CHAPTER II
MACHINABILITY

2.1 Introduction

A general definition of machinability is the relative ease or difficulty of removing metal in transforming a raw material into a finished product. Such a comprehensive measure requires information from tool life or wear tests, cutting force tests, power consumption tests, surface finish tests, and cutting temperature tests. Even with reliable results from such a range tests, the user of these data must combine the information in a way that will provide meaningful comparisons between different materials being machined using different types of tools and tool material [45]. The term machinability is often applied to work materials to describe their machining properties and is an involved term with many ramifications.

The ease with which a metal can be machined is one of the principal factors affecting a product's utility, quality and cost. The usefulness of a means to predict machinability is obvious. Unfortunately, machinability is so complex a subject that it cannot be unambiguously defined. Depending on the application, machinability may be expressed in terms of tool wear rate, total power consumption, attainable surface finish or several other benchmark. Machinability depends a great deal on the viewpoint of the observer; in fact, the criteria for one application frequently conflict with those for another. Another difficulty is that machinability depends on the joint influence of a large number of factors, many of which are quite complex. For example, machinability is certainly closely linked to the physical and mechanical properties of the work piece: hard and brittle materials being generally difficult to machine than soft and ductile ones. It also strongly depends on the type geometry of tool used, the cutting operation, the machine tool, metallurgical structure of the tool and work piece, the cutting/cooling fluid etc. It is therefore not surprising that some researchers have concluded that machinability simply cannot be precisely described. Despite the considerable body of research that has been devoted to the subject, the term can have little meaning except in a loose quantitative sense [46].
Generally a material is said to have good machinability if tool wear is low or tool life is long, the surface finish produced is good and cutting forces are low. For example, when two materials are machined under same conditions (tool, machine and operating conditions) and if machinability is defined taking force as a parameter, then the material which induces lesser cutting force is said to have good machinability [47].

2.2 Factors Affecting Machinability

Machinability is influenced by the variables pertaining to the machine, the cutting tool, cutting conditions and work material [48]. These variables are briefly explained in the sections to follow.

2.2.1 Machine Variables

a) Rigidity of the machine and work holding devices: The efficiency of any machining operation depends on the overall rigidity of the system consisting of the machine tool, the cutting tool and the workpiece. The machine on which the material is to be machined should be rigid and should have sufficient power to withstand the induced cutting forces and to minimize deflections.

b) Capacity of the machine (Power, torque and accuracy of the machine): If the machine is not sufficiently rigid and has less power, the tool life will be reduced in addition to affecting the accuracy and surface finish. Lower values of cutting speeds have to be employed and the dimensions of cut namely feed and depth of cut, have to be reduced to limit the induced cutting forces. Thus the machinability of the work material is indirectly affected by the machine variables.[13]

2.2.2 Tool Variables

a) Tool materials: The most basic factor governing machinability is the cutting tool. If the cutting operation has to be performed efficiently the cutting tools must be made from proper tool material and having proper geometry, even though all other machining variables are closely controlled. If the cutting tool is not optimized, the material removal rates must be reduced in order to obtain a reasonable value of tool life, otherwise machining costs will be increased. The selection of a particular tool
material for a given job depends on the work material, machining conditions, wear resistance of the tool material and the cost of the tool material.

b) Tool geometry: For efficient machining operations proper tool geometry is essential and it should be selected depending on the work material and machining conditions.

c) Nature of engagement of tool with work: If the tool is continuously in contact with the workpiece the tool life will be generally higher than in the case of an interrupted cut. The tool is subjected to impact and shock loading as it enters and leaves the interruption and it is liable to fail quickly.

