rate
7) noise
8) vibrations
9) cutting temperature
10) chip characteristics

However, it may be added that the machining process input variables may not precisely represent machinability. For example, materials of same composition but different metallographic structure may have different machinability characteristics. Moreover as the machining process output variables are functions of machining process input variables, the majority of researchers have prefered the machining process output variables for the machinability evaluation of work materials [49].

### 1.3.4 Taguchi Approach

#### 1.3.4.1 Background

Most of the body of knowledge associated with the quality sciences was developed in the United Kingdom as design of experiments and in the United States as statistical quality control. Dr. Genichi Taguchi,who has won some of Japan's most prestigious awards for quality achievement including four Deming Awards, has added to this body of knowledge. In 1986, Taguchi received the most prestigious prize from the International Technology Institute – TheWillard F. Rockwell Medal for Excellence in Technology. Genichi Taguchi (January 1, 1924 – June 2, 2012) is a Japanese engineer who has been active in the improvement of Japan's industrial products and processes since the late 1940s. He has developed both the philosophy and methodology for process or product quality improvement that depends heavily on statistical concepts and tools, especially statistically designed experiments. Many Japanese firms have achieved great success by applying his methods.Thousands of engineers have performed tens of thousands of experiments based on his teachings. Although Dr. Taguchi successfully applied the technique in many companies throughout the world, it was introduced to USA and other western countries only in the early1980's.

Taguchi's major contribution has involved combining engineering and statistical methods to achieve rapid improvements in cost and quality by optimizing product design and manufacturing processes. Since 1983, after Taguchi's association with the top companies and institutes in USA (AT & T Bell Laboratories, Xerox, Lawrence Institute of Technology (LIT), Ford Motor Company etc.), his methods have been called a radical approach to quality, experimental design and engineering. Taguchi methods is now a term that refers to the approaches developed by Taguchi to manufacture high quality products. Taguchi tactics refer to the collection of specific methods and techniques used by Genichi Taguchi, and Taguchi strategy is the conceptual framework or structure for planning a product or process design experiment. Taguchi addresses design and engineering (off-line) as well as manufacturing (on-line) quality. This fundamentally differentiates TM from statistical process control (SPC), which is purely an on-line quality control method [50, 51].

**1.3.4.2 Taguchi Philosophy**

Taguchi's ideas can be distilled into two fundamental concepts:

(a) Quality losses must be defined as deviations from targets, not conformance to arbitrary specifications .

(b) Achieving high system-quality levels economically requires quality to be designed into the product.

Quality is designed, not manufactured, into the product. Taguchi methods represent a new philosophy. Quality is measured by the deviation of a functional characteristic from its target value. Taguchi technique is one of the latest optimization techniques that are being applied successfully in industrial applications for optimal selection of process variables in the area of machining. In the recent optimization technique Taguchi methods is latest design techniques widely used in industries for making the product/process insensitive to any uncontrollable factors such as environmental variables. Taguchi approach has potential for savings in experimental time and cost on product or process development and quality improvement.The Taguchi methods of quality engineering emphasize the importance of the following concepts

*Enhancing cross functional team interaction:* Design engineers and manufacturing engineers communicate with each other in a common language. They quantify the relationships between design requirements and manufacturing process selection.

*Implementing experimental design:* The factors involved in a process or operation and their interactions are studied simultaneously [52, 53].

#### 1.3.4.3 Experimental Design

As engineers and product developers, it is important to become accustomed to using Design Of Experiments (DOE) as part of your routine development process.

Design of Experiments is a systematic method of simultaneously changing a number of factors following a predetermined plan to investigate their effects on the output of the system. Using DOE is a key enabler for gaining quick, effective, low-cost solutions to complex problems. Planning an experiment begins with carefully recognizing and stating the problem. The problem statement should be written as your experimental objective.

The objective of an experiment is best determined by a team discussion.

Typical objectives are to:

Choose between several alternatives

Determine which factors are most important

Maximize or minimize a response, hit a target, reduce variation or make a product or process robust.

**A parameter diagram** (p-diagram) is a system model which is useful in scoping the problem, understanding the system, and formalizing the objectives of DOE. The p diagram helps you to visualize the system as a combination of machines, methods, people, processes and other resources that transforms an input into an output with one or more observable responses.

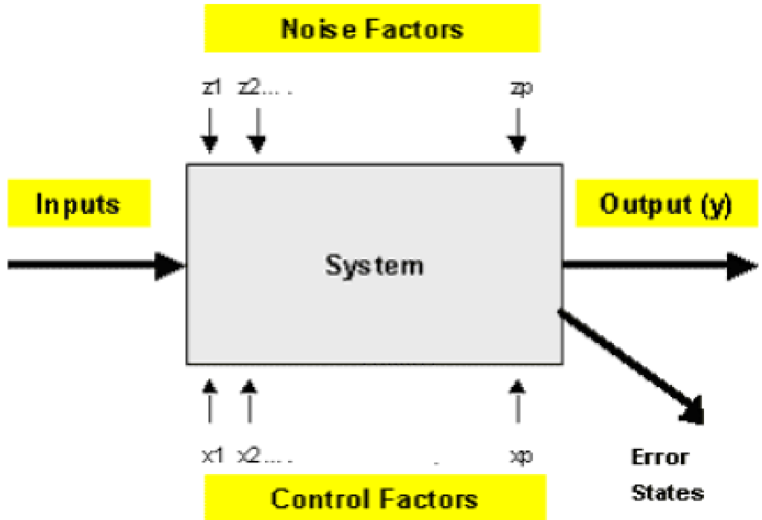



**Figure 1.16.** Inputs Outputs [53]

Inputs: The system input could include material, energy, actions, etc.

Output: The output (signified by y) is the result of the system acting upon the inputs.

Control factors: (signified by x) represent the design variables identified to define the specific design.

Noise factors: (signified by z) affect the output and are factors that either cannot be controlled or which the designer chooses not to control. Noise factors may be:

Experimentally Controllable: A factor which varies naturally and uncontrollably in the actual process but can be controlled for the experiment.

Uncontrollable: A factor which (realistically) cannot be controlled during the experiment. If it can be measured, then that may help the analysis.

Error States: Identifies typical error states for the system.

Choose Factors and Levels

A factor is a product or process parameter, or variable, that is changed in the experiment. A factor is also called a design parameter, treatment or input variable.

Factors are chosen based on engineering judgment.

Levels are the factor settings used in the experiment.

Select Response Variable(s)

The response variable identifies what aspect of the system is measured and is used to determine the success of the experiment's objective.

Choose Experimental Design

The choice of experimental design depends on the objectives of the experiment and the number of factors to be investigated.

If you identify only one factor, running a single factor experiment is appropriate.

If there are two factors, consider a full factorial experimental design.

If there are three or four factors, consider a full factorial or fractional factorial experimental design.

If there are five or more factors, consider a fractional factorial design.

DOE is a systematic method of simultaneously changing a number of factors following a predetermined plan to investigate their effect on the output of the system (process or product).

DOE provides methods to identify the minimum number of experiments required and provides a statistical basis to analyze the experimental data to determine the significance and relevance of the experimental results.

DOE is not testing one factor at a time and is not reactive in its execution (although multiple experiments may be needed to draw final conclusions).

It is important to note that effective experimentation requires process knowledge and engineering judgment in addition to knowledge of DOE.

Next is an opportunity to check your knowledge of the process [53].

**1.3.4.4 Taguchi Methods**

The term "Taguchi methods" (TM) refers to the system design, parameter design, tolerance design, quality loss function, on-line quality control, design of experiments using orthogonal arrays, and methodology applied to evaluate measuring systems. The focus of system design phase is on determining the suitable working levels of design factors. While system design phase helps to identify the levels, parameter design seeks to determine the factor levels that produce the best performance of the product/process under study. Parameter design is the selection of the optimal conditions (parameters), so that the product is least sensitive to noise variables. The concept uses Orthogonal Arrays, response tables, and the metrics of S/N ratios, variances, and averages to obtain the appropriate parameters. Tolerance design is a step used to fine tune the results of parameter design by tightening the tolerance of factors with significant influence on product. It uses analysis of variance (ANOVA) to determine which factors contribute to the total variability and the loss function to obtain a trade off between quality and cost.

Design of Experiments (DOE) using the Taguchi Approach is a standardized form of experimental design technique (referred as classical DOE) introduced by R. A. Fisher in England in the early 1920's. It is popularly known as the Factorial Design of Experiments. As a researcher in Japanese Electronic Control Laboratory, in the late 1940's, Dr. Genichi Taguchi devoted much of his quality improvement effort on simplifying and standardizing the application of the DOE technique.

Basically, experimental design methods were developed originally by R. A. Fisher .The method helps an experimenter determine the possible combinations of factors and to identify the best combination. However, classical experimental design methods are too complex and not easy to use. Furthermore, a large number of experiments have to be carried out when the number of the process parameters increases. To solve this problem, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments only. Taguchi works with a smaller number of tests. He selects a particular factorial design (orthogonal array) that produces the most important information. The experimental results are then transformed into a signal-to-noise (S/N) ratio. Taguchi recommends the use of the S/N ratio to measure the quality characteristics deviating from the desired values. Usually, there are three categories of quality characteristic in the analysis of the S/N ratio, i.e. the-lower-the-better, the-higher-the-better, and the-nominal- the-better. The S/N ratio for each level of process parameters is computed based on the S/N analysis. Regardless of the category of the quality characteristic, a greater S/N ratio corresponds to better quality characteristics. Therefore, the optimal level of the process parameters is the level with the greatest S/N ratio. Furthermore, a statistical analysis of variance (ANOVA) is performed to see which process parameters are statistically significant. With the S/N and ANOVA analyses, the optimal combination of the process parameters can be predicted. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the parameter design. To summarize, the parameter design of the Taguchi method includes the following steps: (1) identification of the quality characteristics and selection of design parameters to be evaluated; (2) determination of the number of levels for the design parameters and possible interactions between the design parameters; (3) selection of the appropriate orthogonal array and assignment of design parameters to the orthogonal array; (4) conducting of the experiments based on the arrangement of the orthogonal array; (5) analysis of the experimental results using the S/N and ANOVA analyses; (6) selection of the optimal levels of design parameters; and (7) verification of the optimal design parameters through the confirmation experiment. Therefore, three objectives can be achieved through the parameter design of the Taguchi method, i.e: (1) determination of the optimal design parameters for a process or a product; (2) estimation of each design parameter to the contribution of the quality characteristics; and (3) prediction of the quality characteristics based on the optimal design parameters [55-60].

#### 1.3.4.5 Experimental Efficiency

In experimental design, the effects of controllable and uncontrollable variables on the product are identified. This approach minimizes variations in product dimensions and properties, and ultimately brings the mean to the desired level.

The methods used for experimental design are complex. They involve the use of factorial design  and orthogonal arrays, both of which reduce the number of experiments required. These methods also are capable of identifying the effects of variables that can not be controlled (called noise), such as changes in environmental conditions in a plant.

The use of factorial design and orthogonal arrays results in (a) the rapid identification of the controlling variables, referred to as observing main effects, and (b) the ability to determine the best method of process control. Control of these variables sometimes requires new equipment or major modifications to existing equipment.

For example, variables affecting dimensional tolerances in machining a particular component can readily be identified, and whenever possible, the correct cutting speed, feed, cutting tool, and cutting fluids can specified.

An important concept introduced by Taguchi is that any deviation from a design objective constitutes a loss in quality. Consider, for example, the tolerancing standards for a shaft with diameter 40 mm±0.03. On the one hand, there is a range of dimensions over which a part is acceptable, on the other hand, the Taguchi philosophy calls for a minimization of deviation from the design objective. A shaft with a diameter of 40.03 mm normally would be considered acceptable and thus would pass inspections. In the Taguchi approach, however, a shaft with this diameter represents a deviation from the design objective. Such deviations generally reduce the robustness and performance of products, especially in complex systems.

In the Taguchi approach, only a small fraction of all possible factor-level combinations are tested in the study. Depending on the number of factors, the fraction of all possible experiments that are carried out (may be viewed as experimental efficiencies) will vary. The larger the number of factors, smaller is the number of fractional experiments. The efficiency with which the experiment designed using the Taguchi orthogonal arrays produce results is analogous to the way a Fish Finder (an instrument used by fishermen) helps track a school of fish.

The experimental efficiency Taguchi offers can be described using the following analogy. Assume that you are asked to catch a big fish from a lake with a circular net. You are also told that the fish usually stays around its hideout. But you have no knowledge of where this place is. How do you go about catching this fish? Thinking analytically you may first circulate the area of the net and the lake, then lay out an elaborate scheme to cover the entire lake. You may find, after all this planning, that you need the whole day to locate the spot where the fish is. Wouldn't it be nice to have a fisher finder that could tell you the approximate locations where to throw your net. The Taguchi approach in experimental studies, to a great extent, works like a fish finder. It tells you which areas to try first and then from the results of trials, you determine, with a high degree of certainty, the most probable location of the fish [60].

- The lake is like all possible combinations (called full factorial)
- The big fish in the lake is like the most desirable design condition.
- The Fish Finder and the fishing net are like the Taguchi DOE technique.

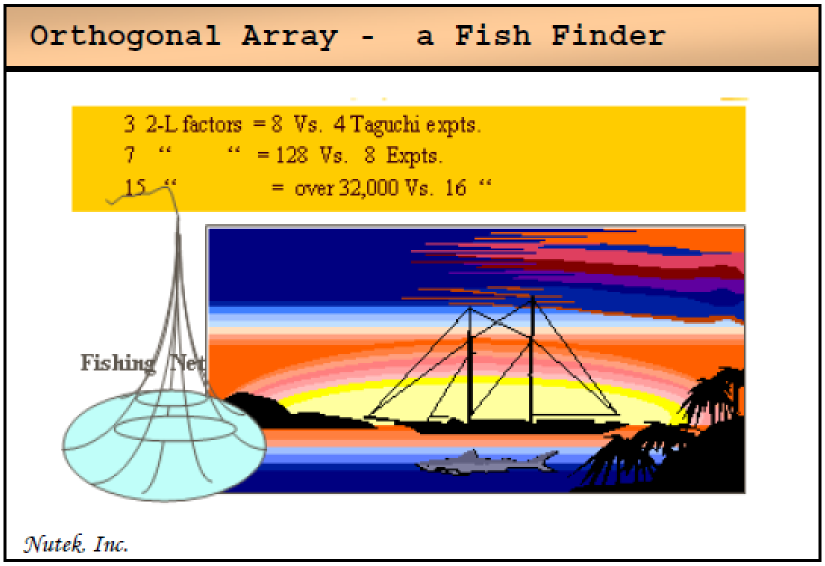



**Figure 1.17** Orthogonal Array- A fish finder [61]

**1.3.4.6 Noises**

Noises (uncontrolled variables) can cause such deviations resulting in loss of quality. Taguchi methods seek to remove the effect of noises. Levels of product and process factors are determined, such that the product's functional characteristics are optimized and the effect of noise factors is minimized. Noise factors are uncontrollable variables that can cause significant variability in the process or the product. Noise factors are classified as ′ outer noise ′, ′inner noise′ and between ′product noise′.

