LITERATURE REVIEW ON TURNING OPERATIONS

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1. Introduction

Turning operation is widely used in workshop practice for applications carried out in conventional machine tools, as well as in NC and CNC machine tools, machining centers and related manufacturing systems. Turning involves the use of a lathe and is used primarily to produce conical and cylindrical parts. With common attachments, flat faces, curved surfaces, grinding and boring can be done with a lathe. Therefore, it is valuable to increase tool life, to improve surface accuracy, to reduce main cutting force, feed force and to reduce machining zone temperatures (chip-tool interface temperature) in turning operations through an optimization study. Cutting fluids are generally used in machining process to reduce friction and wear, thus improving the tool life and surface finish. These are also used to reduce the cutting forces and energy consumption, to cool/lubricate the machining zone, wash away the chips, and to protect the machined surfaces from environmental corrosion.

Machinability is defined as ease of machining of a material, characterized by low cutting forces, high material removal rate, good surface finish, accurate and consistent work piece geometrical characteristics, low tool wear rate and good curl or chip breakdown of chips etc.

In machinability studies investigations, statistical design of experiments is used quite extensively. Statistical design of experiment refers to the proper planning of the experiment so that a reliable data may be obtained under all possible combinations of parameters and can be analyzed using statistical methods, resulting in valid and objective conclusions (Montgomery, 2005), With statistical design of experiments large data is selected in small number of experimental value.

In order to establish an adequate functional relationship between the tool life and cutting parameters a large number of tests are needed in one-factor-at-a-time approach. So, the experimentation cost also increases (Chaudhury, 1998). Most researchers have investigated the effects of various cutting parameters on responses (output) by the one variable at a time approach. The present study takes into account the simultaneous variation of cutting speed, feed, depth of cut, tool nose radius and percentage concentration of solid-liquid lubricants according to factorial design of experiment, and predicts, the responses. This approach is known as response surface methodology (RSM). Response surface methodology (RSM) is a statistical method for heuristic optimization, which is basically a combination of design of experiments, regression analysis and statistical inferences. It is very useful technique for modeling and analysis of problem in which a response of interest is influenced by several variables and the objective of this approach is to optimize the response (Montgomery, 2005). By using this approach mathematical models have been developed based on experimental results. The purpose of developing mathematical models relating to the machining response and their factor is to facilitate the optimization of the machining process. Modeling and optimization are necessary for the control of the steel turning process to achieve improved product equality, high productivity and low cost.

In this work experimental investigations have been conducted to study the machinability of En31 steel while turning with tungsten carbide tools. En-31 is selected for machinability studies, 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. (Kalapakjian, 1997)). Turning is the main machining process for the production of these parts (HMT, 1996).

Main interest of present research is to a solid-liquid lubricant for chip-tool interface while turning, so that the machinability of En-31 steel is improved and an attempt a new technique of applying the lubricant so that real minimum quantity lubricant can be achieved.

2. Machinability Criteria and Minimum Quantity Lubrication

Suresh et al. (2002) developed a surface roughness prediction model for turning mild steel using a response surface methodology. Surface roughness prediction model has also been optimized by using genetic algorithms.

Chen (2000) found out that while finish cutting of hardened steel, the radial force became the largest among three cutting force components and was the most sensitive to the changes of cutting edge chamfer, tool nose radius and flank wear. He reported that although an un chamfered tool with a small nose radius generated low radial force and hence reduce the tendency to chatter, such geometry decrease the tool life. By applying high-pressure coolant during machining the tool life and surface finish are found to improve significantly decreasing the heat and cutting forces generated.

Senthil et al. (2002) performed experimental investigation on ASSAB-718 steel material during end milling operation using single uncoated A-30N tungsten carbide insert and a Tin-Al-CN coated insert at a speed of 150 m/min with feed rate of 0.05mm/tooth and depth of cut 0.35mm, they showed the effectiveness of high pressure coolant in terms of improved surface finish, reduced tool wear and cutting forces, and control of chip shape. The tool wear with high pressure coolant is significantly better than that dry cut and conventional coolant. Hence this reduces the friction at the tool workpiece interface and increases the surface finish.

Zafer (2004) found that when turning AISI304 stainless steel with WC ISO p10 cemented carbide cutting tool, average chip thickness decreases as the cutting speed increases regardless of the feed. At the same time, power consumption decreases owing to low chip thickness during chip removal. Less vibration was observed and surface roughness got better due to the decrease of power consumption.

George (2002) reported that the chip thickness reduces as the cutting speed increases. Less energy was used as the cutting speed increases as the material softened by high temperature. This will result the lower compressive deformation caused by the tool face against the chip. This will result in the thinner chips due to lower compressive deformation as the chip is less deformed, also noted that higher force required to produce thicker chips. The force decreases with cutting speed and this would automatically produce thinner chips.

Sreejith et al. (2000) reported that dry machining is the machining of future. They concluded that the dry machining can eliminate cutting fluids and this is possible due to the advancement of the cutting tool materials.

Completely dry cutting has been a common industry practice for the machining of hardened steel parts. These parts typically exhibit a very high specific cutting energy. Traditional beliefs indicate that completely dry cutting of them as compared to flood machining lowers the required cutting force and power on the part of the machine tool as a result of increased cutting temperature. However achievable tool life and part finish often suffer under completely dry condition. Therefore, the permissible feed and depth of cut have to be restricted. Under these considerations, the concept of minimum quantity lubrication presents itself as a possible solution for steel turning in achieving slow tool wear while maintaining cutting force/power at reasonable levels.