2.2.3 Cutting Conditions

a) Cutting Speed: It is the travel of a point on the cutting tool relative to the work piece in unit time in accomplishing the primary cutting motion and is expressed either in m/min or rpm. This is the most common factor affecting the machinability of materials because it gives an indication of the speed to be used for a particular material and also provides an idea of the cost of machining operations. Cutting forces are fairly independent of the cutting speed and as a variable has the greatest influence on tool life.

b) Feed: Feed is the amount of tool advancement per revolution of the job parallel to the surface being machined. Higher feeds cause roughing cuts, rigidity cuts. Lower feeds are used for finishing cuts, fragile setups. Feed is expressed in mm/rev. It influences the cutting forces and material removal rate and has an impact on tool wear to some extent.

c) Depth of Cut: Depth of cut is the perpendicular distance measured from the machined surface to the uncut surface of the work piece. It is expressed in mm. It certainly has influence on the cutting force and material removal rate and has least influence on the tool wear.

2.2.4 Work Material Variables

a) Hardness: Increasing the hardness of the metal by alloying or heat treatment decreases its machining characteristics. In general the harder the material, the more difficult it is to machine. Also the cutting force increases with increase in hardness. Higher hardness shortens the tool life.
b) Chemical Composition: When various alloying elements are added to pure metals, they have differing effects on the machinability of the alloy. Some of the elements when added in certain quantities to the parent metals improve the machinability of the alloy. If the addition of elements exceeds the prescribed limit, it may worsen the machinability of the parent material.

c) Microstructure: The abrasiveness & nature of inclusions & interfaces in the metallic matrix affect the machining qualities.

d) Degree of Cold Work: Cold working of metals increases the tool life and consequently permits an increase in the cutting speed.

e) Coefficient of friction: Coefficient of Friction varies with the type of material & reaction of it to the tool material at the chip interface.

f) Other factors viz., Tensile Strength, Shape & Dimension of Work, Strain Hardenability Rigidity of Work Piece and Thermal Conductivity also affect the machinability.

A thorough knowledge of the above factors serves as a guiding factor in the assessment of machinability characteristics of materials.

2.3 Criteria for Machinability Assessment

Assessment of machinability depends on the employed machine tool, cutting tool, work material and cutting conditions and also on the preference of the user for a particular choice. General criteria commonly adopted for evaluating machinability are tool life or tool wear rate, cutting force and surface finish produced on the workpiece.

Machinability can also be assessed based on specific parameters like temperature of cutting tool, work hardening, ease of chip disposal etc. From practical considerations, tool life or tool wear rate, cutting force and surface finish are the most commonly accepted measures of machinability. The actual values of tool life, cutting force and the finish obtained, when a given material is cut, vary with the machining conditions. Further, if the materials are rated in relative order based on tool life, cutting force and surface finish, under a certain set of conditions, this relative order need not be the same for other set of conditions. These facts make it almost impossible to prescribe any single test or a combination of test conditions that will give an unequivocal rating of machinability which can be used for assessing the behaviour of the material in any or every type of machining.
operation. They serve as first approximations of the actual behaviour of the materials during machining [13].

2.3.1 Criterion Based on Cutting Forces

In any metal cutting process, considerable amount forces are involved and in order to design tool holders and work holders that will withstand these forces, it is very important to establish magnitude of these forces and the direction in which they act. In addition, by knowing the magnitude of these forces one can determine the power required by the machine tool to operate.

Turning is a very important machining process in which a single-point cutting tool removes material from the surface of a rotating cylindrical workpiece. The cutting tool is fed linearly in a direction parallel to the axis of rotation. Turning is carried out on a lathe that provides the power to turn the workpiece at a given rotational speed and to feed the cutting tool at a specified rate and depth of cut. In a turning operation, it is an important task to select cutting parameters for achieving high cutting performance. Therefore, three cutting parameters, i.e. cutting speed, feed rate and depth of cut need to be determined in a turning operation [39]. The forces acting on a cutting tool during turning operation on a lathe in the case Oblique cutting is shown in the Figure 1.

\[ F_x = \text{The axial component of the force that acts in the direction of traverse. It contributes little to the power consumed. It is also known as feed force.} \]
F_y = The radial component, acts in the direction along the tool shank and perpendicular to 
the other two components. It is also called thrust force.