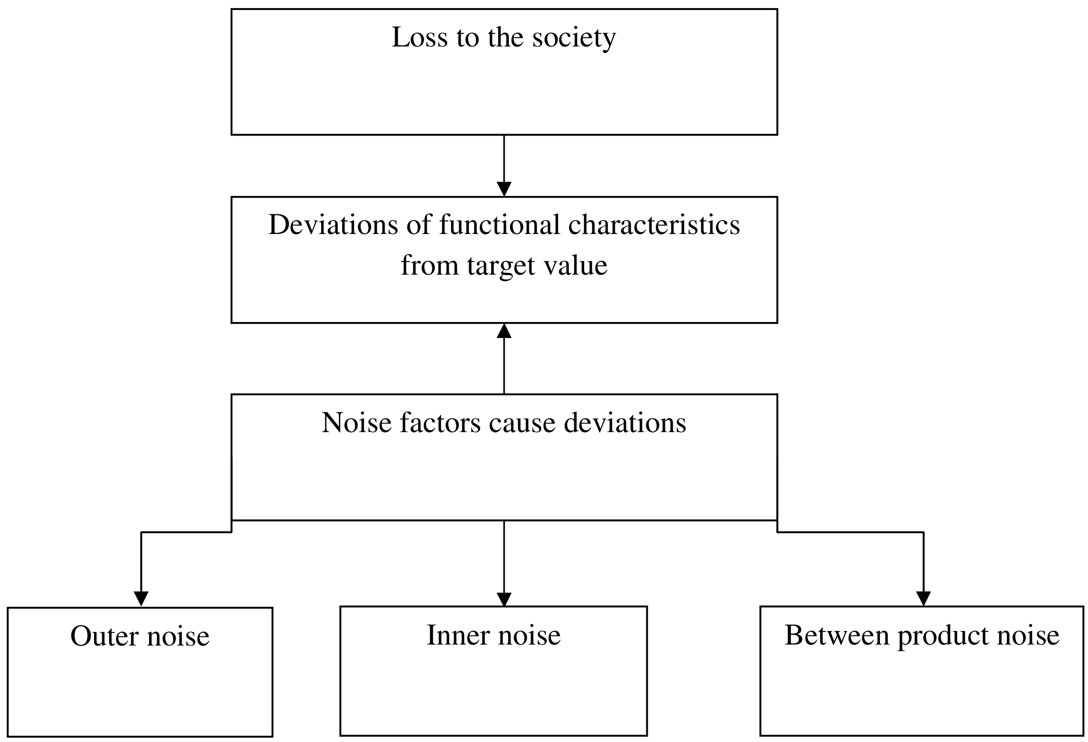
1. Outer noise: variation caused by environmental conditions (e.g.pressure,temperature, humidity, dust, input voltage,people)
2. Inner noise: deterioration of elements or materials in the product
3. Between product noise: piece to piece variation between products

A refrigerator temperature control will serve as an example to help clarify the noise concept. Outer noise is due to the actions of the user, such as the number of times the door is opened and closed, amount of food inside, the initial temperature, and so forth. Between product noise is due to variation during production such as seal tightness, control sensor variations and so forth. Although this type of noise is inevitable, every effort should be made to keep it to a minimum. Inner noise due to deterioration is caused by leakage of refrigerant, mechanical wear of compressor parts, and so forth.

This type of noise is primarily a function of the design. Noise factors cause deviation from the target, which causes a loss to society [62-64].

**Table 1.5** Examples of factors

| Product design | Process design |
|---|---|
| | Outer noise |
| Consumer's usage conditions | Ambient temperature |
| Low temperature | Humidity |
| High temperature | Seasons |
| Temperature change | Incoming material variation |
| Shock | Operators |
| Vibration | Voltage change |
| Humidity | Batch to batch variation |
| | Inner Noise |
| Deterioration of parts | Machinery ageing |
| Deterioration of material | Tool wear |
| Oxidisation (rust) | Deterioration |
| | Between product |
| Piece to piece variation where they are supposed to be the same | Process to process variation where they are supposed to be the same |
| | Controllable factors |
| All design parameters (such as dimensions, material and configuration) | All process design parameters<br>All process setting parameters |




Variation in operating environments

• Deterioration

• Manufacturing imperfections

- Human errors

**Figure 1.18** Contribution of noise factors to deviation of product functional characteristics from target value

### 1.3.4.7 Signal-to-Noise (S/N) Ratio

A loss function is defined to calculate the deviation between the experimental value and the desired value. Taguchi recommends use of the loss function to measure the performance characteristic deviating from the desired value. The value of the loss function is further transformed into a signal-to-noise (S/N) ratio.

In Taguchi's DOE method, the term "signal" represents the desirable value and "noise" represents the undesirable value. The objective of using S/N ratio is to obtain a measure of performance to develop products and processes insensitive to noise factors. The S/N ratio indicates the degree of the predictable performance of a product or process in the presence of noise factors. Taguchi used the signal-to-noise (S/N) ratio as the quality characteristic of choice. S/N ratio is used as a measurable value instead of standard deviation because as the mean decreases, the standard deviation also decreases and vice versa. In less technical terms, signal-to-noise ratio compares the level of a desired signal (such as music) to the level of background noise. The higher the ratio, the less obtrusive the background noise is. Process parameter settings with the highest S/N ratio always yield the optimum quality with minimum variance. The S/N ratio for each parameter level is calculated by averaging the S/N ratios obtained when the parameter is maintained at that level.

When a person puts his/her foot on the brake pedal of a car, energy is transformed with the intent to slow the car, which is the signal. However, some of the energy is wasted by squeal, pad wear, heat, and so forth. The figure 1.19 emphasizes that energy is neither created nor destroyed. At the bottom of the figure the concept is written in the form of a ratio.

Signal factors ( $\bar{y}$ ) are set by the designer or operator to obtain the intended value of the response variable. Noise factors ($s^2$) are not controlled or are very expensive or difficult to control.

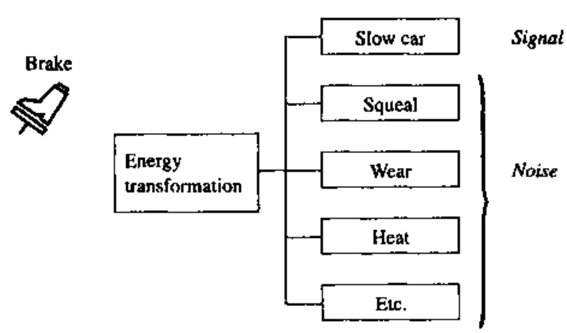



**Figure 1.19** Concept of Signal-to-Noise (S/N) Ratio

$$S/N = \frac{\text{Amount of energy for intended function}}{\text{Amount of energy wasted}} = \frac{\text{Signal}}{\text{Noise}}$$

Both the average, $\bar{y}$, and the variance, $s^2$, need to be controlled with a single figure of merit. In elementary form, S/N is $\bar{y}/s$, which is the inverse of the coefficient of variation and a unitless value. Squaring and taking the log transformation gives

$$S/N_N = \mathrm{Iog}_{10}(\bar{y}^2/s^2) \qquad (1.21)$$

Adjusting for small sample sizes and changing from Bels to decibels by multiplying by ten yields which is the nominal-the-best $S/N_N$ ratio.

$$S/N_N=10\ \log10[(\bar{y}^2/s^2) - (1/n)] \qquad (1.22)$$

The average and sample standard deviation are squared to eliminate any negative averages and to use the variance, which is an unbiased measure of the dispersion. By taking the log transformation, the calculated value becomes a relative one.

There are many different S/N ratios. Six basic ones are

1. Nominal-the-best
2. Target-the-best
3. Smaller-the-better
4. Larger-the-better
5. Classified attribute
6. Dynamic

*Nominal-the-Best*

The equation for nominal-the-best was given in the initial discussion. It is used wherever there is a nominal or target value and a variation about that value, such as dimensions, voltage, weight, and so forth. The target is finite but not zero. For robust (optimal) design, the S/N ratio should be maximized. The nominal-the-best S/N value is a maximum when the average is large and the variance is small. When the average is off target on the high side, the $S/N_N$ value can give more favorable information; when off target on the low side, the value can give less favorable information. Taguchi's approach is to reduce variation and then bring the average on target. Another $S/N_T$ ratio, called target-the-best, eliminates these problems provided the target is known.

*Smaller-the-Better*

The S/$N_S$ ratio for smaller-the-better is used for situations where the target value is zero, such as computer response time, automotive emissions, or corrosion. The equation is

$$S/N_S = -10\log_{10}[\text{MSD}] = -10\log_{10}[\left(\sum y^2\right)/n] \quad (1.23)$$

The negative sign is used to ensure that the largest value gives the optimum value for the response variable and, therefore, robust design. Mean standard deviation (MSD) is given to show the relationship to the loss function.

*Larger-the-Better*

The third S/N ratio is larger-the-better. It is used where the largest value is desired, such as weld strength, gasoline mileage, or yield. From a mathematical viewpoint, the target value is ∞. Like the loss function, it is the reciprocal of smaller-the-better. The equation is

$$S/N_L = -10\log_{10}[\text{MSD}] = -10\log_{10}[\sum(1/y^2)/n] \quad (1.24)$$

Although signal-to-noise ratios have achieved good results, they have not been accepted by many in the statistical community. The controversy has focused more attention on variation or noise, whereas in the past the entire focus was on the average or signal. It is our opinion that with computer programs, it is quite easy to use three metrics average, variance, and signal-to-noise. Also, note that the advantages of the log transformation can be used with the average and the variance.

### 1.3.4.8 Loss Function

Taguchi has defined quality as the loss imparted to society from the time a product is shipped. Societal losses include failure to meet customer requirements, failure to meet ideal performance, and harmful side effects. Many practitioners have included the losses due to production, such as raw material, energy, and labor consumed on unusable products or toxic by-products.

### 1.3.4.9 Case Study 1: Vinyl Covers

The loss-to-society concept can be illustrated by an example associated with the production of large vinyl covers to protect materials from the elements. Figure 1.20 shows three stages in the evolution of vinyl thickness. At (1), the process is just

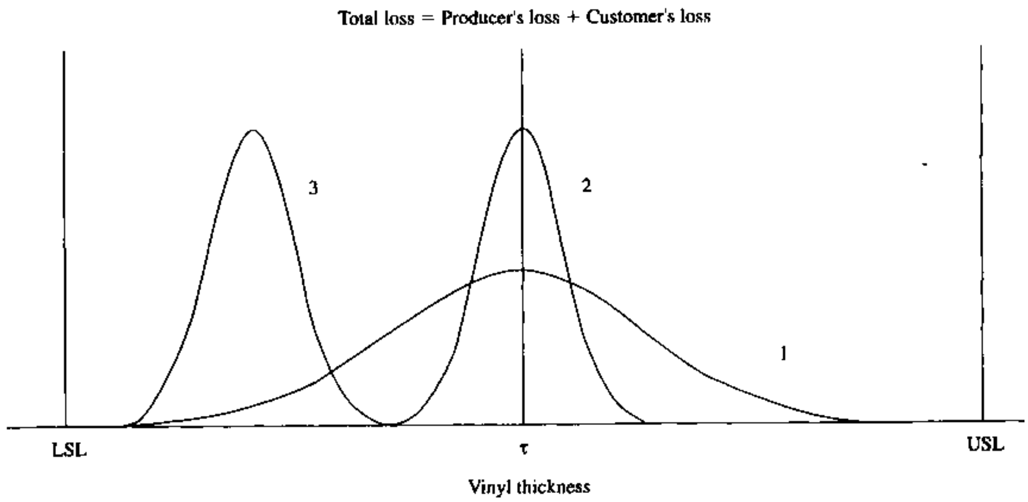



**Figure 1.20** Loss to Society

Reproduced, with permission, from *Taguchi Methods: Introduction to Quality Engineering* (Allen Park, Mich.: American Supplier Institute, Inc., 1991) capable of meeting the specifications (USL and LSL); however, it is on the target *tau,τ ( Taguchi uses the symbol m for the target).* After considerable effort, the production process was improved by reducing the variability about the target, as shown at (2). In an effort to reduce its production costs, the organization decided to shift the target closer to the LSL, as shown at (3). This action resulted in a substantial improvement by lowering the cost to the organization; however, the vinyl covers were not as strong as before. When farmers used the covers to protect wheat from the elements, they tore and a substantial loss occurred to the farmers. In addition, the cost of wheat increased as a result of supply-and-demand factors, thereby causing an increase in wheat prices and a further loss to society. The company's reputation suffered, which created a loss of market share with its unfavorable loss aspects.

Assuming the target is correct, losses of concern are those caused by a product's critical performance characteristics deviating from the target.

#### 1.3.4.10 Case Study 2 : Sony Televisions

The importance of concentrating on "hitting the target" is documented by Sony. In spite of the fact that the design and specifications were identical, U.S. customers preferred the color density of shipped TV sets produced by Sony-Japan over those produced by Sony-USA. Investigation of this situation revealed that the frequency distributions were markedly different, as shown in Figure 1.21. Even though Sony-Japan had 0.3% outside the specifications, the distribution was normal and centered on the target.

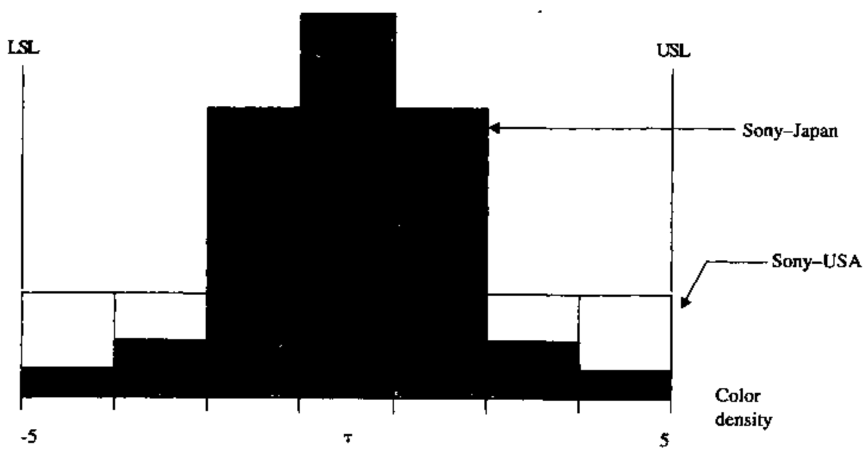



**Figure 1.21** Distribution of Color Density for Sony-USA and Sony-Japan

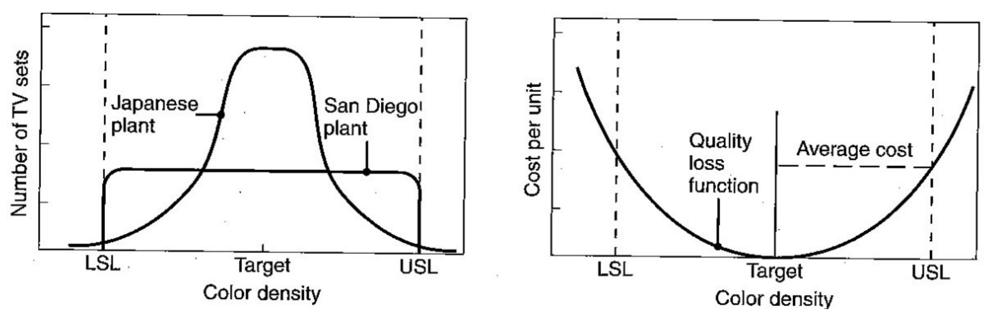



**Figure 1.22** (a) Objective function value distribution of color density for television sets. (b) Taguchi loss function, showing the average replacement cost per unit to correct quality problems

The distribution of the Sony-USA was uniform between the specifications with no values outside specifications. It was clear that customers perceived quality as meeting the target (Japan) rather than just meeting the specifications (USA). The marketplace proves that minimizing deviations is a worthwhile quality goal. The SONY case showed that quality is more than just producing between upper and lower limits- quality is achieving the target as much as possible and limiting deviations from the target.

