CHAPTER 1
INTRODUCTION

1.1 Significance and Objectives

Machinability is defined as ease of machining of a material. It may be characterized by an optimal combination of factors such as low cutting force, high material removal rate, good surface finish, accurate and consistent workpiece geometrical characteristics, low tool wear rate and good curl or chip breakdown of chips etc.

In any metal cutting operation, a lot of heat is generated due to plastic deformation of work material, friction at the chip-tool interface and friction between the clearance face of the tool and work piece. The heat generated in machining adversely affects the quality of the products produced (dimensional accuracy and surface finish). The temperature of the tool plays an important role in the thermal distortion and dimensional accuracy of the machined parts, as well as on the tool life. It also weakens the surface integrity of the product by inducing tensile residual stresses and surface and subsurface micro cracks in addition to rapid oxidation and corrosion. Tools become softer and wear more rapidly by abrasion as temperature increases, and in many cases constituents of the tool may diffuse into the chip or react chemically with the work piece or cutting fluid. Generally such problems are tried to be controlled by conventional (flood) cooling with soluble oil. In metal cutting process the use of cutting fluids is the most common strategy to improve the tool life, the product surface finish and the size accuracy. The cutting fluids also make chip-breaking and chip transport easier. However, the introduction of cutting fluids often introduces air borne mist, smoke and other hazards in the shop floor environment, leading to environmental pollution, and health and safety concerns. In addition, the cost of using cutting fluids is several times higher than the tool costs (Kloke et al. 1997). The economical and environmental concerns on the use of cutting fluid leads to the research of minimum quantity lubrication (MQL) technique or near dry machining (NDM) (Klocke et al. 1997).

Cutting fluids have seen extensive use and have commonly been viewed as a required addition to high productivity and high quality machining.
operations. In 2002 over 2 (two) billion gallons of cutting fluids were used by North American manufactures (King et al. 2001). Traditionally, cutting fluids have been widely used in machining operations to increase cooling and lubricity, so that tool life is enhanced and process variability reduced. However, over the last decade it has become apparent that fluid–related decisions have all too frequently been based upon industrial folklore rather than knowledge-based quantitative evidence. Recently there has been a change in this situation, in part because of the fact that costs associated with fluid used often constitute between 7% and 20% of total production cost as compared to 4% tooling costs (King et al. 2001). Thus in comparison to cutting tools cost, the cooling lubricant cost is significantly higher. As a result the need to reduce the cutting fluids consumption is strongly felt. Fluid related expenses include the cost of installing a fluid supply system, and system for maintenance and discarded fluid (waste) treatment. Fluid related costs are large because high production manufacturing plants frequently utilize several cutting fluid reservoirs each containing thousand of gallons of cutting fluid and often an entire reservoir is flushed to clean the system when quality issues arise (Filipuvic et al. 2000). Certainly, reducing the amount of fluid can produce significant cost and waste savings. Two relatively recent strategies focused on reducing fluid use are minimum quantity lubrication (MQL) and dry machining.

Further an extensive use of cutting fluids in machining operation leads to a sizeable waste stream. Responsible handling of used (waste) fluid is needed to avoid the contamination of lakes, rivers, and ground water. Such handling includes the pre-treatment and treatment of cutting fluid wastes, but even the most disciplined manufacturer may still have fluid relative environmental concerns associated with chip-work piece fluid carry off. It is worth noting that the cost of fluid pre-treatment is sometimes higher than the purchase price of the fluid itself, and since the treatment is not always totally effective, disposal may lead to advertent water contamination.

In addition to the environmental challenges of managing a used cutting fluid waste stream, cutting fluids also introduce several health (safety) concerns as emphasized earlier. The national Institute for occupational safety and health (NIOSH) estimates that 1.2 million workers involved in machining,
forming and other metal working operations are exposed to metal working fluids annually (NIOSH, 1998). Dermal exposure to these fluids represents a health concern, as does the inhalation of air born fluid particulates. The application of cutting fluid in a machining operation often produces an air born mist and medical evidence has linked worker exposure to cutting fluid mist with respiratory ailments and several types of cancer. This makes the use of cutting fluids a health issue with the potential of both long and short term consequences.