F_z = The main tangential component of the force on the drive mechanism. It is also known 
as main cutting force.

The Resultant Force is given by

\[ F_r = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3.1) \]

There are several important reasons for measuring or calculating cutting forces which 
include:

1) To evaluate the role of major cutting parameters on forces.
2) To survey the characteristics of new work and tool materials by investigating tool 
   forces.
3) To estimate the cutting power requirements of a machine tool.
4) To estimate tool forces that must be resisted by machine tool components like 
   spindles, bearings, jigs and fixtures etc.
5) To study the mechanics of machining.

Determination of the cutting forces in machine tool by analytical methods using classical 
formulae gives the approximate results. To get the exact value, empirical relations are to 
be formulated and used. This is possible only by experimentation.

The measurements of cutting forces may be made by:

1) Indirect power measurements
2) By calorimetric methods
3) By suitable tool force dynamometers.

For research purposes, direct measurements by dynamometers have won general 
acceptance and since then many researchers in the field of metal cutting have tackled the 
problem of constructing dynamometers to measure forces [14].

The cutting forces are mainly affected by cutting parameters, tool geometry, cutting 
conditions and tool wear. The cutting process is defined as being a stochastically 
stationary process so that its prediction cannot be made on the basis of its theoretical 
analysis. Since the cutting force is known to be very sensitive to even the smallest
changes in the cutting process attentions are directed to the selection of the conditions of
the tests and experimental methodology. Therefore, instead of calculating the cutting
force theoretically, measuring them in process by dynamometers is preferred. In order to
measure cutting forces (main cutting force $F_z$, feed force $F_x$, and thrust force $F_y$), a three
component turning dynamometer can be used [11].

2.3.2 Criterion Based on Tool Life

Tool life is usually the most important of the three main parameters used for assessing
machinability. Tool life is a direct function of the cutting speed [12]. The higher the
cutting speed a material allows for a certain tool life, the better is its machinability. The
useful life of tool is limited by tool wear. Under usual cutting conditions, wear due to
interaction between the chip and the tool and between the work and the tool are the main
processes by which a cutting tool fails. After the tool has been in use for some times,
wear land will appear at the flank of the tool below the cutting edge extending
approximately parallel to the cutting edge. The wear will also appear on the tool face
forming a characteristic cavity known as crater which begins at a certain distance of the
cutting edge [49].

The phenomenon of tool wear may be due to the following basic causes which can
operate singly or in various combinations to produce tool wear.

1. Micro-transfer type Mechanical wear process: This type of wear takes place in
two predominant ways:

   a) Abrasion Wear: The abrasive action of the work on the tool is basically due to
effects:

      i) The inherently hard constituents such as segregated carbides, inclusions etc.,
present in the microstructure of the material being cut.

      ii) The strain hardening induced in the chip and work by the cutting process, and the
formation of built-up edge.

   Abrasive wear is caused when these hard particles are swept over the tool surface. This
action is much more pronounced on the tool flank because of the nature of contact and
rigid backing provided by the work.

   b) Adhesion Wear: When metallic surfaces are brought into intimate contact under
moderate loads, a metallic bond between adjoining materials takes place. This
phenomenon is known as adhesion. The strength of the bonding at the points of adhesion is often so great that while attempting to free the surfaces, separation takes place not along the interface but in one of the material itself transferring and removing materials often with the sliding member of the pair. Quantity of metal transferred is apparently proportional to the real area of the contact, as well as on the hardness the mating pair under prevalent environment.

2. Micro-transfer type thermo-chemical process like diffusion: If the mechanical process involved in adhesion is capable of increasing the localized temperature of the real areas in contact, as surface or interstitial diffusion shall occur allowing a more intimate approach of the two surfaces. Diffusion is a time and temperature dependent process and also depends on bonding affinity of the pair and the degree of atomic agitation. Diffusion wear occurs because of the diffusion of metal and carbon atoms from the tool surface in the work material and the chips. Diffusion wear is a major cause of tool wear though the actual amount removed by this process is not considerable. It does however cause a chain reaction making the tool more prone to abrasive wear and to plastic deformation as a result of depletion of elements like carbon from the tool.