Out of specification is the common measure of quality loss. Although this concept may be appropriate for accounting, it is a poor concept for all other areas. It implies that all products that meet specifications are good, whereas those that do not are bad. From the customer's point of view, the product that barely meets specification is as good (or bad) as the product that is barely out of specification. It appears the wrong measuring system is being used. The loss function corrects for the deficiency described above by combining cost, target, and variation into one metric.

**1.3.4.11 Orthogonal Arrays**

Orthogonal arrays (OA) are a simplified method of putting together an experiment. The original development of the concept was by Sir R. A. Fischer of England in the 1930s. Taguchi added three OAs to the list in 1956, and the National Institute of Science and Technology (NIST) of the United States added three.

In design of experiments, orthogonal means ″balanced″, ″separable″ , or not ″mixed″.The Taguchi method utilizes orthogonal arrays from design of experiments theory to study a large number of variables with a small number of experiments.

OAs are constructed in such a way that, for each level of any one factor, all levels of other factors occur an equal number of times thereby giving a balanced design. As compared with a full factorial design, the number of experiments in Taguchi's technique are thereby substantially reduced. At first glance, Dr Taguchi's methods seem to be nothing more than an application of Fractional Factorials. In his approach to quality engineering, however, the primary goal is is the optimization of product/process design for minimal sensitivity to noise. Dr. Taguchi stresses the need for a confirmatory experiment. If there are strong interactions, a confirmatory experiment will show them. If predicted results are not confirmed, the experiment must be re-developed.

The convention for naming arrays is $L_a(b^c)$ where a is the number of experimental runs, b the number of levels of each factor, and c the number of columns in the array.

Arrays can have factors with many levels, although two and three level factors are most commonly encountered. For the selection of a particular OA, the number of parameters, the number of levels, and their possible interactions must be taken into consideration.

To determine the appropriate orthogonal array, use the following procedure:

1. Define the number of factors and their levels.
2. Determine the degrees of freedom.
3. Select an orthogonal array.
4. Consider any interactions.

Degrees of Freedom

The number of degrees of freedom is a very important value because it determines the minimum number of treatment conditions. It is equal to the sum of

(Number of levels - 1) for each factor.

(Number of levels - l)(number of levels - 1) for each interaction.

One for the average.

*Selecting the Orthogonal Array*

Once the degrees of freedom are known, the next step, selecting the orthogonal array (OA), is easy. The number of treatment conditions is equal to the number of rows in the OA and must be equal to or greater than the degrees of freedom. Table 1.6 shows the orthogonal arrays that are available, up to OA36. Thus, if the number of degrees of freedom is 13, then the next available OA is OA16. The second column of the table has the number of rows and is redundant with the designation in the first column.

**Table 1.6.** Orthogonal Array Information

| OA | Number of Rows | Maximum Number of Factors | MAXIMUM NUMBER OF COLUMNS | | | |
|---|---|---|---|---|---|---|
| | | | 2- Level | 3-Level | 4-Level | 5-Level |
| OA2 | 4 | 3 | 3 | - | - | - |
| OA8 | 8 | 7 | 7 | - | - | - |

| | | | | | | |
|---|---|---|---|---|---|---|
| OA9 | 9 | 4 | - | 4 | - | - |
| OA12 | 12 | 11 | 11 | - | - | - |
| OA16 | 16 | 15 | 15 | - | - | - |
| OA16[1] | 16 | 5 | - | - | 5 | - |
| OA18 | 18 | 8 | 1 | 7 | - | - |
| OA25 | 25 | 6 | - | - | - | 6 |
| OA27 | 27 | 13 | - | 13 | - | - |
| OA32 | 32 | 31 | 31 | - | - | - |
| OA32[1] | 32 | 10 | 1 | - | 9 | - |
| OA36 | 36 | 23 | 11 | 12 | - | - |
| OA36[1] | 36 | 16 | 3 | 13 | - | - |
| . | . | . | . | . | . | . |
| . | . | . | . | . | . | . |
| . | . | . | . | . | . | . |

The third column gives the maximum number of factors that can be used, and the last four columns give the maximum number of columns available at each level.

Analysis of the table shows that there is a geometric progression for the two-level arrays of OA4, OA8, OA16, OA32,..., which is $2^2$,$2^3$,$2^4$,$2^5$,..., and for the three-level arrays of OA9, OA27, OA81, . . . , which is $3^2$, $3^3$, $3^4$,……. Orthogonal arrays can be modified.

For example, in L9 orthogonal array, the columns are mutually orthogonal. That is, for any pair of columns, all combinations of factor levels occur; and they occur an equal number of times. Here there are four parameters A, B, C, and D, each at three levels. This is called an "L9" design, with the 9 indicating the nine rows, configurations, or prototypes to be tested. Specific test characteristics for each experimental evaluation are identified in the associated row of the table. Thus, L9 means that nine experiments are to be carried out to study four variables at three levels. The number of columns of an array represents the maximum number of parameters that can be studied using that array.

Note that this design reduces 81 ($3^4$) configurations to 9 experimental evaluations [65-69].

**Table 1.7**. L9 array

| | Column | | | |
|---|---|---|---|---|
| No. | A | B | C | D |
| 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 2 | 2 | 2 |
| 3 | 1 | 3 | 3 | 3 |
| 4 | 2 | 1 | 2 | 3 |
| 5 | 2 | 2 | 3 | 1 |
| 6 | 2 | 3 | 1 | 2 |
| 7 | 3 | 1 | 3 | 2 |
| 8 | 3 | 2 | 1 | 3 |
| 9 | 3 | 3 | 2 | 1 |

# CHAPTER 2

## 2. MATERIAL AND METHOD

This study is planned at two stages in general. The first stage consists of the experimental part and the second stage is the numerical modeling part.

For this study, the workpieces used in the turning tests were cylindrical bars with a diameter of 45 mm and length of 290 mm ( useful cutting length100 mm) of magnesium alloy. Test materials Mg were provided by MMM International Trading CO.A Johnford TC 35 CNC lathe was used. In the experimental study, Used cutting tools which are made exclusively by Ingersoll External Tool Holders THSNR/L. During each test, cutting forces, surface roughness, hardness and cutting temperature are measured and compared. The surface roughness value on the workpiece obtained after the machining process was measured by MAHR Perthometer surface roughness measuring instrument. Three measurements were performed on the machined surfaces to determine the Ra values. For the force measurements, KISTLER 9121 force sensor, KISTLER 5019b charge amplifier and DynoWare analysis program were used. Turning operation was performed with Kistler 9121 three component dynamometer. The integrated cable from the dynamometer was connected to the three channel charge amplifier (model type 5019b). The output of the amplifier was connected to the data acquisition system.

Temperature measurements were taken with infrared camera. The purpose of the temperature measurement using infrared camera was to measure the temperature of the machined surface. When using the infrared camera, the emissivity of the material is a critical parameter and will greatly influence the accuracy of the measurement results. An emissivity of **0.1** and humidity of 45% were used for this study. The hardness on the workpiece material was measured by Instron Wolpert Hardness tester. The MQL experiments were conducted with air pressure of 6 bar and a flow rate of 40 ml/hour through the external nozzle.

Minimum quantity lubrication systems for external feed

Metered lubricant is atomized by compressed air in a spray nozzle. That produces micro-droplets that make their way together with the carrier air to the friction point without any mist being formed. Devices for external feed transport the lubricant and the separate atomisation air to near the contact point. This takes place in a coaxial or parallel pipework packet. At the end of the pipes, the lubricant is atomised with a spray nozzle and fed to the tool as an aerosol from outside. Low cost, simple retrofitting and the option of deploying conventional tools are the key advantages of these systems. However, all of these systems have disadvantages that limit their use owing to the principle involved. The nozzles have to be manually adjusted or adjusted via supplementary positioning axes to the tool; there are also losses due to dispersion and shadowing effects. Figure 2.1 shows External Minimal Quantity Lubrication System & Microdroplets sprayed by a triple concentric flow nozzle.

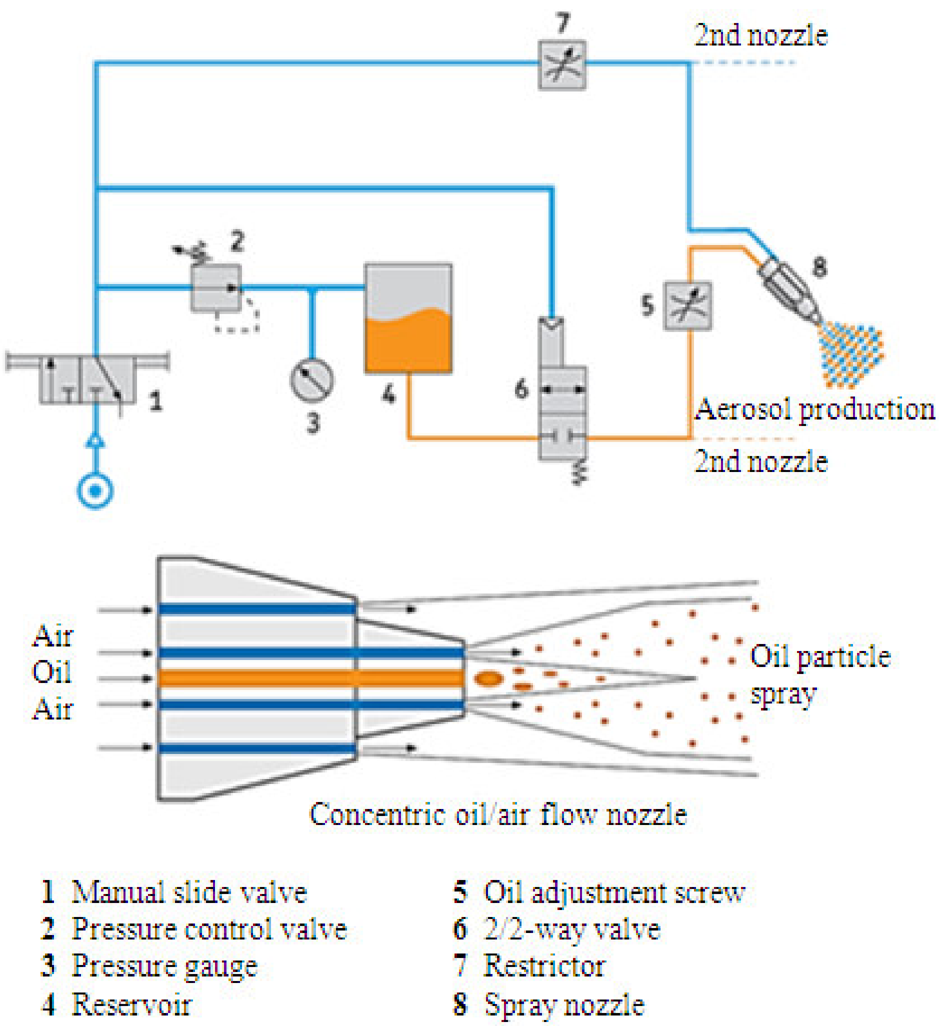



**Figure 2.1** External Minimal Quantity Lubrication System & Microdroplets sprayed by a triple concentric flow nozzle

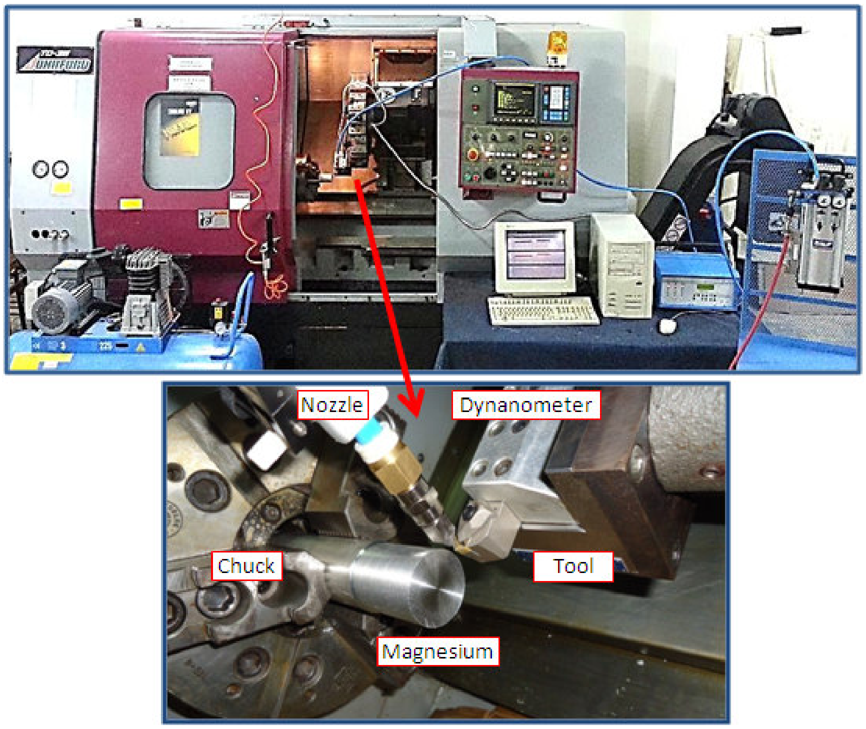



**Figure 2.2** Photographic view of the experimental set-up for turning under minimum quantity lubricant conditions

The experimental conditions are given in Table 2.1.