In all machining processes, tool wear is a natural phenomenon and it leads to tool failure. The growing demands for high productivity of machining need use of high cutting velocity and feed rate. Such machining inherently produces high cutting temperature, which not only reduces tool life but also impairs the product quality.

Metal cutting fluid changes the performance of machining operations because of their lubrication, cooling and chip flushing functions, but the use of cutting fluid has become more problematic in terms of both employee health and environmental pollution. The minimization of cutting fluid also leads to economic benefits by way of saving lubricant costs and workpiece/tool/machine cleaning cycle time. The concept of minimum quantity lubrication (MQL) has been suggested since a decade ago as a means of addressing the issues of environmental intrusiveness and occupational hazards associated with the airborne cutting fluid particles on factory shop floors.

Khan et al. (2006) reported that the cutting performance of MQL machining is better than that of dry machining because MQL provides the benefits mainly by reducing the cutting temperature, which improves the chip-tool interaction and maintains sharpness of the cutting edges. Water + vegetable oil provided as coolant at the cutting zone through a jet. MQL jet provides reduced tool wear, improves tool life and better surface finish as compared to dry machining of steel. Surface finish and dimensional accuracy improved mainly due to reduction of wear and damage at the tool tip by the application of MQL. Such reduction in tool wear would either enhance tool life or productivity, allowing higher cutting velocity and feed. MQL by vegetable oil reduced the cutting forces by about 5% to 15%.

In turning change over to the new concept of minimum quantity of cutting fluid application is possible without loss in productivity or quality. A small amount of highly efficient lubricant is fed to the cutting zone, which is completely used and gives dry cutting. The above mentioned studies indicate that the machining response can be improved by reducing the tool wear. Dry machining and machining with the flooded cutting fluids have not responded to improved tool life and surface finish. he use of minimum quantity of lubrication method in metal cutting may be a viable alternative to cutting fluids (flooded condition) as has been reported in some of the above mentioned studies.

Machado et al. (1997) applied 200-300 ml/hr of soluble oil when turning steel bars. The coolant was delivered in a flowing air stream at a pressure of 29-34 psi. The experimental results showed that surface roughness, chip thickness and cutting forces variations were improved compared to the conventional flood cooling situation. The authors found the following phenomena. Cutting and feed forces were reduced with the use of cutting fluids when turning medium carbon steel bars under low cutting speeds and high feed rates. In some cases, cutting with near dry cooling had better results than conventional flood cooling, reduced variation in cutting forces and extended the tool life, the effect of near dry cooling on surface finish and chip thickness was only noticeable at low cutting speeds and high feed rates and application of near dry cooling reduced the cost of cutting fluids and related equipment. However, the aerosol concentration increased compared with traditional flood cooling case.

Varodarajan et al. (2002) claimed to have used 2ml/hr oil in a flow high pressure air at 20 M Pa, while hard turning AISI4340 steel. This may call to be near dry turning. It was found that cutting under near dry had better performance than that in dry and wet cutting in terms of cutting forces, cutting temperatures, surface roughness, tool life, cutting ratio and chip-tool contact length. Lower cutting force, lower cutting temperatures, better surface finish, shorter chip-tool contact length, larger cutting ratio and longer tool life were observed in near dry cutting compared with those in dry or wet cutting. They have used tool-work thermocouple technique for the measurement of temperatures during hard turning AISI4340 steel, but there was not any comparison between predicted cutting temperatures and measured values. Maclure et al. (2001) called it “micro lubrication.” The minimization of cutting fluid also leads to economic benefits by way of saving lubricant costs and work piece/tool/machine cleaning cycle time.

Dhar et al. (2006) investigated performance of minimum quantity lubrication technique with a spray of air and vegetable oil during turning medium carbon steel (AISI 43400) with uncoated carbide cutting tool. During turning of medium carbon steel with minimum quantity lubrication, cutting temperature, chip reduction coefficient, cutting forces and surface roughness have been measured and compared with dry turning. It was found that cutting temperature; chip reduction coefficient, cutting forces and surface roughness are minimum in MQL machining as compared to dry machining.

Dhar et al. (2006) investigated the influence of near dry lubrication on cutting temperature, chip formation and dimensional accuracy when turning AISI 1040 steel. The lubricant was supplied at 60 ml/hr through an external nozzle in a flow of compressed air (7bar). Based on the experimental results the authors concluded that near dry lubrication resulted in lower cutting temperatures compared with dry and flood cooling. The dimensional accuracy under near dry lubrication presented a notable benefit of controlling the increase of the work piece diameter when the machining time elapsed where was observed and dimensional accuracy was improved with the use of near dry lubrication due to the diminution of tool wear and damage.

Dhar et al. (2001) discussed the role of cryogenic cooling on tool wear and surface finish in plain turning of AISI1060 steel at different speed-feed combinations for two different inserts. They evaluated the effectiveness of cryogenic cooling, compared with the dry and conventional cooling counter parts. The LN2 jets were impinged using specially designed nozzles along the main cutting and auxiliary cutting edges. The observations showed that dry machining steel cause maximum tool wear and surface roughness while wet machining did not show any appreciable improvement. But cryogenic machining using LN2 provided reduced tool wear, improved tool life and surface finish. The beneficial effects of cooling may also contribute to effective lubrication, retention of tool hardness and favorable chip tool and work tool interaction.

Dhar et al. (2002) performed a study on cryogenic machining of plain carbon steels C-40 under varying cutting velocities and feed rate and concluded that cryogenic cooling if properly employed not only provides the environment safety but also improves Mach inability characteristics.