3. Electro-chemical process: This type of wear occurs when ions are passed between the tool and the workpiece causing an oxidation of the tool surface and a consequent breakdown of the tool material in the region of the chip-tool interface. Not much data is available regarding this type of wear in metal cutting in order to evaluate its relative importance.

Chemical wear is due to the interaction between tool and work material. This may be accelerated in the certain cutting fluid environments, where the fluid is active with respect to the tool. Related to chemical wear is that due to possible galvanic corrosion between tool and work materials. If the cutting fluid is an electrolyte, tool wear by galvanic action may occur.

4. Attrition Wear: At relatively low cutting speeds, the flow of the material past the cutting edge is irregular and less streamlined. Sometimes built up edge may be formed and contact with the tool may not be continuous. Under these conditions, fragments of tool are torn intermittently from the tool surface. This phenomenon is called attrition. This type of wear progresses slowly in the case of continuous cutting, but with interrupted cutting or where vibrations are severe due to lack of rigidity of the machine tool or
uneven work surfaces, it leads to rapid destruction of the cutting edge. As the cutting speed is increased, the flow of metal becomes uniform and attrition disappears. When carbide tools are used at low cutting speeds where built-up edge is likely to form, the wear is largely controlled by attrition. [48, 49, 50].

2.3.2.1 Tool Failure

A cutting tool can be regarded to have failed by any one of the following processes.

i) Plastic Deformation: The tool is normally hard but under certain cutting conditions when the temperature and the stresses are high, plastic deformation may cause loss of ‘form stability’, i.e. cutting ability of the tool. The occurrence of plastic deformation is in itself an indication of the over-stressing of the tool material. The severity should be construed as limit of the cutting conditions which should never be exceeded.

ii) Mechanical Breakage: When the cutting force is very large or by the development of fatigue cracks under chatter conditions, breakage of tool occurs.

iii) Gradual Wear: Also known as Progressive wear, which is the result of interaction between the work and the tool material. When the form stability has been achieved, wear is the process by which a cutting tool fails.

The progressive wear of the cutting tools can take two forms:

a) Flank Wear: Wear on the tool flank characterized by the formation of a wear land as result of the newly cut surface rubbing against the flank. As a rule the extent of wear is considered a dependable criterion for judging the life of the cutting edge. In case of carbide tools, through proper alloying of tungsten carbide with titanium or tantalum carbides, sufficient resistance to crater is obtained so that most tools do not fail by cratering or deformation, before a reasonable amount flank wear is obtained on the flank of the tool. The flank wear can be more easily observed and measured than other types of wear and it is relatively easy to predict when a given amount of wear will be reached once the wear rate has been established.

b) Crater Wear: Tool wear on the rake face characterized by the formation of a crater or a depression, as result of chip flowing over the tool rake face. The tendency of the cutting tool to fail by the cratering increases with increasing cutting speed. The tool-chip interface temperature increases with cutting speed, and at these higher temperatures the
rate of material removed from the tool increases. The pattern of crater wear indicates that the wear in this region is primarily due to diffusion or chemical reaction between the tool and chip material. The cavity of crater has its origin not along the cutting edge, but at some distance away from it and within the chip contact area. It is to be noted that the maximum tool-chip interface occurs at a distance from the cutting edge, and in this region the crater is initiated. As the crater wear progress with time, it becomes wider, larger and deeper, and approaches the edge of the tool. If the crater wear is allowed to go too far, the cutting edge becomes too weak and breaks down suddenly. The depth of the crater and the distance of the centre line of the crater from the cutting edge are measured for the quantitative assessment of the crater wear. Crater wear can be measured with any surface measuring instrument or with the help of a dial indicator having a sharp point. Crater wear is usually specified with regard to the maximum depth of crater and from the original rake face and the distance of the centre of the crater from the centre of the cutting edge.