**Table 2.1**. Experimental Conditions

| Experimental Conditions | |
|---|---|
| Machine Tool | A Johnford TC 35 CNC Lathe |
| Work Specimen | |
| Materials | Magnesium,( Mg= 99.91%, Ca=0.0036%, Mn= 0.027%, Cu= 0.0018%, |
| | Fe= 0.028%, Si= 0.018%, Zn= 0.0028%, Al= 0.016%, Ni= 0.0007% |
| | Cl= 0.0033%, Pb= 0.0028%, Na= 0.0031%) |
| Size | φ 45X290 mm |
| | Cylindrical bars with a diameter of 45 mm and length of 290 mm ( useful cutting length 100 mm) |

| | |
|---|---|
| Cutting tool( insert) | |
| Cutting insert | Ingersoll HNMG GU negative 120$^o$ hexagonal inserts for medium roughing |
| Tool holder | Ingersoll external tool holders thsnr |
| Cutting Parameters | |
| Cutting Speed | 230, 330, 430 m/min |
| Feed Rate | 0.2, 0,35, 0,5 mm/rev |
| Depth of Cut | 1, 2 and 3 mm |
| MQL supply | Air: 6 bar, Lubricant: 40ml/h (through external nozzle) |
| Environment | Dry and minimum quantity lubrication (MQL) |

**2.1 Equipment and Device**

**Materials:**

CNC Lathe

Kistler Dynamometer

Infrared Camera

CNC Simulator

HT 600 Computer

DEA Gamma 0101 CNC Measuring Machine

Form Talysurf. Intra 50 surface roughness measuring instrument

Gagamaster Optical Comparator

Surtronic 3P portatable finish measuring instrument

Mitutoyo Digital Micrometer

ISI (100) Scanning Electron Microscope

Cutting Tools with different specifications

Magnesium Alloyed Materials

**CNC LATHE**

**Specifications:**

**Manufacturer:** Johnford

**Year:** 1998

**Swing Over Bed:** 500 mm

**Swing Over cross.:** 355 mm

**Between Centres:** 810 mm

**X axis travel:** 290 mm

**Y axis travel:** 650 mm

**Spindle Bore:** 85 mm

**Spindle motor:** 20 HP.

**Spindle speed:** 30-3500 rpm.

**Spindle nose:** A2-8

**Normal machining dia.:** 350 mm

**Chuck size:** 250 mm

**Bar capacity:** 75 mm

**Bed inclination:** 45 deg.

**Turret (no of tools):** 12

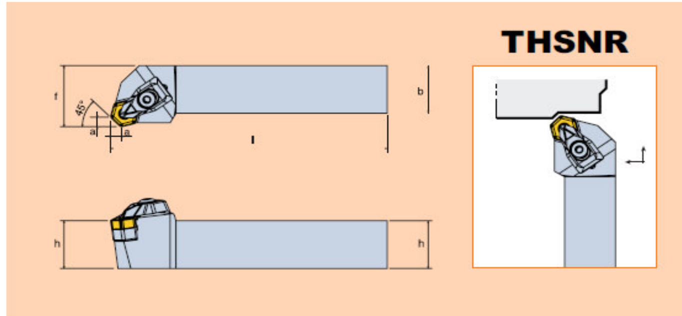
**Physical dim.:** 4200 mm L x 2030 mm W x 2350 mm H

**Weight:** 7484.27 kg

## Cutting Tool

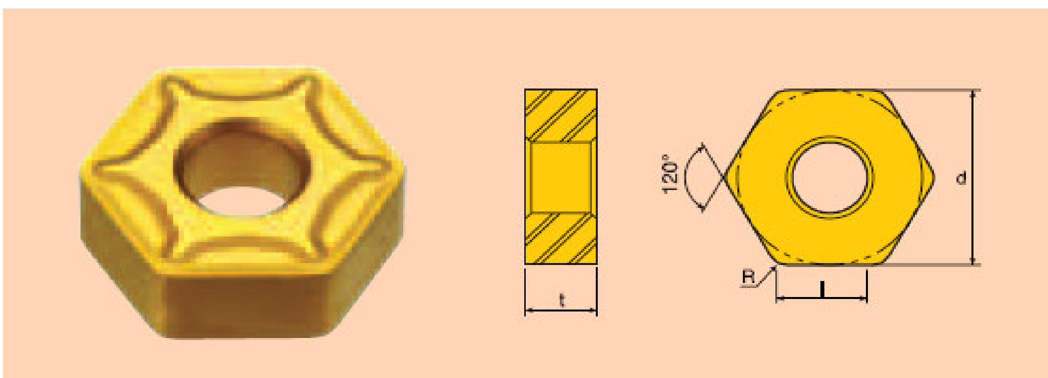
Used cutting tools which are made exclusively by Ingersoll.

**HEXAGON INSERT**


| Designation | Stock | | Dimensions (inch) | | | | | Insert | Clamp | Clamp Screw | Shim | Shim Screw | Spring | Clamp Wrench |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | R | L | h | b | l | f | a | 120° | | | | | | |
| THSNR/L 16-4D | • | • | 1.00 | 1.00 | 6.00 | 1.25 | .165 | HN□G 43□ | DLM4 | DLS4 | TSH44 | SO40050I | DSP4 | L-W3 |
| THSNR/L 20-4D | • | • | 1.25 | 1.25 | 6.00 | 1.57 | .165 | | | | | | | |

**Figure 2.3** External tool holders THSNR/L




| Designation | | Recommended Machining Conditions | | P M K N S H | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | feed (ipr) | ap (inch) | Grades & Vc (sfm) | | | | | | | | | | | | | | |
| ANSI | ISO | | | PV3010 | CT3000 | | TT1300 | TT1500 | TT3500 | TT5030 | TT5100 | TT7100 | TT8020 | | P10 | P20 | K10 | K20 |
| HNMG 432 GU | HNMG050408GU | .014 (.006-.024) | .080 (.020-.138) | | | | • 900 | | • 920 | | • 705 / 495 | | | | | | | |

**Figure 2.4** HNMG GU chipbreaker negative 120° hexagonal inserts for medium roughing

**Table 2.2.** The dimensional and mechanical properties of the cutting tools

| Designation | l | d | t | R |
| --- | --- | --- | --- | --- |
| HNMG432GU | .244 | .500 | .187 | .031 |

**Kistler Dynamometer**

3-component toolholder dynamometer for measuring force components during turning. Quartz three-component dynamometer for measuring the three orthogonal components of a force. The dynamometer is used to measure cutting forces on turning machines with tool turret.The dynamometer Type 9121 consists of four three-component force sensors fitted under high preload between a base plate and a top plate. Each sensor contains three pairs of quartz plates, one sensitive to pressure in the z direction and the other two responding to shear in the x and y direction respectively. The force components are measured practically without displacement. The four sensors are mounted ground-isolated. Therefore ground loop problems are largely eliminated. The dynamometer is rustproof and protected against penetration of splashwater and cooling agents. Together with te connecting cable Type 1689B5 it coresponds to the protection class IP67.

Applications

• Cutting force measurements on turning machines with tool turret. In conjunction with the calibrated partial ranges the high sensitivity and low threshold allow also precise measurements on small tools.

• Calibration of the force measuring device of tool monitoring systems.

Mounting

Dynamometer, revolver adapter, toolholder and connecting cable are assembled as a unit.

The mounted measuring device is then fixed to the tool turret by means of the clamping system. Electronics Besides the dynamometer, a three-component force measuring system also needs three charge amplifiers, which convert the dynamometer charge singals into output voltages proportional to the forces sustained.

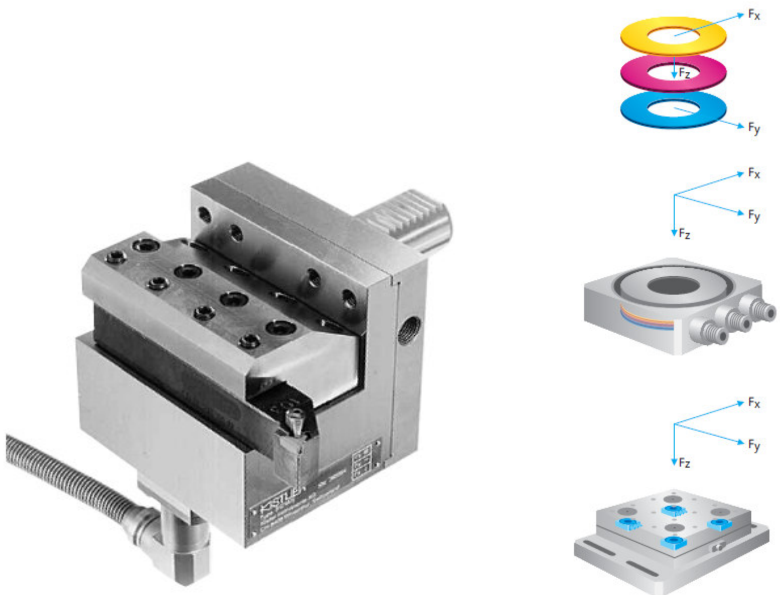



**Figure 2.5** Construction of a 3-component dynamometer ( $F_x$, $F_y$, $F_z$)

Two shear quartz – for Fx and Fy – and one pressure quartz – for Fz – incorporated in a single case constitute a 3-component sensor.

**Table 2.3.** Technical Data of Kistler Dynamometer

| Specifications | | | Type 9121 |
|---|---|---|---|
| Calibration | | | calibrated |
| Measuring Range | Fx, Fy | kN | –3 ... 3 |
| | Fz | kN | –6 ... 6 |
| Sensitivity | Fx, Fy | pC/N | ≈-7.9 |
| | Fz | pC/N | ≈-3.8 |
| Linearity, all ranges | | % FSO | ≤ ±1 |
| Hysteresis, all ranges | | % FSO | ≤ 0.5 |
| Cross talk, all axes | | % | ≤±3 |
| Natural Frequency | | Hz | ≈1000 |

| | | | |
|---|---|---|---|
| Rigidity | cx, cy, cz | | ≈ 600 N/ìm |
| Operating temperature range | | °C | 0...70 |
| Capacitance (of channel) | | pF | ≈170 |
| Isolation resistance, at 20 °C | | Ω | $>10^{13}$ |
| Height | | in | 3.78 |
| Mass | | kg | 5 |

Turning operation was performed with Kistler 9121 three component dynamometer. The integrated cable from the dynamometer was connected to the three channel charge amplifier (model type 5019b). The output of the amplifier was connected to the data acquisition system.

**Figure 2.6** For the force measurements, KISTLER 9121 force sensor, KISTLER 5019b charge amplifier and DynoWare analysis program were used.

The dynamometer is capable of measuring feed force, thrust force and main cutting force which occurs during turning operations as seen in Figure 2.6.

The surface roughness value on the workpiece obtained after the machining process was measured by MAHR Perthometer surface roughness measuring instrument (see Figure

2.7). The hardness on  the workpiece material was measured by Instron Wolpert Hardness tester (see Figure 2.8).


**Figure 2.7** MAHR Perthometer surface roughness measuring instrument

**Figure 2.8** Instron wolpert hardness tester

## 2.2 Method

The magnesium based material was formed by applying the orthogonal cutting. In this study, MQL turning performance was compared to dry conditions. The CNC Lathe was used for both cutting processes. The settings of turning parameters were determined by using Taguchi experimental design method.

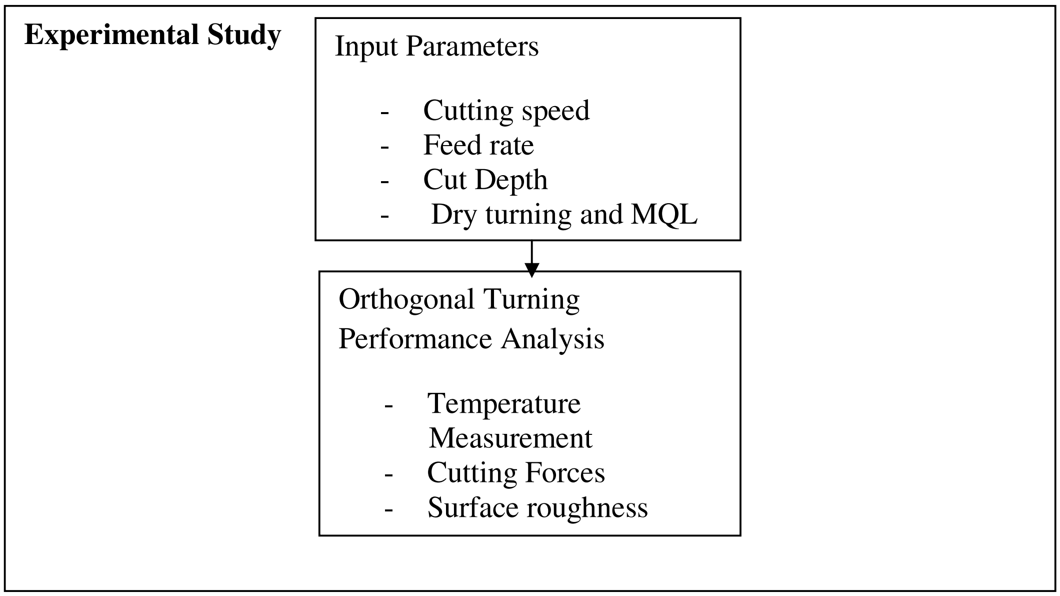



**Figure 2.9** Experimental Study

Orthogonal arrays of Taguchi, the signal-to-noise (S/N) ratio, the analysis of variance (ANOVA) analyses were carried out to determine the optimal levels and to analyze the effect of turning parameters such as cutting speed, feed rate, cutting depth on hardness, surface roughness, cutting temperature and cutting forces during dry and MQL turning.

The first step is to determine cutting parameters and their levels (input parameters).The ranges of cutting speed and feed rate were selected based on the tool manufacturer's recommendation and industrial practices.

TaeguTec Inspected

Cutting speed (m/min): 330 (300-370)

Cutting depth (mm): 2.0 (0.5-3.5)

Feed (mm/rev): 0.35 (0.15-0.6)

The next step is to identify performance characteristics (output parameters). The third step is to plan the experiment by orthogonal arrays using Minitab 16 Software.

Orthogonal Array is a matrix of numbers arranged in rows and columns in such a way that each pair of columns is orthogonal to each other. When used in an experiment, each row represents the state of factors in a given experiment. Each column represents a specific factor or condition that can be changed from experiment to experiment. The array is called orthogonal because the effects of the various factors in the experimental results can be separated from each other.

Taguchi Method is an experimental design technique that reduces the number of experiments significantly by using the orthogonal arrays. For example, L9 means that nine experiments are to be carried out to study four variables at three levels. The number of columns of an array represents the maximum number of parameters that can be studied using that array. Note that this design reduces 81 ($3^4$) configurations to 9 experimental evaluations. There are greater savings in testing for the larger arrays. Orthogonal arrays (OA) are a simplified method of putting together an experiment. Taguchi selects a particular factorial design (orthogonal array) that produces the most important information.