On the other hand, completely dry machining has been a common industry practice for machining of steel parts. These parts typically exhibit a very high specific cutting energy. Traditional beliefs indicate that completely dry machining of steel, as compared to flood coolant cutting, lowers the required cutting force and power on the part of the machine tool as a result of increased cutting temperature. However, achievable cutting tool life and part finish often suffer under completely dry machining (condition). Therefore, the permissible feed and depth of cut have to be restricted. Cutting forces and temperature were found to be reduced while machining steel with tribologically modified carbide inserts (Sreejith et al. 2000). Cryogenic machining with liquid nitrogen (Dhar et al. 2002) and machining with MQL (Dhar et al. 2006) have improved machinability of steel to a certain extent under normal cutting conditions. It has also been reported that though machining steel with liquid nitrogen improves the machinability index (Dhar et al. 2002); still it is not used in industrial practice due to high cost of liquid nitrogen and sharp increment of notch wear under nitrogen rich atmosphere. Under these considerations, the concept of minimum quantity lubrication presents itself as possible solution for steel turning to achieve slow tool wear while maintaining cutting force (power) at reasonable low levels.

In order to alleviate the economical quality and environmental impacts, minimum quantity lubrication machining has addressed as an alternative to the traditional flood cooling and dry cutting application. Minimum quantity lubrication refers to the use of cutting fluids of only a minute amount (small amount of cutting fluid), typically of a flow rate of 50 to 500 ml/hour. It is about three to four orders of magnitude lower than the amount commonly used in flood cooling condition, where, for example, up to 10 liters of fluid
can be disposed per minute. Varodarajan et al, (2002) used 2ml/hr oil in a flow of high pressure air at 20Mpa, while hard turning AISI4340 steel. This may be called to be near dry turning. Kloke et al. (1997) also referred it as near dry lubrication. Maclure et al. (2001) called it micro lubrication. The minimization of cutting fluid also leads to economical benefits by a way of saving lubricant costs and work piece/tool/machine cleaning cycle time. The concept of near dry machining (NDM) is based on the principle of loss of lubrication with the dry surface after the machining process. Therefore, near dry machining is also recognized as minimum quantity lubrication (MQL) machining.

MQL has been widely studied in many machining processes such as drilling milling, tapping, turning & reaming, grinding etc. (Machado et al. 1997, Rahman et al. 2000), (Davim et al. 2006) and Dhar et al. (2006) etc., who employed MQL technique in turning of AISI 1040 steel and the results clearly indicated that machining with a mixture of compressed air and soluble oil better than the conventional flood coolant system.

However, MQL (solid +liquid) is still a relatively new research area, and only a few researchers have studied machining with solid lubricants (Shaji, et al. 2003), (Silva, 2005), (Gopal, 2004). They have properly applied solid lubricant i.e. graphite powder and MoS₂ powder during milling, grinding and metal forming process. They have reported solid lubricant assisted machining is a novel concept to control the machining zone temperature without polluting the environment. To the best of author’s knowledge the effect of Solid-liquid MQL on machinability in turning process has not yet been studied.

From the above literature review it is readout that development of lubricants that are eco-friendly and economical are acquiring importance. In this context, using MQL of solid lubricant mixed with base oil SAE-40 has proved is a feasible alternative to the conventional cutting fluids. Machining solid lubricant mixed with SAE-40 base oil (MQL), is an environmentally safe alternative to conventional cooling condition machining. Hence an attempt has been made in the present research work to investigate the effect of solid lubricants mixed with SAE-40 oil on metal cutting performance while turning En-31 steel with tungsten carbide inserts. SAE-40 base oil is chosen
as the mixing medium, due to its higher viscosity and hence improved lubricating properties of minimum quantity lubricant. These lubricants are applied to the cutting zone with a brush that seeps into the chip-tool interface and provides lubrication of the interface while turning EN-31 steel.

So, the objectives of the present work are:

1. To study the effect of Minimum Quantity solid-liquid mixture Lubricants on various machinability criteria in turning EN31 steel viz-
   a-viz dry and flooded coolant machining
2. To select an efficient solid-liquid lubricant and to determine its composition which yields optimum machinability
3. To develop statistical models for different machinability parameters under different machining conditions.
4. To determine the best combination of machining parameters that give optimum machinability indices.
5. Application of multi variable technique for optimization of multi-
   performance characteristics in turning EN31steel
6. To study the effect of temperature of MQL on these machinability criteria and to attempt multi variable optimization of output responses

1.2. Methodology

For this study a tool-work thermocouple has been designed and fabricated for measurement of chip-tool interface temperatures, and a new technique of calibrating the thermocouple has been successfully used. This technique is specially designed, fabricated and calibrated in Mechanical Engineering lab, AMU, Aligarh, India. Detailed procedure is given in chapter III.