2.3.3 Criterion Based on Surface Finish

Surface finish assesses the effect of machining processes on the surface quality of the work piece material. Kahles defines surface integrity as "the unimpaired or enhanced surface condition or properties of a material resulting form a controlled manufacturing process. When the surface finish on the job is of primary importance, the criterion for machinability should be surface finish. Though a given material may allow higher cutting speeds or induce lower cutting forces, it may not produce good surface finish. Where the finish produced on the parts is a cause for rejection, this consideration has an important bearing on the cost. The higher the surface finish obtained on a material under a given set of conditions, the better is its machinability [48, 49].

In this research work Resultant Force and Tool Flank Wear have been chosen as the criteria for assessing machinability.

2.4 Machining of Metal Matrix Composites

Composite materials being non homogeneous, anisotropic and reinforced by abrasive components, these materials are difficult to machine. Significant damage to the workpiece may be introduced and high wear rates to the cutting tools are experienced. Conventional
machining practices, such as turning, drilling and milling, are widely applied to the machining of composite materials in view of the availability of the equipment and experience in conventional machining. Although some of the materials used as reinforcements in composites, such as glass, boron, alumina and silicon carbide, are highly abrasive and hard, conventional machining is considered because their reinforcements are brittle and material separation is accomplished by brittle fracture rather than plastic deformation ahead of the tool. However, the cutting tool materials must be attentively chosen to minimize wear due to the hard abrasive constituents of the reinforcing phase in the composite representing the work material. Machining of composite materials depends on the properties and relative content of the reinforcements and the matrix materials as well as on its response to the machining process.

Machining of composite materials differs significantly in many aspects from machining conventional metals and their alloys. In the machining of composites, the material behavior is not only non-homogeneous and anisotropic, but also depends on diverse reinforcement and matrix properties, and the volume fraction of matrix and reinforcement. The tool encounters alternatively matrix and reinforcement, whose response to machining can be entirely different. Thus machining of composite materials imposes special demands on the geometry and wear resistance of the cutting tools. Accordingly tool wear mechanisms and development must be attentively considered to establish correct cutting tool selection.

The main problem in machining Aluminium Matrix composites is the high tool wear, which under certain circumstances, leads to an uneconomical production process or makes the process impossible. The extensive tool wear is caused by the very hard and abrasive reinforcements. The main reason for wear is the direct contact between the reinforcing particles or fibers and the cutting edge which causes both a mechanical and thermal load on the cutting edge. The dominant wear mechanism is abrasion, which is generated by impacts at the cutting edge and by the sliding motion of the particles relative to the rake and the clearance face. Different wear mechanisms are responsible for the abrasive tool wear. These are known as micro-ploughing, micro-fatigue, micro-cutting and micro-cracking.
Additionally, a thermal load stresses the cutting edge. This thermal load results from hot spots which are generated by micro-contacts between the cutting edge and the reinforcement. Despite the relatively low process temperature, this thermal load is limited by the melting temperature. Also alternating stress resulting from inhomogeneity of the work piece material also contributes to the wear [8].

With the vast and rapid progress in science and technology, modern industry has introduced a new generation of composite materials having low density and very light weight with high strength, hardness and stiffness to meet the current needs of modern technological needs. Advanced Al-SiC composites are gradually becoming very important materials for their scope of uses in manufacturing industries mainly aerospace, defence and automobile industries. But Al-SiC composite machining is one of the major problems that is preventing its wide spread engineering application.