To select an appropriate orthogonal array for experiments, the total degrees of freedom need to be computed. The degrees of freedom are defined as the number of comparisons between process parameters that need to be made to determine which level is better and specifically how much better it is. For example, a three-level process parameter counts for two degrees of freedom. The degrees of freedom associated with interaction between two process parameters are given by the product of the degrees of freedom for the two process parameters. In the present study, the interaction between the cutting parameters is neglected. Therefore, there are six degrees of freedom owing to the three cutting parameters in turning operations. Once the degrees of freedom required are known, the next step is to select an appropriate orthogonal array to fit the specific task. Basically, the degrees of freedom for the orthogonal array should be greater than or at least equal to those for the process parameters.

The smallest three level OA, L9, has four 3 level columns. With three 3 level factors in this study, the L9 is appropriate for the design. The factors are placed in the first three columns, leaving the fourth column unused. Note that this design reduces 27 ($3^3$) configurations to 9 experimental evaluations. Table 2.4 shows the experiment design.

**Table 2.4.** Experimental design for the Taguchi method

| | Factors | Cutting Speed (m/min) | Feed Rate ( mm/rev) | Depth of cut (mm) |
|---|---|---|---|---|
| LEVELS | 1 | 230 | 0.20 | 1 |
| | 2 | 330 | 0.35 | 2 |
| | 3 | 430 | 0.50 | 3 |
| Run Order | | | | |
| 1 | | 1 | 1 | 1 |
| 2 | | 1 | 2 | 2 |
| 3 | | 1 | 3 | 3 |
| 4 | | 2 | 1 | 2 |
| 5 | | 2 | 2 | 3 |
| 6 | | 2 | 3 | 1 |
| 7 | | 3 | 1 | 3 |
| 8 | | 3 | 2 | 1 |
| 9 | | 3 | 3 | 2 |

The fourth step is to conduct the experiments .

For the next step, the signal-to-noise (S/N) ratio, the analysis of variance (ANOVA) were carried out to determine the optimal levels and to analyze the effect of turning parameters such as cutting speed, feed rate, cutting depth on hardness, surface roughness, temperature and cutting forces during dry and MQL turning.

The experimental results are transformed into a signal-to-noise (S/N) ratio. Taguchi recommends the use of the S/N ratio to measure the quality characteristics deviating from the desired values. Usually, there are three categories of quality characteristic in the analysis of the S/N ratio, i.e. the lower the better, the higher the better, and the nominal the better. The S/N ratio for each level of process parameters is computed based on the S/N analysis. Regardless of the category of the quality characteristic, a greater S/N ratio corresponds to better quality characteristics. Therefore, the optimal level of the process parameters is the level with the greatest S/N ratio. The smaller the better charecteristic from the Taguchi method was applied to the average roughness Ra, cutting forces, and cutting temperature. The greater the hardness of the metal, the greater resistance it has to deformation. It can generally be assumed that a strong metal is also a hard metal. For hardness, Larger the better characteristic was applied.

With the S/N and ANOVA analyses, the optimal combination of the process parameters can be predicted. The purpose of ANOVA is to investigate which cutting parameters significantly affect the performance characteristic. A statistical package (Minitab) is used to conduct analysis of variance (ANOVA). Data collected from experiments are analysed by ANOVA. The purpose of ANOVA is to separate the total variability of the data, which is measured by the sum of the squared deviations from the mean value, into contributions by each of the factors and the error [22,23]. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the parameter design. The confirmation experiment is intended to verify the experimental predictions.

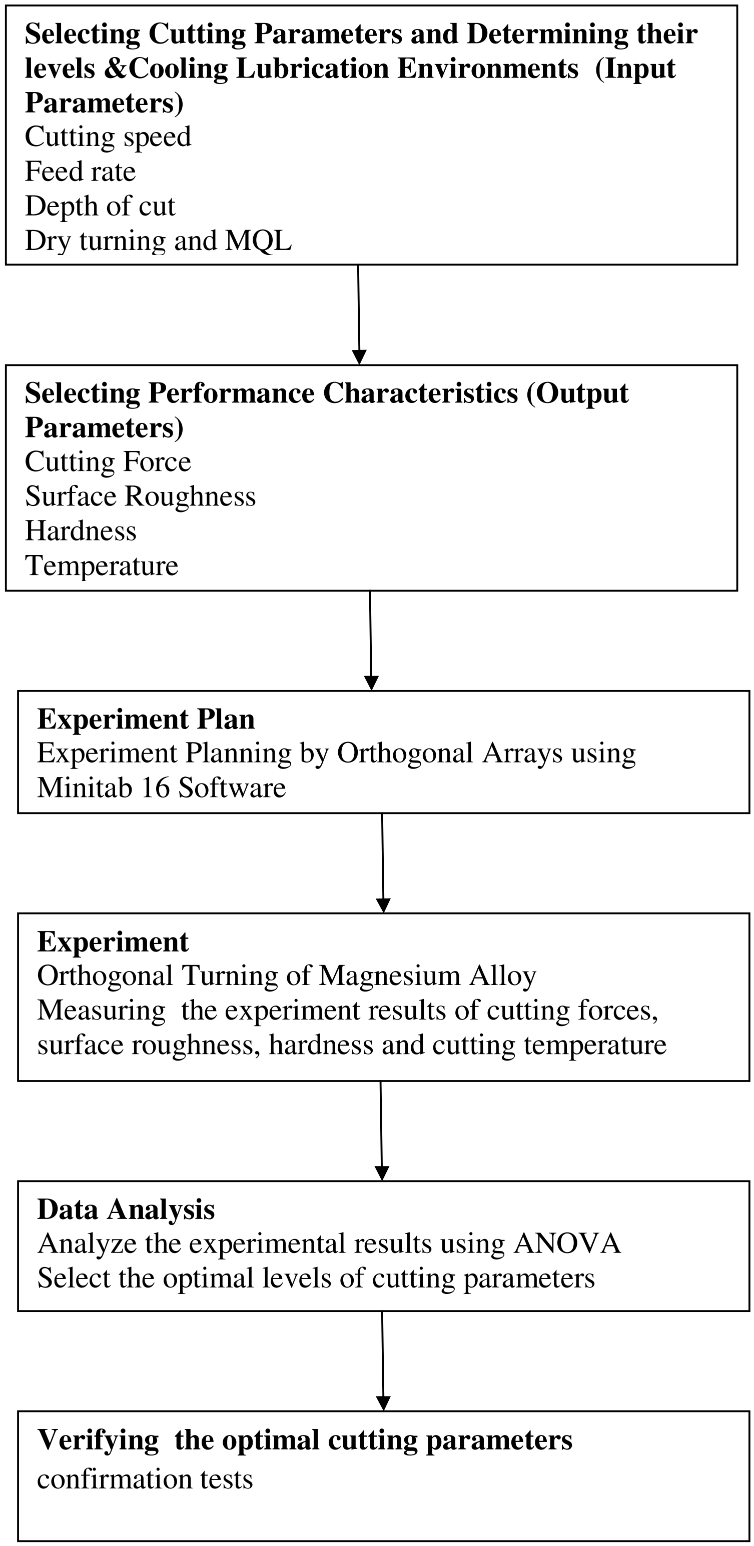



**Figure 2.10** Experimental Procedure

# CHAPTER 3

## 3. Results and Discussion

In this chapter, results of the cutting experiments are studied using the S/N and ANOVA analyses. Based on the results of the S/N and ANOVA analyses, optimal settings of the cutting parameters for cutting forces, surface roughness, hardness and cutting temperature are obtained.

### 3.1 Results

#### 3.1.1 Selecting the optimal cutting conditions

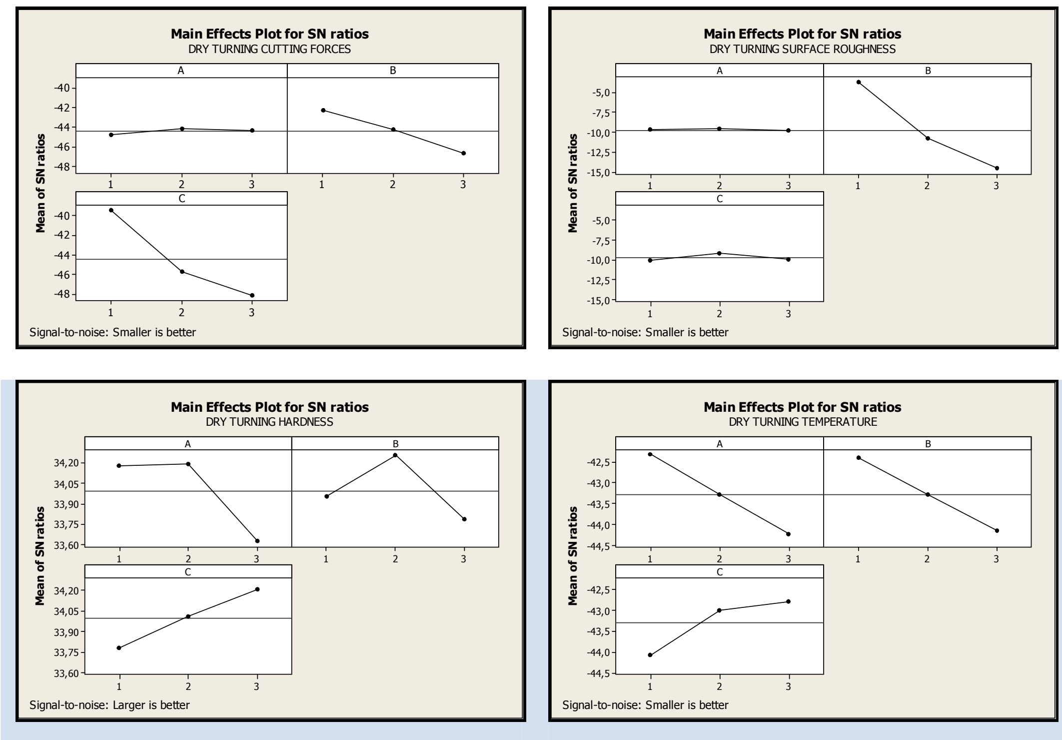



**Figure 3.1** Main effects plot for SN ratios (DRY machining, cutting forces, surface roughness, hardness, cutting temperature)

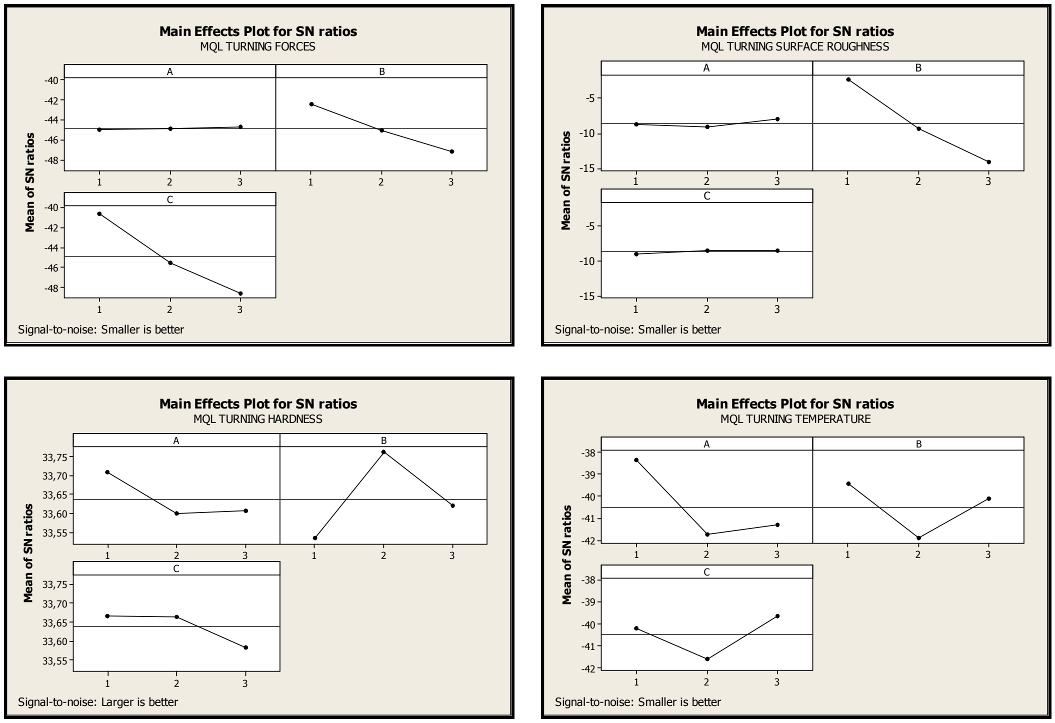



**Figure 3.2** Main effects plot for SN ratios (MQL machining, cutting forces, surface roughness, hardness, cutting temperature)

The S/N ratio for each level of process parameter is computed based on S/N analysis. Regardless of the category of the performance characteristic, the larger S/N ratio corresponds to a better performance characteristic. Therefore, the optimal level of a process parameters is the level with the highest S/N ratio.The signal to ratio (S/N) was used for the analysis of the results. The smaller the better charecteristic from the Taguchi method was applied to the average roughness Ra, cutting forces, and cutting temperature. For hardness, Larger the better characteristic was applied.

The present work has led to the following results

**Table 3.1** . Optimal conditions comparison

| | Predicted Value | Confirmation Tests Value | Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) |
|---|---|---|---|---|---|
| | | | **DRY TURNING** | | |
| **Cutting Forces** | 35N | 38.5 N | 330 | 0.2 | 1 |
| **Surface Roughness** | 1.32µm | 1.37µm | 230 | 0.2 | 2 |
| **Temperature** | 107 °C | 114 °C | 230 | 0.2 | 3 |
| **Hardness** | 54 kg/mm² | 53.5 kg/mm² | 330 | 0.35 | 3 |
| | | | **MQL TURNING** | | |
| **Cutting Forces** | 46 N | 50 N | 430 | 0.2 | 1 |
| **Surface Roughness** | 1.16 µm | 1.14 µm | 430 | 0.2 | 2 |
| **Temperature** | 63 °C | 68 °C | 230 | 0.2 | 3 |
| **Hardness** | 49.3 kg/mm² | 48.4 kg/mm² | 230 | 0.35 | 1 |

### 3.1.2 Cutting Forces

In this study, dry conditions reduced the average cutting force by about 3.6%.