In this study En-31 steel was turned at different combinations of speed, feed, depth of cut and tool nose radius. Turning was performed with tungsten carbide tool under

a) Dry conditions
b) Flooded cooling conditions
c) Cooling and lubricating the chip-tool interface with different concentration of the following solid lubricants mixed with SAE-40 base oil by weight.
   i) Graphite, ii) MoS$_2$, iii) Boric acid
En-31 steel has been chosen for this study because it is widely used in automotive industry for the production of axle, roller bearings, ball bearings, shear blades, spindle mandrels, forming and molding dies, rollers, blanking and forming tools, knurling tools and spline shafts, etc. The turning operation is the main process used for making these parts. Tungsten carbide inserts were used due to its low cost as a cutting tool material for optimizing the minimum quantity lubrication parameters during machining of En-31 steel. Different concentrations of three solid lubricants 1%, 2%, 3%, 4%, 5%, 10%, 12%, 13%, 15%, 17%, 20%, and 23% were applied in the pilot runs and the percentage of solid lubricant that gave stable lower cutting forces was 10% to 20% solid lubricant + SAE-40 base oil as optimum. Therefore for further studies this concentration was used.

Experimental conditions were planned according to factorial design ($2^4 + 8$) for dry and flooded cooling condition and ($2^5 + 8$) for MQL machining. Factorial design is a composite design, which was proposed by Box (1980). Experimental investigations were conducted and the results of average of three replicates were recorded. The data was taken and analyzed graphically as well as statistically.

The following were the machinability performance parameters studies:

1) Chip-tool interface temperature
2) Cutting forces
3) Surface roughness
4) Chip thickness
5) Total tool wear
6) Chip micro-hardness
7) Power consumption during machining
8) Chip-tool contact length
9) Chip compression ratio
10) Maximum machining ratio

Under the assumption of orthogonal cutting, shear angle and coefficient of friction were determined to ascertain if the improvement in machinability was due to lubrication effect of the solid-liquid coolant/lubricant. The assumption is valid because this is used for comparative studies only.
In machinability studies, statistical design of experiments is used quite extensively. Statistical design of experiments refers to the process of planning the experiment, so that the appropriate data can be analyzed by statistical models, resulting in valid and objective conclusions (Montgomery, 2005). The parameters that have significant effect on different machinability parameters at 95% confidence level have been determined through analysis of variance (ANOVA). Mathematical models are developed for the prediction and analysis of the effect of the cutting parameters on responses in turning process of En-31 steel using response surface methodology (RSM) combined with the factorial design of experiments. A statistical software program, Minitab version – 15 and Microsoft excel (M.S.OFFICE- 2007) were employed in the model training. The cutting speed, feed rate, depth of cut and tool nose radius were chosen at three levels each.

Optimum combination of cutting parameters for surface roughness, tool wear rate, cutting temperatures, chip thickness, cutting forces and chip micro-hardness were determined by response surface methodology (RSM). The effect of the lubricant on the chip-tool interface temperature, main cutting force, tool wear rate and surface roughness was studied by using combined multiple attribute decision-making methods (AHP-TOPSIS). The effect of lubricants such as SAE-40 base oil, wet (soluble oil Koolkut-40), dry and different concentration of solid-liquid lubricant such as (10 % graphite, 10 % MoS₂, 10 % boric acid and 15 % graphite, 15 % MoS₂, and 15 % boric acid powder mixed with SAE-40 base oil separately) on chip-tool interface temperature, cutting force, tool wear rate and surface roughness were studied.

Further, the cooling efficiency of MQL lubricants were also determined by cooling efficiency equation and it was optimized by ROVOP method.

A comparative performance analysis of MQL (graphite + SAE-40, MoS₂+ SAE-40 and boric acid + SAE-40 base oil) assisted machining with dry and wet machining was conducted in order to identify the best possible solution for machining En-31 steel.

Optimal machining parameters were also determined by the grey relational grade obtained from the grey relational analysis for multi performance characteristics (surface roughness, chip-tool interface temperature, chip thickness, cutting forces and tool wear rate). Lastly the
effect of the temperature of solid-liquid lubricant on machinability of EN-31 steel was studied. For this study, Taguchi parameteric design and Taguchi Utility concept was used for determining the optimum combinations of cutting parameters for different machining conditions for optimal multi-performance characteristics (minimum surface roughness and power consumption in metal cutting).