Nanda et al. (2002) studied cryogenic machining of two types of steels AISI1040 and AISI4320 using carbide inserts and concluded that the cooling by LN2 jets can substantially reduce the cutting forces during machining without affecting the working environment. It provides benefits mainly by reducing the cutting temperatures, which helps in improving the chip-tool interaction and maintains sharpness of the cutting edges.

Chen et al. (2001) studied the effects of oil-water combined mist on turning stainless steel with the use of 17 ml/hr oil and 150 ml/hr water mixture. The use of oil-water combined mist could prevent the production of built-up-edge (BUE) while BUE was observed when cutting dry or with mist. BUE is an important factor of work-piece surface roughness. Therefore the work-piece surface finish under oil water combined mist was better than that under dry, oil mist or wear soluble oil applications. Lower cutting temperatures were also observed with the use of oil-water combined mist compared to cutting dry or with oil mist.

Klock et al. (1997) dealt with drilling tests using minimum cooling lubrication systems, which are based on atomizing the lubricant directly to the cutting zone.

Small quantities of lubricant, in order of 10-50 ml/h, were mixed with compressed air for external feeding via a nozzle or for internal feeding via spindle and tool. Internal feed systems with their ability to deliver the mixture very close to the drill work-piece contact point may achieve very good results in terms of surface finish and tool life.

Rahman et al. (2002) performed experiments in end milling with the use of lubricant at 8.5 ml/hr oil flow rate. The oil was supplied by the compressed air at 0.52MPa. The work piece material was ASSAB 718HH steel. The experimental results showed that tool wear under dry lubrication was comparable to that under flood cooling when cutting at low feed rates, low speeds and low depth of cuts. The surface finish generated by near dry machining is significantly higher than flood cooling. Cutting forces were close in both near dry machining and flood cooling. Fewer burrs formed during near dry machining compared to dry cutting and flood cooling application. The tool-chip interface temperature under dry lubrication was lower than in dry cutting but higher than in flood cooling machining.

Lopez et al. (2006) studied the effects of cutting fluid on tool wear in high speed milling. Both near dry lubrication and flood cooling were applied when cutting aluminum alloys. In addition to experiments, they also performed computational fluid dynamics (CFD) simulations for estimating the penetration of the cutting fluid to the cutting zone. The oil flow rates of 0.04 and 0.06 ml/min were studied. The pressurized air was applied at 10bar. They reported that with the help of compressed air, the oil mist could penetrated the cutting zone and provide cooling and lubricating while the CFD simulation showed that the flood coolant was not able to reach the tool teeth, the nozzle position relative to feed direction was very important for oil flow penetration optimization.

Braga et al. (2002) studied the cutting forces, tool wear and quality of hole when drilling aluminum-silicon alloys with minimum quantity lubricant and diamond coated tool. The minimum quantity lubrication was 10 ml/hr soluble oil in a flow of 4.5 bar compressed air. The experimental results revealed that the power consumed under minimum quantity lubrication was lower than the power required in flood cooling, regardless of the tool material. It was inferred that with flood cooling, the work-piece did not heat as much and it required more power to cut the aluminum silicon alloys. The tool wear behavior and hole quality was similar for both MQL and flood machining conditions. The hole roundness improvement was significant by introducing the MQL lubrication for the diamond coated drill and negligible for the uncoated drill.

Kelly et al. (2002) applied near dry lubrication to optimum drilling cast aluminum alloys. A flow of 20 ml/hr oil was delivered with the compressed air at the gauge pressure of 6 bars. The authors reported that the feed force, drill torque and surface roughness under near dry lubrication were the lowest compared with those in flood cooling, compressed air or dry cutting. However, the experimental results also showed that the accuracy of hole for near dry drilling was worse than that for flood cooling situation.

Hafenbraedl et al. (2000) evaluated the near dry lubrication with ester oil based on internal cylindrical grinding tests. These tests were performed when cutting AISI 52100 hardened steel with oil flow rate of 12 ml/hr mixing with 69 kPa compressed air. The experimental results showed that with the application of near dry lubrication, lower specific cutting energy, better surface finish and higher G-ratio were observed when comparing with cutting completely dry or under flood cooling. However, the elevated bulk temperature was observed as well as thermal distortion of the work-piece for near dry grinding. This indicated that the cooling from the mixture of ester oil and cold air was not sufficient. The size accuracy would be a problem due to the thermal distortion.

Brinksmeier et al. (1999) applied minimum quantity lubrication in grinding. Two different work materials were used: hardened steel (16MnCr5) and tempered steel

(42CrMo4V). The minimum quantity lubrication was implemented under 0.5 ml/min oil flow rate and 6 bar pressurized air. With reference to the grinding tests, they have concluded that both dry and near dry grinding would cause thermal damage on the hardened material with the creep feed grinding operation. Minimum surface roughness values were obtained under minimum quantity lubrication technique when material removal rate was low. The analysis of the cooling effect of cutting fluid for both minimum quantity lubrication and flood cooling was also presented. However, there was not a comparison between predicated and measured cutting temperatures.

Dhar et al. (2007) employed minimum quantity lubricant technique turning of AISI 1040 steel and the results clearly indicated that a mixture of air and soluble oil machining is better than conventional flood coolant system. That appeared to be ineffective for applications involving high temperature. Similarly liquid lubricants (flooded conditions) appear to be ineffective for applications of involving high temperatures (Edemir, 1994).