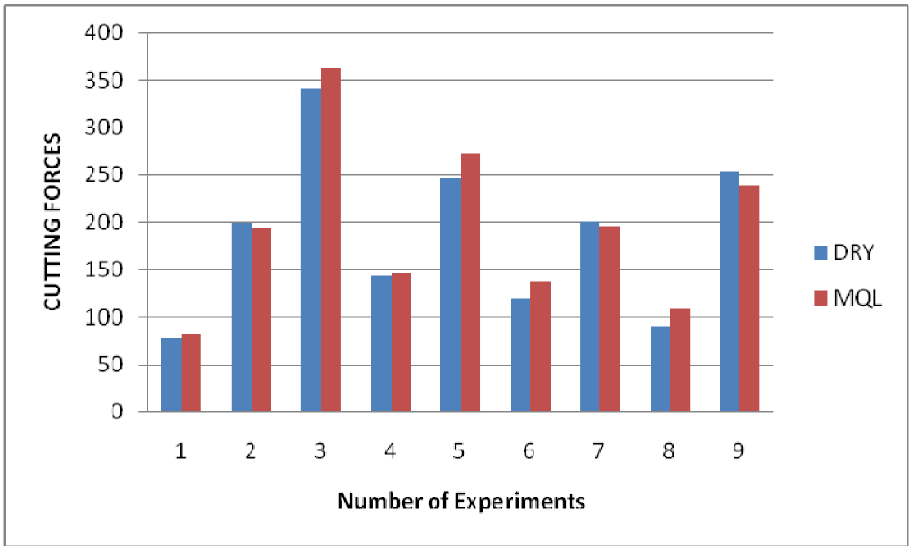



**Figure 3.3** Cutting Forces Comparison

The optimal cutting parameters for cutting forces are cutting speed at level 2, feed rate at level 1, and depth of cut at level 1 under dry conditions (Vc=330 m/min , f= 0.2 mm/rev, d=1 mm). The predicted result for cutting force is 34.7 N for optimal cutting parameters **2, 1, 1** under dry conditions **.**

The optimal cutting parameters for cutting forces are cutting speed at level 3, feed rate at level 1, and depth of cut at level1 under mql conditions (Vc=430 m/min , f= 0.2 mm/rev, d=1 mm). The predicted result for cutting force is 46.14 N for optimal cutting parameters **3, 1, 1** under minimum quantity lubricant conditions **.**

Results of ANOVA indicate that depth of cut is the most significant cutting factor for affecting the cutting forces.

From the analysis of Table 3.2 for dry turning, we can observe that the depth of cut (73%), the feed rate (24%), and the cutting speed (2.4%) have statistical and physical significances on cutting forces, especially cutting depth.

The depth of cut is the cutting condition that has highest physical as well as statistical influence on the cutting forces (72%), right after the feed rate (27%) , and the cutting speed (0.68%) according to Table 3.3 for turning with minimum quantity lubrication.

**Table 3.2** ANOVA results for the  cutting forces for dry turning of magnesium

| ANOVA dry turning cutting forces | | | | | |
|---|---|---|---|---|---|
| Source | df | SS | MS | F | % |
| v | 2 | 2057.3 | 1028.7 | 2.98 | 2.4 |
| f | 2 | 14290.1 | 7145.0 | 20.69 | 24 |
| d | 2 | 42525.4 | 21262.7 | 61.58 | 73 |
| Error | 2 | 690.5 | 345.3 | | |
| Total | 8 | 59563.4 | | | 100 |
| Significance at 95% confidence | | | | | |

**Table 3.3** ANOVA results for the cutting forces for mql turning of magnesium

| ANOVA mql turning cutting forces | | | | | |
|---|---|---|---|---|---|
| Source | df | SS | MS | F | % |
| v | 2 | 1758 | 879 | 1.19 | 0.68 |
| f | 2 | 16635 | 8317 | 11.27 | 27 |
| d | 2 | 41819 | 20910 | 28.33 | 72.32 |
| Error | 2 | 1476 | 738 | | |
| Total | 8 | 61688 | | | 99.82 |
| Significance at 95% confidence | | | | | |

The analysis is performed by noting the sources of variation in the left hand column, which are, of course, the three factors under test in the experiment. The column labelled df indicates the degrees of freedom for the factor. The next coloumn labelled SS, is the sum of squares for the factor. The column labelled MS is the mean sum of squares, i.e. the sum of squares for the factor divided by the degrees of freedom in that factor. The columnn labelled F is the results of the traditional Fisher test for significance, and asterisks denote whether the factor was significant at 95% confidence. Confidence, in statistical sense, means thereis some chance of a mistake. Percent contribution (%) is described as the significance rate of the turning parameters such as cutting speed (v) , feed rate (f), cutting depth (d) on surface roughness, temperature and cutting forces during dry and MQL turning . Percent contribution is shown in the right hand column.

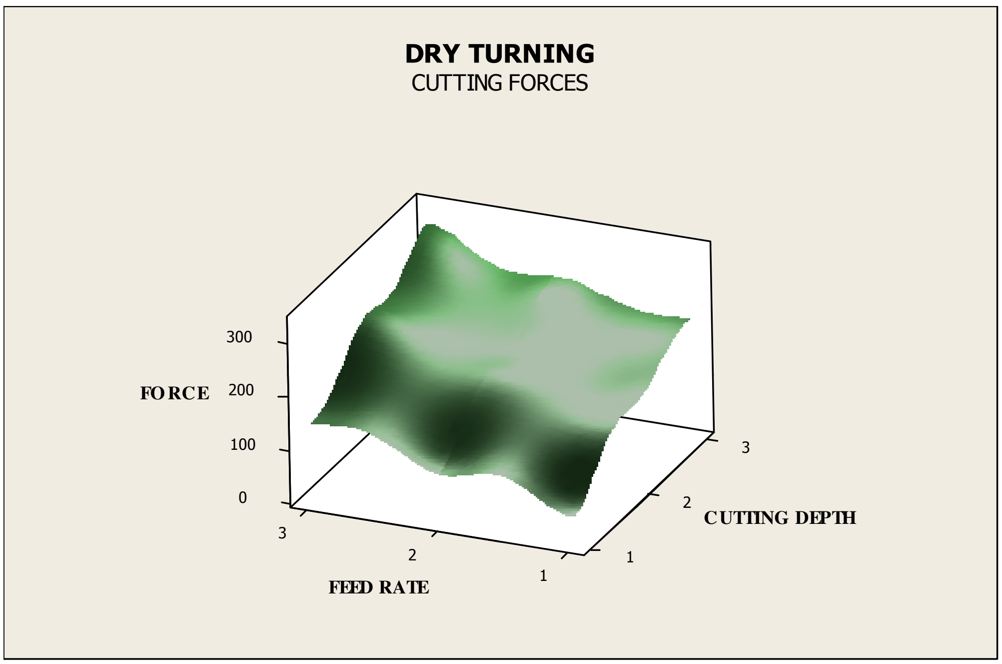



**Figure 3.4** The effect of feed rate and cutting depth on cutting force

### 3.1.3 Surface Roughness

It is found that the application of MQL can effectively reduce surface roughness by 10%.

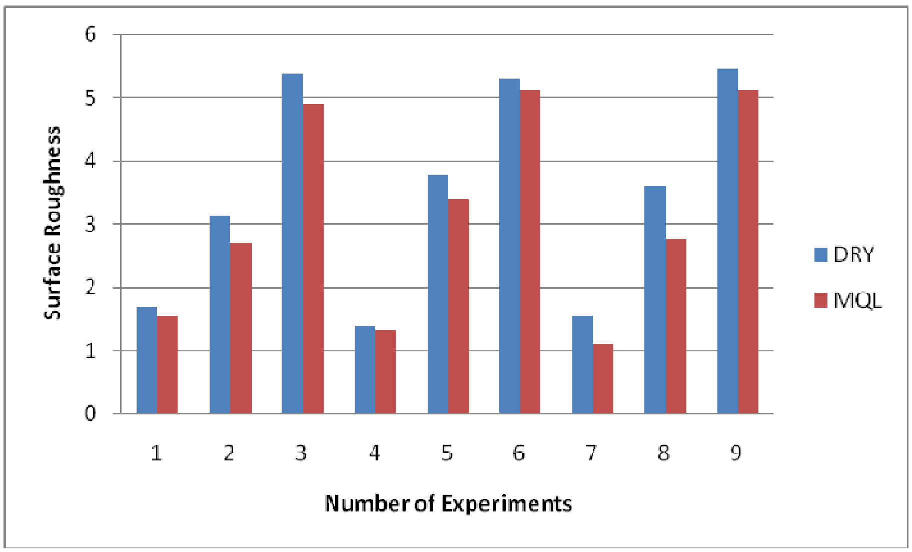



**Figure 3.5** Surface Roughness Comparison

The optimal cutting parameters are cutting speed at level 1, feed rate at level 1, and depth of cut at level 2 under dry conditions (Vc=230 m/min , f= 0.2 mm/rev, d=2 mm). The predicted result for surface roughness is 1.31 µm for optimal cutting parameters 1, 1, 2 under dry conditions **.**

The optimal cutting parameters are cutting speed at level 3, feed rate at level 1, and depth of cut at level 2 under minimum quantity lubricant conditions (Vc=430 m/min , f= 0.2 mm/rev, d=2 mm). The predicted result for surface roughness is 1.16 µm for optimal cutting parameters 3, 1, 2 under mql conditions.

The principal result is that the best surface finishes are obtained for low feeds. The best surface finish has been obtained for a feed of 0.2 mm/rev. As a result, it was observed that effect of cutting feed on roughness was great, cutting speed was less and cutting depth was the least. Compared with dry machining, surface finish substantially improved by the application of minimum quantity lubricant.

ANOVA results show the significance of factors on surface roughness for dry and mql turning of magnesium (see Table 3.4 and 3.5)

**Table 3.4** ANOVA results for the surface roughness for dry turning of magnesium

| ANOVA dry turning surface roughness | | | | | |
|---|---|---|---|---|---|
| Source | df | SS | MS | F | % |
| v | 2 | 0.0290 | 0.0145 | 0.18 | 0.6 |
| f | 2 | 22.0068 | 11.0034 | 133.41 | 99 |
| d | 2 | 0.1014 | 0.0507 | 0.61 | 0.3 |
| Error | 2 | 0.1650 | 0.0825 | | |
| Total | 8 | 22.3022 | | | 99.9 |
| Significance at 95% confidence | | | | | |

**Table 3.5** ANOVA results for the surface roughness for mql turning of magnesium

| ANOVA mql turning surface roughness | | | | | |
|---|---|---|---|---|---|
| Source | df | SS | MS | F | % |
| v | 2 | 0.1433 | 0.0716 | 0.54 | 0.6 |
| f | 2 | 20.9053 | 10.4526 | 78.22 | 98 |
| d | 2 | 0.0146 | 0.0073 | 0.05 | 1.2 |
| Error | 2 | 0.2673 | 0.1336 | | |
| Total | 8 | 21.3304 | | | 99.8 |
| Significance at 95% confidence | | | | | |

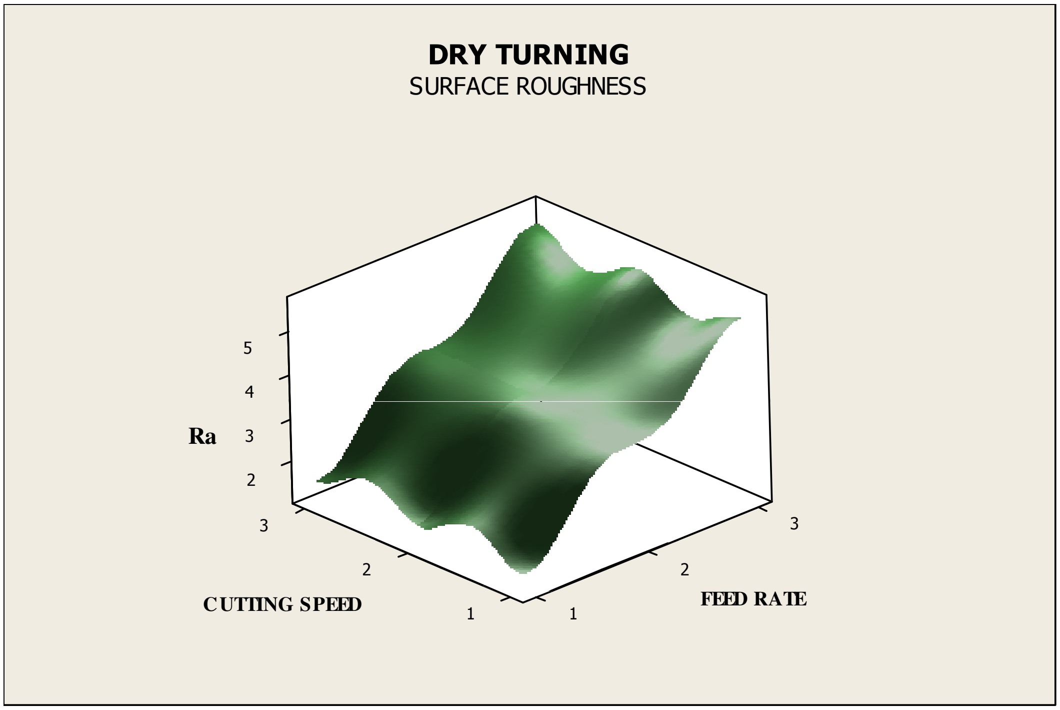



**Figure 3.6.** The effect of cutting speed and feed rate on surface roughness

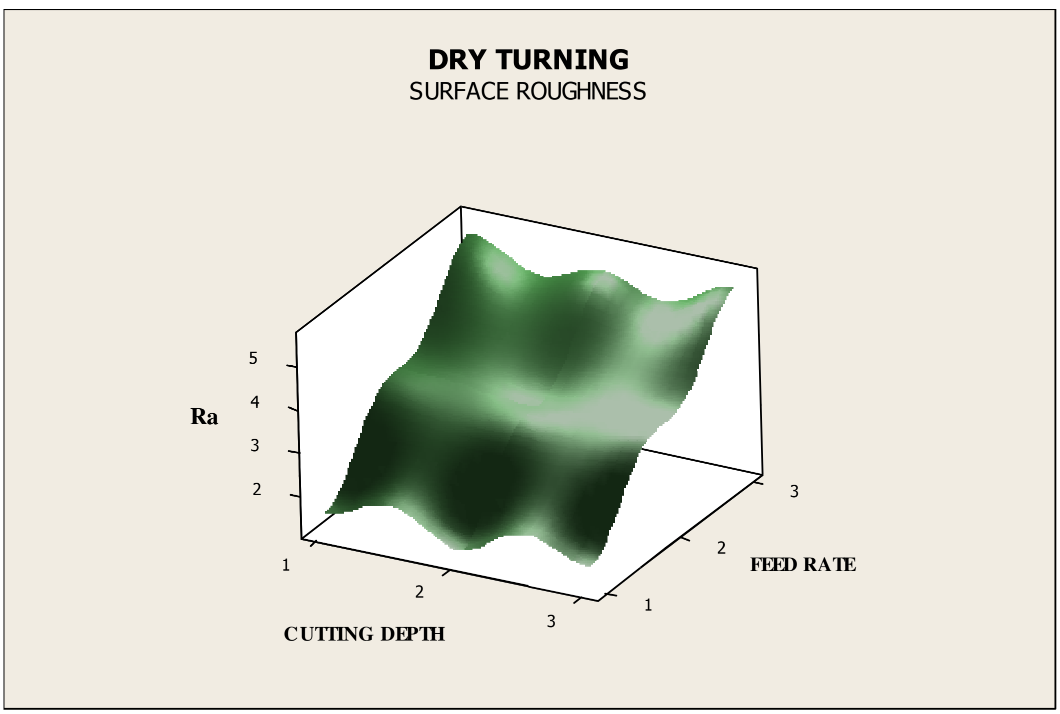



**Figure 3.7** The effect of cutting depth and feed rate on surface roughness

### 3.1.4 Hardness

The hardness generated by the dry turning is higher. Dry conditions increased hardness by about 4%.