From some early conventional turning tests on Al-SiC composites, it is found that the tool wear is excessive and surface finish is very poor when carbide tools are used for machining. During machining of Al-SiC composites use of coolant increases tool wear and as well as produces very poor surface finish. The hard SiC particles of Al-SiC composites, which intermittently come into contact with the cutting tool, act as small cutting edges like those of a grinding wheel on the cutting tool edge which in due course is worn out by abrasion and resulting in formation of poor surface finish during turning. When the Al-SiC composite slides over a hard cutting tool edge during turning it always presents a newly formed surface to the same portion of the cutting edge and consequently due to friction, high temperature and pressure the particles of the Al-SiC composites adhere to the cutting tool edge. This way more particles will join up with those already adhering and the so-called built up edge is formed and if this process is continued for some time, it appears like it was nibbled away on the turned surface and produces very poor surface finish during turning. Hence, cost-effective machining with the generation of good surface finish on the Al-SiC composites during turning operation is a challenge to manufacturing engineers in practice [16].

2.5 Significance of Machinability Evaluation Studies

The accelerated application of automation to machining processes has focused on the desirability of reliable machinability data ensure optimum production from modern costly
equipment. Even in conventional production much more should be done to provide reliable data for manufacturing engineers enabling them to set realistic standards of performance for the different machining operations [51].

Since industrial revolution machining operations have been the core of manufacturing industry. The study of machinability can be related especially to process planning and machining operations. The machinability aspect is of considerable importance for production engineers to know in advance the machinability of work materials so that processing can be planned in the most efficient manner. If there are a finite number of work materials from which the best material has to be chosen and if each work material satisfies the required design and functionality of the product, then the main criterion in choosing the work materials is its operational performance during machining i.e., machinability. Since there is no universally accepted methodology for evaluating the machinability of work materials and numerous new materials enter the market every year, many manufacturers are encountering difficulties in selecting the most appropriate material for their products. It has been observed from machinability studies that the usual criteria for machinability assessment of different work materials include tool life or wear, cutting temperature, cutting forces, processed surface finish or specific energy consumed, precision obtained on the processed surface etc. Besides playing a major role in material selection, machinability study can also be a basis for cutting tool and cutting fluid performance evaluation and machining parameter optimization [52].

Technology development is frequently attributed to the application of new materials, for example, air and land vehicles. From steels through aluminium alloys to composite materials are used for higher specific stiffness and strength [10]. Increase in industrial applications of composite materials brings the matter of shaping of these materials. From this point of view, it is natural that the methods of production by machining are considered initially, for why machining has a prevalence of approximately 70% among all production methods. [13].

Cutting force is one among the basic factor, which measures the machinability any material. The determination of cutting forces by experimental means is more common as there is no general mathematical model available to predict the cutting forces developed as a function of machining and material parameter. Despite the recent developments in
the near net shape manufacture composite parts often require post mold machining to meet dimensional tolerances, surface quality and other functional requirements [12].

Although the combination of a high strength ceramic reinforcement in a ductile metal matrix is exciting from the point of view of materials properties, metal matrix composites have yet to make major inroads into high volume automotive and aerospace applications. This is largely because the alloys are costly, difficult to fabricate and difficult to machine. Even with near net shape manufacturing methods such as squeeze casting, the need for machining cannot be completely eliminated, and hence, if the cost of manufacturing is to be minimized, it is important that machinability is understood [14].

The properties that make MMCs appealing to engineering designers can however, present a major challenge when attempting to machine these materials because of their brittle behaviour and high hardness. The presence of hard reinforcements presents considerable difficulties when machining these materials. Machining of these MMCs often involves frequent and expensive tool changes and therefore increased job-completion times. Machining processes such as turning, drilling and milling of MMCs therefore requires the use of carbide, diamond or hard-nitride-coated tools. The difficulties associated with the machining of MMCs must be minimized if these materials are to be used more extensively. Consequently, the machinability of MMCs is now considered as one of the most important areas manufacturing science requiring urgent attention [21].

Thus in general machinability testing aims at evaluation of the comparative machining performance of work piece, cutting tools, cutting fluids and establishment of machining conditions producing a satisfactory part meeting desired dimensional surface finish and functional integrity economically [10].

2.6 Summary

In this chapter general definition of machinability, factors affecting machinability and criteria machinability assessment are discussed. Machining of metal matrix composites and significance of machinability studies have also been discussed.