Solid lubricants are the only option available for controlling wear and friction between tool and work piece in all types of tribo systems involving severe tribological condition and any environment (high temperature, corrosive media vacuum environment high load, and speed and dry condition). Strong adhesion is essential for long service of solid lubricant films. Ion – beam processes are capable of imparting strong adhesion between solid lubricant films and ceramic substrates. Ion-beam mixing of ceramics with conventional solid lubricants, such as MoS2, is feasible and appears promising for demanding aerospace applications. A unique solid lubricant, boric acid, has been recently been discovered. It has been established that this lubricant can impart remarkably low friction coefficients to sliding ceramics interfaces in humid environments, where Molybdenum disulphide is known to be ineffective (Edemir, 1994).

Application of solid-liquid lubrication in cutting has proved to be feasible alternative to cutting fluids, if it can be applied properly. If the friction at the machining zone can be minimized by providing effective lubrication, the heat generated can be reduced to some extent. If a suitable lubricant can be successfully applied in the machining zone, it leads to process improvement. Some researchers have reported the use of solid lubricants in the machining process.

Sen et al. (1994) used large amount of solid lubricant in metal forming processes. Particularly, in extrusion processes, solid lubricant such as MOS2 powder, graphite based grease; lithium grease, graphite grease etc. They have been used to reduce the extrusion force and improve the surface quality.

Popke et al. (1999) reported longer tool life with a with a minimum quantity of cutting fluid application as compared with dry and flood type applications while drilling, counter boring and reaming steel material C45 and is clear that minimum quantity cutting fluid application is more appropriate with high speed steel tools for clean manufacturing.

Bennett (1983) studied the overall effect of cutting fluids on the worker safety and on the environment through bacterial cultures. In some applications the consumption of

cutting fluids has been reduced drastically by using mist lubrication. However mist in the industrial environment can have a serious respiratory effect on the operator.
Shaji et al. (2002) reported the use of solid lubricants in grinding as an alternative for the conventional coolants. They have investigated the effect of solid lubricant like graphite on the surface grinding process. Results showed an improvement on surface finish in case of hardest material with the application of solid lubricant. The solid lubricant applied in this investigation was graphite, calcium fluoride, barium fluoride, and molybdenum trioxide. Improved process results related to friction have been reported in this study.
Boric acid (H_3BO_3) is one of the most popular solid lubricant and has excellent lubrication properties without calling for expensive disposal techniques. The most important characteristics of boric acid for use as a lubricant are that it is readily available and cheap and environmentally safe. There is no side effect of boric acid on health of the operators, non-toxic and water-soluble (Erdemir, 2008). Several studied friction and wear between tool and sliding steel surface were related to the lubrication properties of boric acid (Erdemir, 1994, 2008). These works have primarily focused on the performance of boric acid in high temperature applications. The studies indicated that boric acid is unique layered inter-crystalline structure; it makes a very promising solid lubricant material because of its relatively high load carrying capacity and low steady state friction coefficient (0.02).
Another study focused on the use of solid lubricant (boric acid and MoS_2) in forming and drilling (Liang et al. 1995). In metal forming applications it is shown that the boric acid provided very low friction between an aluminum work piece and steel forming tool.
Shaji Radhakrishnan (2003) investigated the possibility of using graphite as a lubricating medium to reduce the heat generated in the grinding zone in surface grinding. Different process parameters like cutting forces, temperature, specific energy and surface roughness were observed and reported to be reduced when compared to those in grinding with conventional coolant.
The author investigated the possibility of using different solid lubricants as graphite, MoS_2 and boric by weight mixed with base oil SAE-40 as a minimum quantity lubricant, to reduce the heat generated in the machining zone (chip-tool interface) in turning process. Different process parameters like cutting forces, cutting temperatures, chip thickness, and surface roughness were observed and reported to be reduced as compared to dry machining. For the similar machining conditions higher reduction in the cutting forces, cutting temperatures, chip thickness and surface roughness in the presence of solid-liquid lubricant is possible, because the lubricant in the metal cutting process will provide the lubricating and cooling effects. They introduced a new concept of applying the solid-liquid lubricant with a brush to the work-piece surface that seeped with the cutting zone. It may be considered as real near dry machining condition.
Suresh et al. (2006) investigated the role of solid lubricant assisted end milling machining with graphite and molybdenum disulphide lubricants on surface quality,

cutting forces and specific energy while machining AISI 1045 steel using cutting tools of different tool geometry (radial rake angle and nose radius). The performance of solid lubricant assisted machining has been studied in comparison with that of wet machining. The results reported that there is considerable improvement in the processes performance as compared to that of machining with cutting fluid in terms of cutting forces, surface quality and specific energy.

Deshmukh et al. (2006) studied the performance of different solid lubricants like MoS2, MoS2 based grease graphite based grease and silicon compound mixed with SAE-20 base oil at different proportions while machining aluminum and brass with carbide cutting tool. The results showed that improved surface quality as compared to wet machining of aluminum and brass.

Latkar et al. (2001) assessed the effect of machining on tool wear and surface roughness with graphite based grease mixed with base oil SAE-20 in varying proportions applied in MQL and compared the results with dry machining while medium alloy steel was machined with tungsten carbide tool. The results reported that tool wear and surface roughness were observed minimum under mixed lubricant as compared to dry machining.

Ingole et al. (2002) studied the effect of lubricants on the surface finish in burnishing of En8 specimens. Using 23 factorial design surface roughness model equations were developed. The burnishing parameters considered were speed, feed and force. Other parameters were kept constant. The lubricants studied were SAE-40, grease and mixture of the two. Out of these SAE-40 was found to be better.