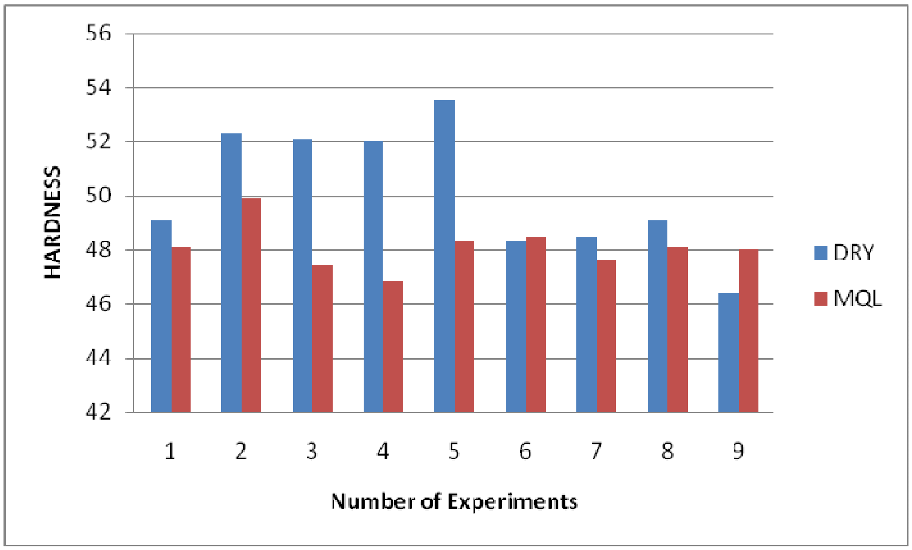



**Figure 3.8** Hardness Comparison

The optimal cutting parameters are cutting speed at level 2, feed rate at level 2, and depth of cut at level 3 (Vc=330 m/min , f= 0.35 mm/rev, d=3 mm). The predicted result for hardness is 54 HV1 for optimal cutting parameters **2, 2, 3** under dry conditions.

The optimal cutting parameters are cutting speed at level 1, feed rate at level 2, and depth of cut at level 1 (Vc=230 m/min , f= 0.35 mm/rev, d=1 mm). The predicted result for hardness is 49 HV1 for optimal cutting parameters **1, 2, 1** under minimum quantity lubricant conditions.

Cutting speed is the cutting condition that has highest physical as well as statistical influence on hardness (56%), right after the feed rate (28%) , and the cutting depth (19%) for dry turning according to ANOVA (see Table 3.6).But for turning with MQL, cutting depth is the most significant cutting parameter (53%),right after cutting speed (46%) and the feed rate (0.9%) according to ANOVA (see Table 3.7).

**Table 3.6.** ANOVA results for the hardness for dry turning of magnesium

| ANOVA dry machining hardness | | | | | |
|---|---|---|---|---|---|
| Source | df | SS | MS | F | % |
| v | 2 | 20.709 | 10.354 | 5.41 | 55.9 |
| f | 2 | 11.282 | 5.641 | 2.95 | 24.7 |
| d | 2 | 9.662 | 4.831 | 2.52 | 19.3 |
| Error | 2 | 3.829 | 1.914 | | |
| Total | 8 | 45.482 | | | 99.9 |
| Significance at 95% confidence | | | | | |

**Table 3.7.** ANOVA results for the hardness for mql turning of magnesium

| ANOVA mql machining hardness | | | | | |
|---|---|---|---|---|---|
| Source | df | SS | MS | F | % |
| v | 2 | 0.682 | 0.341 | 0.29 | 46 |
| f | 2 | 2.462 | 1.231 | 1.07 | 0.9 |
| d | 2 | 0.436 | 0.218 | 0.18 | 53 |
| Error | 2 | 2.378 | 1.189 | | |
| Total | 8 | 5.876 | | | 99.9 |
| Significance at 95% confidence | | | | | |

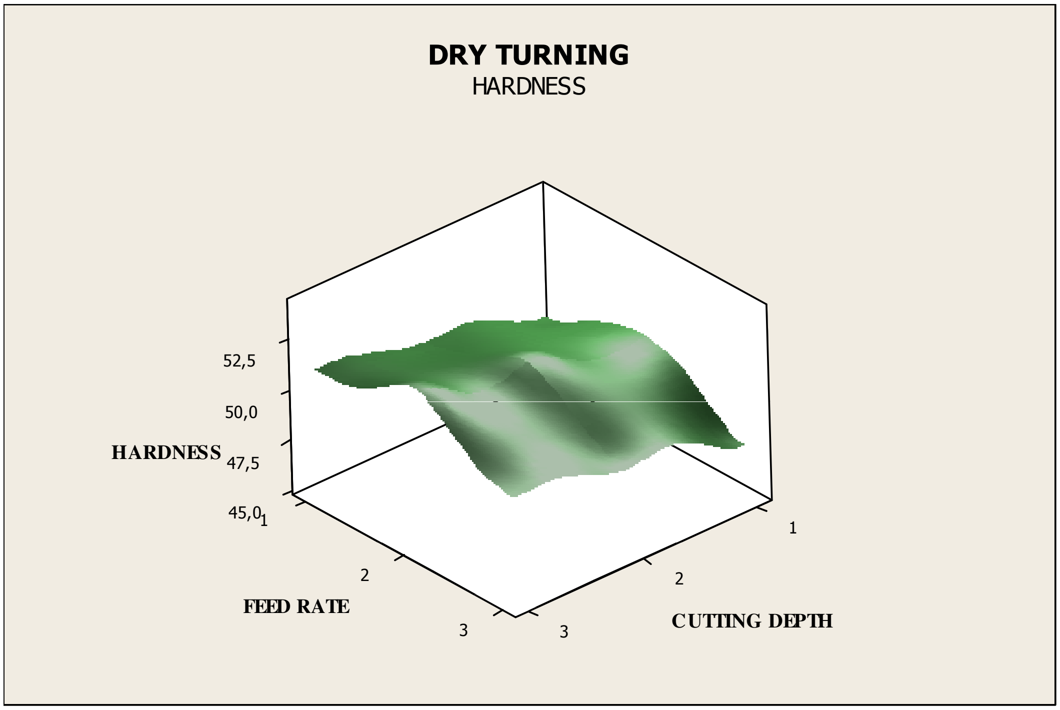



**Figure 3.9** The effect of feed rate and cutting depth on hardness

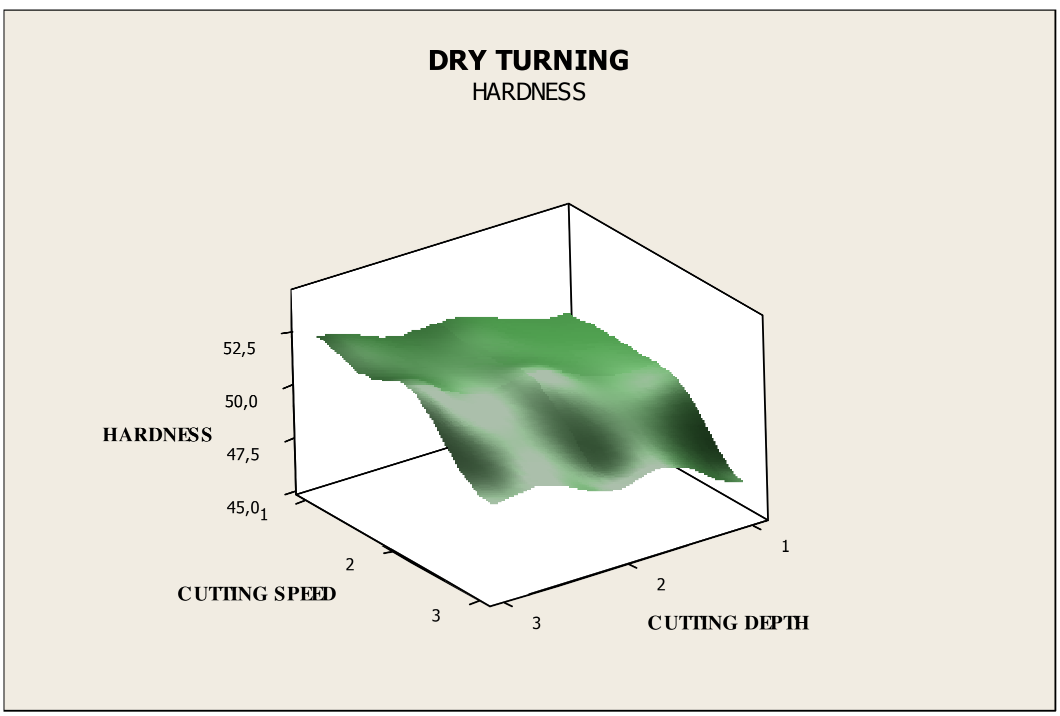



**Figure 3.10** The effect of cutting speed and cutting depth on hardness

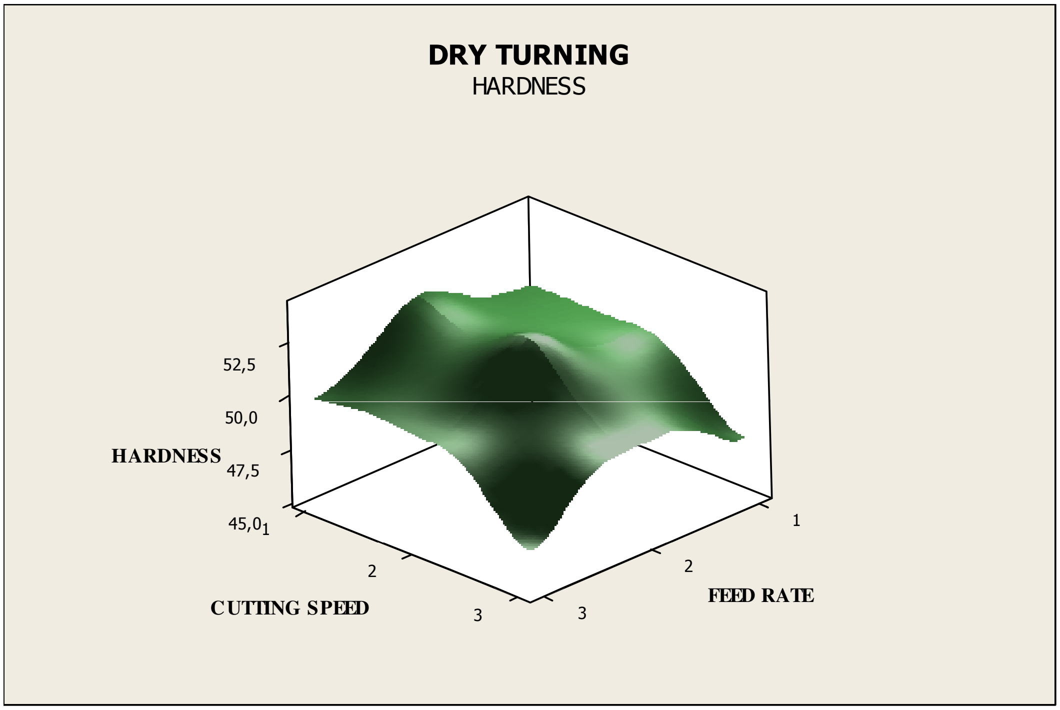



**Figure 3.11** The effect of cutting speed and feed rate on hardness

### 3.1.5 Cutting Temperature

In the case of cutting temperature, all of the cutting conditions, cooling lubrication environment variables have impact.MQL enabled reduction in average chip tool interface temperature up to 27%.

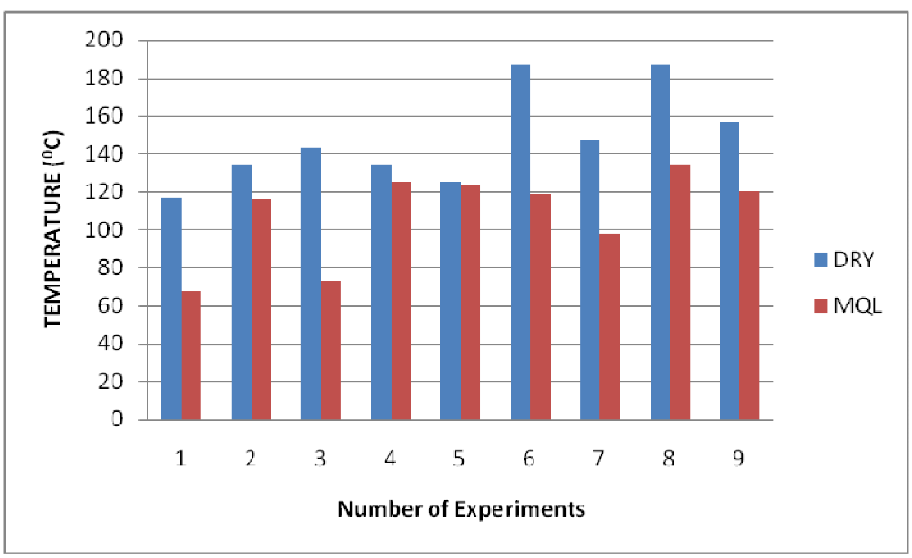



**Figure.3.12** Temperature comparison

The lowest material removal rate results show lowest cutting temperature and the highest cutting temperature was obtained with the highest material removal rate.

The optimal cutting parameters for temperature are cutting speed at level 1, feed rate at level 1, and depth of cut at level 3 under dry conditions (Vc=230 m/min , f= 0.2 mm/rev, d=3 mm). The predicted result for temperature is 107 $^{o}$C for optimal cutting parameters **1, 1, 3** under dry conditions.

The optimal cutting parameters for temperature are cutting speed at level 1, feed rate at level 1, and depth of cut at level 3 by using minimum quantity lubricant in turning process. The predicted result for temperature is 63 $^{o}$C for optimal cutting parameters **1,1,3** under mql conditions (Vc=230 m/min , f= 0.2 mm/rev, d=3 mm).

The results indicate that the use of minimum quantity lubrication leads to reduced cutting temperature. The cutting speed is the most significant cutting factor for affecting the cutting temperature according to the results of ANOVA. Cutting speed is the cutting condition that has highest physical as well as statistical influence on the cutting temperature (55%), right after the feed rate (31%) , and the cutting depth (13%) under dry conditions (see Table 3.8) .