Venugopal et al. (2004) investigated the use of graphite as a lubricating medium in grinding process to reduce the heat generated at the grinding zone. The effective role of graphite as lubricant is evident from the overall improvement in the grinding process. Different process performance parameters like cutting forces, cutting zone temperatures specific energy and surface roughness were observed and reported to be reduced when compared to those with grinding with conventional coolant.

Vamsi et al. (2008), studied the performance of solid lubricants like graphite and boric acid with SAE-40 oil while machining EN8 steel with cemented carbide tool. After conducting one-factor-at-a-time experiment the results showed that minimum tool wear, surface roughness and cutting forces were observed as compared to wet and dry machining. Among the lubricants 20% boric acid in SAE-40 oil provided better performance for the selected work-tool material combination and cutting conditions. However, there was not any comparison between predicted chip tool interface temperatures and measured chip-tool interface temperatures.

Shirsat et al. (2004) studied the influence of burnishing parameters on surface finish in burnishing of aluminum specimens. The finishing parameters considered were speed, feed rate, burnishing force. It was found that the surface roughness improves initially with an increase in these parameters. After a certain stage, the surface finish deteriorates and fatigue life decreases. The lubricant studied were Kerosene, SAE-30 oil, 5% graphite by weight in SAE-30 oil and 10% graphite by weight in SAE-30 oil. Out of this Kerosene was found to be better.

3. Cutting Tool Temperature and Tool Wear

In metal cutting, the heat generated on the cutting tool is important for the performance of the tool and quality of the workpiece. Maximum heat is generated on the tool-chip interface during machining. The machining can be improved by the knowledge of cutting temperature on the tool. The cutting temperature is a key factor which directly affects tool wear, work piece surface integrity and machining precision according to the relative motion between the tool and workpiece. The amount of heat generated varies the type of material being machined. The cutting parameters especially cutting speed, feed rate and depth of cut influence on the chip-tool interface temperature, Temperature in the cutting zone depends on contact length between tool and chip, cutting forces and friction between tool and work piece material. A considerable amount of heat generated during machining is transferred into the cutting tool and work piece. The remaining heat is removed with the chips. The highest temperature is generated in the flow zone. Therefore, contact length between the tool and the chip affects cutting conditions and performance of the tool and tool life (Shaw, 1989). In a single point cutting, heat is generated at three different zones during metal cutting as shown in Figure 1 (Trent et al. 1989).

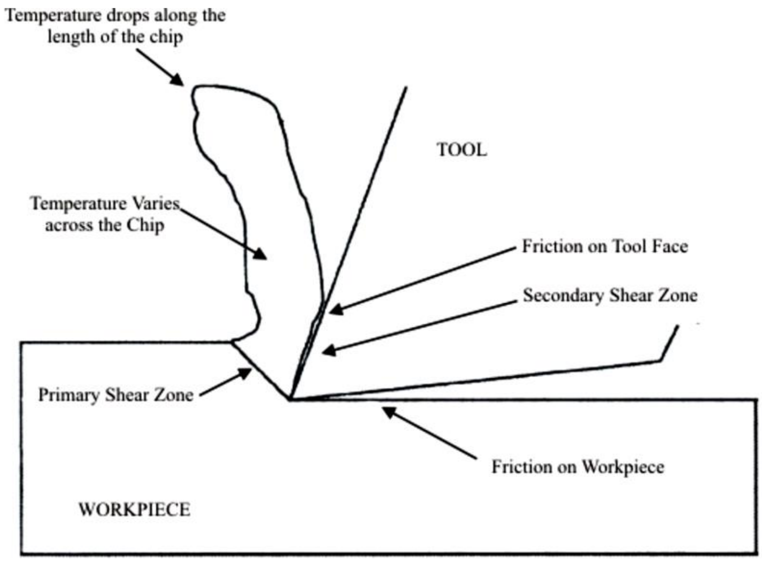

Figure 1 Heat generated by chip formation (Trent et al, 1989)

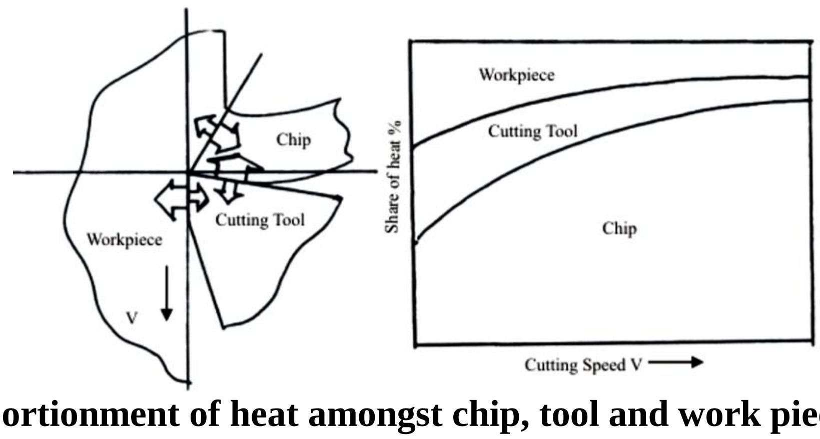

Figure 2 Apportionment of heat amongst chip, tool and work piece (Rao, 2002)
(Temperatures developed in turning AISI 52100steel, tool material K3H carbide)

1) Heat is produced in the primary shear zone as the workpiece is subjected to large irreversible plastic deformation.
2) Heat produced by friction and shear on the tool rake face, or secondary shear zone.
3) Heat produced at the tool-work interface, where the tool flank runs along the workpiece surface and generates heat through friction.

The heat generated is shared by the chip, cutting tool and the work-piece. Figure 2 shows the maximum amount of heat is carried away by the flowing chip. From 10% to 20% of the total heat goes into to the tool and some heat is absorbed in the work-piece. With the increase in cutting speed, the chip shares heat increasingly (Rao, 2002). The effect of cutting temperature, particularly when it is high, is mostly detrimental to both the tool and the job. Due to the high shear and friction energies dissipated during a machining operation the temperature in the primary and secondary shear zones are usually very high, hence affect the shear deformation and tool wear. Total tool wear rate and crater wear on the rake face are strongly influenced by the temperature at chip-tool interface. Therefore, it is desirable to determine the temperatures of the tool and chip interface to analyze or control the process. Several experimental and analytical techniques have been developed for the measurement of temperatures generated in cutting processes. Due to the nature of metal cutting, it is not possible to measure temperature precisely in the cutting zone and thus it difficult to verify the theoretical results in a precise manner. Because of nature of the metal cutting (elasto-plastic nature of the chip tool contact), tool geometry and variation of thermal properties of tool-work combination with temperature, determinations of internal temperatures on the cutting tool are very difficult. Actual measurements give a true picture of cutting temperatures. For measuring of this temperatures generated in the cutting zone, several methods have been developed. Since at the interface there is a moving contact between the tool and chip, experimental techniques such as standard pre calibrated thermocouples cannot be used to measure the interface temperature. The main techniques used to evaluate the cutting temperature during machining are embedded thermocouple, tool-work thermocouple, calorific method, single wire thermocouple, PVD film method, Infrared thermometers, Infrared cameras etc. (Silva et al. 1999, Davis et al. 2010). Out of these methods the tool-work thermocouple is easy and simple technique for measuring chip-tool interface temperature (average temperature) during metal cutting.

The thermocouple methods are based on the thermocouple principle that states that two contacting materials produce an electromotive force (e.m.f.) due to difference in temperatures of cold and hot junctions (Barrow, 1973). Tool-work thermocouple has always become a popular tool to be used in temperature measurements during metal cutting. This method is very useful to indicate the effects of the cutting speed, feed rate, and cutting parameters on the temperature. Thermocouples are conductive, rugged and inexpensive and can operate over a wide temperature range. In machining applications, a thermoelectric emf is generated between the tool and the work piece. With this method, the entire tool-work is used as a part of the thermocouple. In this method, the thermo-electric emf generated between the tool and the work-piece during cutting is measured. The cutting zone forms the hot junction, while the workpiece forms the cold junction. The tool and work-piece need be electrically insulated from the machine tool. This cutting temperature measurement technique is easy to apply for the measurement of chip-tool interface temperature during metal cutting over the entire contact area as reported by Shaw (1989). Based on this measurement using the thermocouple method Stephenson (1993) stated that the average emf is generated in tool- work piece interface. The difficulty of this method is concerned with the necessity for an accurate calibration of the tool and work-piece materials as a thermocouple pair.

Shaw (1989) used a lead bath for the heated junction medium in the calibration of the tool-work thermocouple. After a lead bath is insulated and uniformly heated, both the tool and work piece chip are inserted into the bath with a thermocouple for calibration.

In the present work, the calibration of the tool-work thermocouple was carried out by external flame heating. This set up is similar to the one used by Stephenson (1992), in which the tool was calibrated directly with the work piece.

In order to measure the cutting edge temperature using a thermocouple two different methods can be used to fix the hot junction close to the cutting edge. In the first method, the thermocouple is clamped in a recess, which is ground off the rake face of the tool to locate the hot junction as close as possible to the cutting edge. In the second method, the thermocouple is inserted in a precisely grooved carbide chip breaker, which is clamped mechanically on the tool such that the hot junction is at the same distance as in the first method. Comparing results obtained by the two methods showed that both methods gave the same results (Wardany et al. 1996). Therefore it was suggested that the second method is better since the recess in the cutting tool would change the temperature distribution along the rake face. In addition the second method is considered easier to implement. In this work the tool-work thermo couple technique was used to measure the chip-tool interface temperature (average cutting temperature) during machining of EN-31 steel alloy.

Shaw (1989) developed analytical prediction model for the measurement of cutting temperature during machining. They concluded that the cutting temperature is the function of cutting speed and feed rate.

$$\theta t = V^{0.5} * t^{0.3} \qquad (1)$$

Where, θt = Average cutting temperature in degree centigrade, v = cutting speed m/min, t = undeformed chip- thickness or feed rate mm/rev, Shaw did not include depth of cut in his model even though its effect may be significant.

The Shaw’s method was found to be the best predictor according to Stephenson (1992). Wardeny et al (1996) suggested that the temperature distribution in the tool may be obtained by using information about the changes in the hardness and microstructure of the steel tool. It is necessary to calibrate the hardness of the tool against the temperature and time of heating and samples of structural changes at corresponding temperatures. These methods permit measurement of temperatures to an accuracy of ± 25oc within the heat affected region. Grzesik (1999) investigated the influence of tool-work interface temperature when machining an AISI1045 and an AISI 304 with coated tools. A standard K-type of thermocouple inserted in the work piece was used to measure the interface temperature. The friction on the flank face had a big influence on the heat generated at about 200 m/min cutting speed.

During metal cutting, the heat generated is significant enough to cause local ductility of the work piece material as well as of the cutting edge. Although softening and local ductility are required for machining hard materials, the heat generated has a negative influence on the tool life and performance. Therefore, the control of cutting temperature is required to achieve the desired tool performance.