**Table 3.8** ANOVA results for the cutting temperature for dry turning of magnesium

| ANOVA dry machining cutting temperature | | | | | |
|---|---|---|---|---|---|
| Source | df | SS | MS | F | % |
| v | 2 | 1570.9 | 785.4 | 1.57 | 55.4 |
| f | 2 | 1322.9 | 661.4 | 1.32 | 31.3 |
| d | 2 | 1136.9 | 568.4 | 1.14 | 13.2 |
| Error | 2 | 1000.2 | 500.1 | | |
| Total | 8 | 5030.9 | | | 99.97 |
| Significance at 95% confidence | | | | | |

According to the ANOVA for turning with MQL, we can observe that cutting speed (57%), the feed rate (28%), and the cutting depth (15%) have statistical and physical significances on cutting temperatures, especially cutting speed (see Table 3.9).

**Table 3.9.** ANOVA results for the cutting temperature for mql turning of magnesium

| ANOVA mql machining cutting temperature | | | | | |
|---|---|---|---|---|---|
| Source | df | SS | MS | F | % |
| v | 2 | 2446.22 | 1223.11 | 23.78 | 56.56 |
| f | 2 | 1264.89 | 632.44 | 12.29 | 28.04 |
| d | 2 | 740.22 | 370.11 | 7.19 | 15.38 |
| Error | 2 | 102.89 | 51.44 | | |
| Total | 8 | 4554.22 | | | 99.98 |
| Significance at 95% confidence | | | | | |

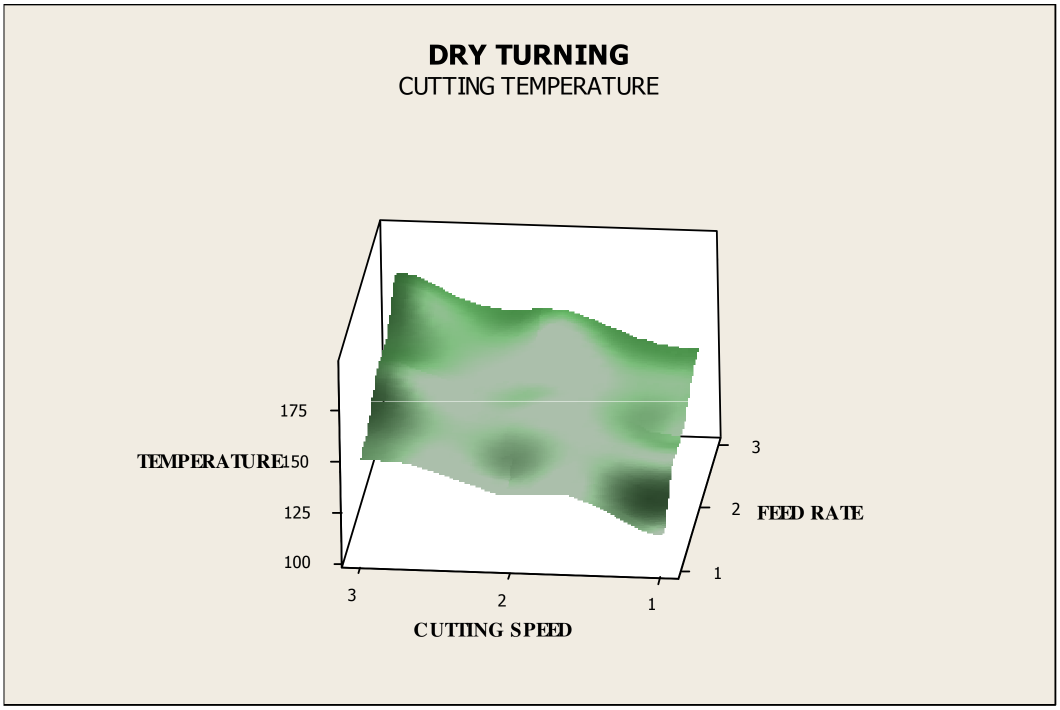



**Figure 3.13** The effect of cutting speed and feed rate on temperature

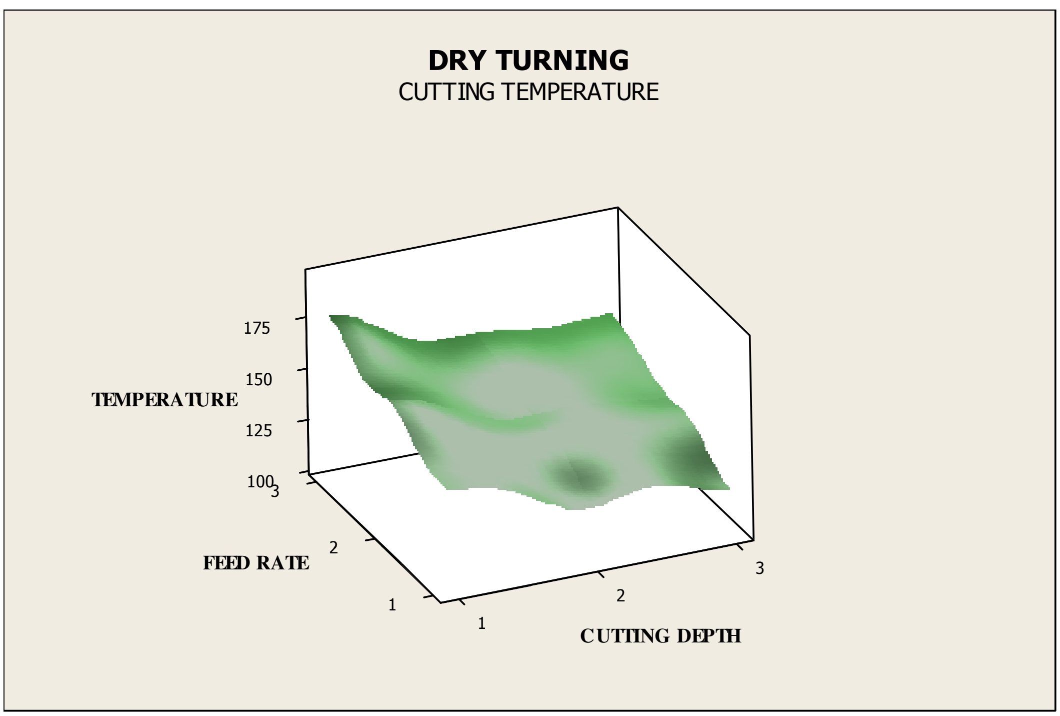



**Figure 3.14** The effect of feed rate and cutting depth on temperature

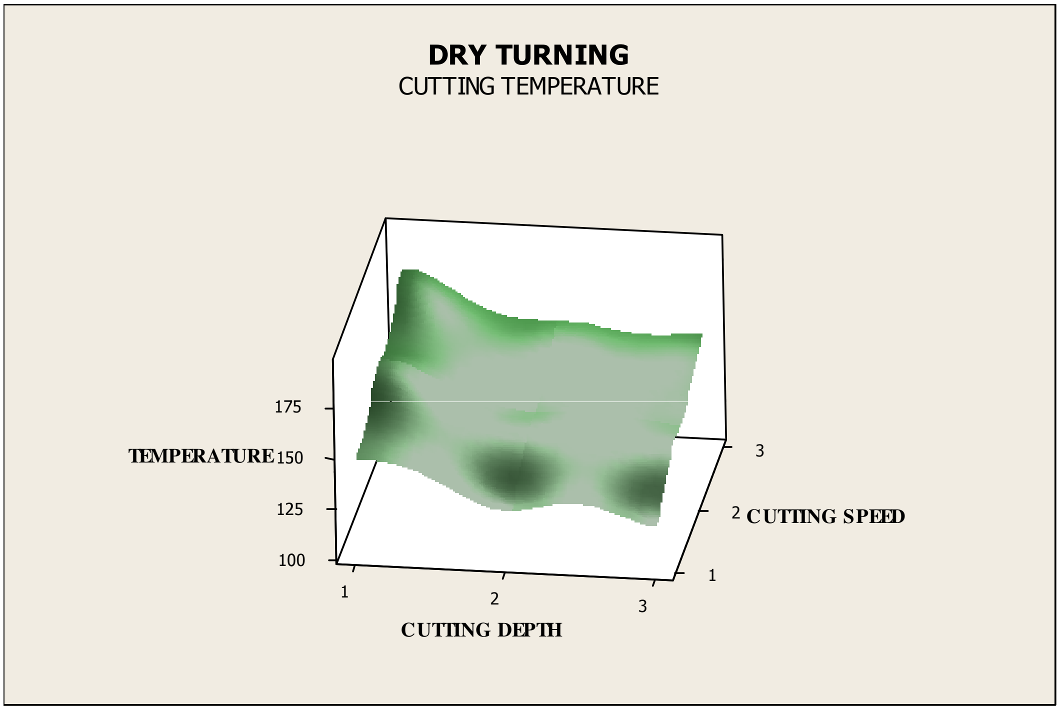



**Figure 3.15** The effect of cutting depth and cutting speed on temperature

## 3.2 Discussion

Problems with dry conditions

In dry conditions, heat generation causes temperature rise at higher speeds. Friction increases, chip stick on the face of the tool and a new shearing geometry created. Build up edge (BUE) acts as a part of tool, effective rake angle increases, energy consumption drops. Dimensional control is lost. MQL provides flushing away chips from the cutting zone. Because one of the functions of a cutting fluid is to flush chips from the cutting zone. This function seems to be problematic with dry machining. However, tool designs have been developed that allow the application of pressurized air,often through the tool shank. The compressed air provides only limited cooling, but is very effective at clearing chips from the cutting interface.

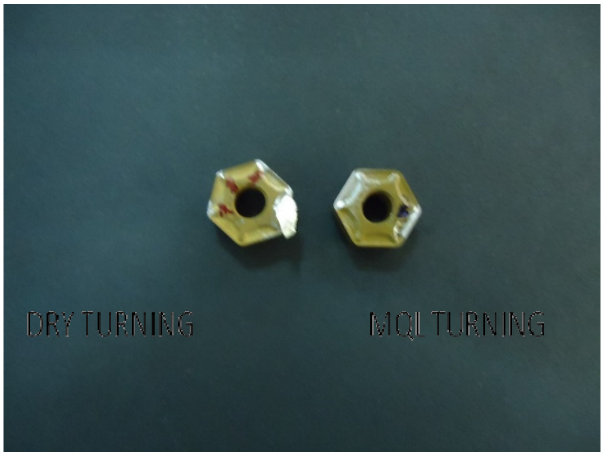



**Figure 3.16** Photographic view of BUE

Shortly, the following conclusions may be drawn from present study:

- **Depth of cut** is the most significant cutting factor for affecting the **cutting forces** right after the **feed rate**, and the cutting speed.
- Effect of **cutting feed** on **surface roughness** was great. The principal result is that the best surface finishes are obtained for low feeds. Compared with dry machining, surface finish substantially improved by the application of minimum quantity lubricant.
- **Cutting speed** has highest influence on the **cutting temperature,** feed rate has less and the cutting depth has the least.
- **Cutting speed** is a dominant parameter on the **hardness** followed by feed rate and depth of cut.

# CHAPTER 4

## 4. CONCLUSIONS

This thesis focuses on sustainable machining of magnesium alloy at various cutting conditions by investigating dry and mql machining processes and comparing the effectiveness of these methods through their optimal cutting parameters. Taguchi DOE technique was used and repeated for each of cooling/ lubrication conditions : dry, mql machining, which were compared under the range of different cutting parameters ( cutting speed, feed rate, depth of cut). Cutting forces, surface roughness, hardness and cutting temperature were measured. Based on the results it can be concluded that MQL machining process shows the better performance. Results show that even improving sustainability issues with using of MQL machining, the productivity as well as quality of machined surface can be improved.

In general, it has been shown that sustainable machining essentially provides:

- enhanced environmental friendliness,
- reduced cost of machining process,
- reduced power consumption,
- reduced wastes
- improved personnel health and safety performance

The findings of this study are summarized below.

The cutting performance of MQL machining is better than that of dry machining because

1) MQL provides the benefits mainly by reducing friction, which increases tool life.
2) Turning with MQL supply is more effective when higher machining efficiency, better surface finish quality and several cutting conditions are required. In our study, it is found that the application of MQL can effectively reduce surface roughness by 10%.
3) As seen Table 3.1, optimal conditions were reached at higher cutting speeds for cutting forces and surface roughness under MQL conditions.
4) Magnesium alloys present some critical problems during their machining due to

their flammability when the high temperatures are reached and the great ease with which their chips and dust auto-ignite. In our study, MQL enabled reduction in average chip tool interface temperature up to 27%. MQL can reduce the danger of fire.

5) MQL provides flushing away chips from the cutting zone. MQL prevents BUE.
6) In our study, dry conditions reduced the average cutting force by about 3.6%. Under dry conditions, the increased temperatures may result in thermal softening of the work material that can result in lower cutting forces .
7) In our study, dry conditions increased hardness by about 4%.

The number of experiments in the same or similar area in turning operations were reduced by using the Taguchi experimental design to determine optimum cutting conditions. Satisfying results were obtained so that they may be used in future academic and industrial studies. From this point of view, this thesis is a useful application of Taguchi Methods.

By adopting MQL lubrication, the cost of manufacturing and environmental hazards can be brought down. Further experiments are required to determine the optimum quantity of the MQL lubrication.

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## APPENDICES

## Appendix A: Experimental design for the Taguchi method: L9 orthogonal array (mixed level design)

| | | | | Dry Turning | | | | Mql Turning | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Inner Parameters | | | Measuring Parameters | | | | Measuring Parameters | | | |
| Experiments | Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of cut (mm) | Cutting Force (N) | Surface Roughness (μm) | Hardness (kg/mm$^2$) | Temperature (°C) | Cutting Force (N) | Surface Roughness (μm) | Hardness (kg/mm$^2$) | Temperature (°C) |
| 1 | 230 | 0.20 | 1 | 77.36 | 1.7 | 49.10 | 117 | 81.63 | 1.54 | 48.1 | 67 |
| 2 | 230 | 0.35 | 2 | 199.44 | 3.12 | 52.30 | 134 | 193.26 | 2.7 | 49.9 | 116 |
| 3 | 230 | 0.50 | 3 | 340.46 | 5.37 | 52.10 | 143 | 362.80 | 4.9 | 47.4 | 73 |
| 4 | 330 | 0.20 | 2 | 143.75 | 1.39 | 52.00 | 134 | 145.75 | 1.34 | 46.8 | 125 |
| 5 | 330 | 0.35 | 3 | 245.88 | 3.78 | 53.50 | 125 | 271.21 | 3.4 | 48.3 | 124 |
| 6 | 330 | 0.50 | 1 | 119.19 | 5.29 | 48.30 | 187 | 137.62 | 5.13 | 48.5 | 119 |
| 7 | 430 | 0.20 | 3 | 200.28 | 1.54 | 48.50 | 147 | 195.75 | 1.11 | 47.6 | 98 |
| 8 | 430 | 0.35 | 1 | 89.57 | 3.60 | 49.10 | 187 | 109.60 | 2.77 | 48.1 | 134 |
| 9 | 430 | 0.50 | 2 | 252.25 | 5.46 | 46.40 | 157 | 238.53 | 5.13 | 48.0 | 120 |

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