Although EN-31 steel alloy is widely used in the automotive metal cutting industry, no attempts have been made to investigate the effect of different process parameters and tool geometry (effective tool nose radius) on the cutting temperature during metal cutting of EN-31 steel.

This study presents the results of the tool-chip interface temperature (cutting temperature) measurements by the tool-work thermocouple technique. Tool-chip interface temperature is analyzed under a wide range of cutting conditions during dry, flooded, and (solid-liquid) minimum quantity lubrication turning of EN-31 steel alloys with tungsten carbide inserts. This work provides a better understanding of the effect of machining parameters on chip-tool interface temperatures during machining of EN-31 steel materials. Then Effect of chip-tool interface temperature on total tool wear rate, effect of tool wear rate on three components of cutting forces, metal cutting power, surface roughness of machined workpiece, chip thickness, forms of chips, chip micro-hardness has also been reported.

Tool-work thermocouple has always become a popular tool to be used in chip tool interface temperature measurements during metal cutting as compared to other. The benefits of using the tool-work thermocouple are the ease of implementation and its low cost as compared to other type of temperature measurement technique. This method is very useful to indicate the effects of the cutting speed, feed rate and cutting parameters on the temperature.

Sullivan et al. (2001) measured the machined surface temperatures with two thermocouples inserted into the work piece when machining aluminum 6082-T6. The results indicated that an increase in cutting speed resulted in a decrease in cutting forces and machined surface temperatures. This reduction in temperature was attributed to the higher metal removal rate that resulted in more heat being carried away by the chip.

According to Trent et al. (1989) during the machining process, a considerable amount of the machine energy is transferred into heat through plastic deformation of the work-piece surface, the friction of the chip on the tool face and the friction between tool and the work-piece. Trent and Wright suggested that 99% of the work done is converted into heat. This results in an increase in the tool and work temperatures.

According to Muller-Hummed et al. (1996) the temperature distribution depends on the heat conductivity and specific heat capacity of the tool and the work piece and finally the amount of heat loss based on radiation and convection. The maximum temperature occurs in the contact zone between the chip and the tool. The heat generated in those zones is distributed among the tool, the work piece, the chip and after that to the environment. Heat generated at the shearing plane can make the cutting action easy, but it can flow into the cutting edge and that will negatively affect the tool life by shortening it. Therefore it is necessary to control the chip-tool interface temperature during metal cutting.

Chaudhary et al. (2003) predicted cutting zone temperatures by natural tool work thermocouple technique, when machining EN-24 steel work piece and HSS with 10% cobalt as the cutting tool. The results indicated that an increase in cutting speed and feed rate resulted in an increase in tool wear. The cutting zone temperature increases with the increase in the cutting speed. In the whole range of feed the temperature increases with increase in feed rate.

Ay et al. (1998) used a technique with K thermocouple to analyze temperature variations in carbide inserts in cutting various materials such as copper, cast iron aluminum 6061 and AISI1045 steel. They observed oscillations in temperature near the cutting edge, which were more marked for ductile materials and less in the hard – machining materials. These observations were attributed to the chip formation, which raises the local temperature upon its contact with the work material.

Kashiway et al. (1998) investigated the effect of cutting temperature on the integrity on machined surface. It has been shown that cutting temperature has a major effect on the integrity on the machined surface. The undesirable surface tensile residual stresses were attributed to the temperature generated during machining. Therefore, controlling the generated tensile residual stresses relies on the understanding of the effect of different process parameters on the cutting temperature.

Fnides et al. (2008) studied the influence of cutting speed, feed rate and depth of cut on cutting pressures, cutting force and on cutting temperature, when machining AISI H11 steel treated to 50 HRC work piece material with mixed ceramic tool. The results show that depth of cut has great influence on the radial cutting pressure and on cutting force. The cutting pressure and cutting force increase with an increase in depth of cut and feed rate. It is found that increase in cutting speed increases cutting zone temperature rapidly. It is also noted that cutting speed seems to influence temperature in cutting zone more significantly than the depth of cut and feed rate.

Trent (1989) used a technique with tool-work thermocouple to analyze chip tool interface temperature variation under different cutting conditions, such as the cutting speed and depth of cut, as well as with different cutting fluids. His results showed that temperatures increased with increase in speed from 0.1m/s to 1m/s. Similarly, temperatures were high when cutting dry, followed by cutting with an oil lubricant, and finally with water as the cutting fluid. Since water is the best conductor of heat among the three choices, it gave the lowest temperature, reinforcing water’s ability as a good coolant. He achieved up to 30 to 40 % increase in cutting speed when machining steel with high speed steel tools using water as coolant. Despite its excellent cooling ability water lacks lubricating properties and causes serious corrosion problems on the machine tool components as well as on the machined work-piece.

Vieira et al. (2001) studied the cooling ability of the cutting fluids. The cutting fluids used were emulsion of mineral oil, semi-synthetic and synthetic cutting fluids, cutting temperatures was measured by tool work thermocouple technique during turning of AISI 1020 steels. The results showed that the chip-tool interface temperature increased with increasing cutting speed during machining. Cutting fluids reduced the mean chip-tool interface temperatures in relation to dry cutting. Out of these cutting fluids the semi-synthetic cutting fluids exhibited the best cooling ability during machining, followed by the emulsion -based mineral oil, and the 5% concentration and 10% concentration of synthetic fluids.

Abou-EI-Hossein, (2008) studied the efficiency of cutting fluids when end milling of AISI 304 stainless steel. Tool life and tool wear mechanisms with wet machining were compared to dry cutting. Results showed that cutting fluid application was efficient at low cutting speeds. Dominant wear mechanisms in dry machining were built-up edge and nose wear, while in wet machining dominant wear mechanisms were notch wear and cutting edge grooving.

Khan (2009) reported the effects of MQL by vegetable oil based cutting fluid on the turning performance of low alloy steel AISI 9310 as compared to completely dry and wet machining in terms chip-tool interface temperature, chip formation, tool wear and surface roughness, chip-tool interface temperature were measured by tool work thermocouple technique during turning of AISI 9310 steels. The results showed that chip- tool interface temperature were reduced by MQL and wet machining as compared to dry machining under different cutting condition with uncoated carbide inserts. During metal cutting, the heat generated is significant enough to cause local ductility of the work piece material as well as of the cutting edge. Although softening and local ductility are required for machining hard materials, the heat generated has a negative influence on the tool life and performance. Therefore, the control of cutting temperature is required to achieve the desired tool performance.

Avila (2001) investigated the effect of cutting fluids on the machining of hardened steel (AISI4340). In this work, the performance of three types of cutting fluids (two emulsions and one synthetic fluid) has been compared to dry machining using mixed alumina inserts. Results show that the application of a cutting fluid based on an emulsion without mineral oil results in longer tool life compared to dry cutting and the use of cutting fluid is responsible for reducing the scatter in the surface finish values at high cutting speeds.

Lin et al. (2008) found that tool life rises with the increase of cutting speed until a maximum is reached where it starts to decrease. In low speed cutting, abrasion is the main form of wear. When cutting speed is increased, a sticking layer is formed and remained on the tool face which protects tool face from wearing. At high cutting speed, the chip is transformed from continuous type to segmented type. Friction force is increased accordingly, and the layer on the tool face is abraded gradually. Since diffusion between work and tool materials becomes more severe at high cutting speed, the bond between the hard particles is weakened, and wear on the rake face is increased drastically. Together with the increase of crater wear, flank wear is increased.

Martin (2006) studied that a finite element of a two-dimensional, orthogonal metal-cutting process is used to study the influence of the cutting speed on the cutting force and the chip formation process. The model uses a generic flow stress law. Friction is neglected as its speed dependence is only poorly known. It is shown that the experimentally observed decrease of the cutting force with the cutting speed. The decrease is mainly caused by a change in the shear angle due to thermal softening. At large cutting speeds, segmented chips are produced. It is also shown by an analytical calculation that segmented chips at large cutting speeds are energetically more favorable than continuous chips.

Diniz et al. (2003) studied the influence of refrigeration/lubrication condition on SAE52100 hardened steel turning at several cutting speeds with CBN tools. Dry and minimum volume of oil showed the similar values of flank wear, which is always smaller than the values for wet machining. Also wet machining did not show better values of surface roughness compared to minimum volume of oil and dry machining.

Bouzid et al. (2005) has studied the variation of tool wear with cutting time. This is to determine the tool life defined as the usable time that has elapsed before the tool wear has reached the criterion value. It is shown that an increase in cutting speed causes a higher decrease of the time of the second gradual stage of the wear process. This is due to the thin coat layer which is rapidly peeled off/when high speed turning. The investigation included the realization of a wear model in relation to time and to cutting speed. An empirical model has also been developed for tool life in terms of cutting speed. They have concluded that it is possible to set optimal cutting speed to achieve the maximum tool life by using their model.

Diniz et al. (2002) carried out experiments in turning operations of AISI1045 steel with coated carbide tools under different cutting conditions. They have studied comparison between dry cutting and cutting with cutting fluid at different feeds and cutting speeds. They concluded that the operation with fluid always lead to a longer tool life when compared with dry turning. The author has used a concept of total tool wear in this study.

Sales et al. (2001) measured the cooling capacity of several cutting fluids and showed that a synthetic fluid at 5% concentration presented a cooling capacity 10.9 times greater than when no cutting fluid was used, and at 10% concentration, the cooling efficiency was 6.6 times greater than when no fluid was used at all. This result shows the significant contribution the cutting fluid has towards the cooling in machining processes, especially in turning, in which the tool-work-piece contact is continuous.

4. Statistical Modeling and Optimization

Ahmed et al. (2007) developed tool life prediction model for turning medium carbon steel by using response surface methodology. Factorial design techniques have been used to study the effects of cutting speed and depth of cut on tool life. The test has been carried out using uncoated carbide inserts under high pressure coolant condition. They have presented first order tool life prediction model within the speed range of 133-226m/min. The results showed that response surface methodology carried with factorial design of experiments is a better alternative to the traditional one-variable-at-a-time approach for studying the effect of cutting variables on surface roughness and tool life. This significantly reduces the total number of experiments.

Davim (2001) developed linear regression models to predict average surface roughness and maximum peak to valley height by conducting experiments on free machining steel based on Taguchi L27 orthogonal array. The predicted values of surface roughness parameters were compared with corresponding values computed using theoretical models.

Noordin et al. (2004) studied the application of response surface methodology in describing the performance of coated carbide tools when turning AISI1045 steel. The factors investigated were cutting speed, feed and side cutting edge angle. The response variables were surface finish and tangential force. ANOVA revealed that feed is the most significant factor influencing the response variables investigated. It was also found that an increase in cutting speed and feed reduces the tool life for KT315 and KT9110. Tangential cutting force is the dominant force for all cutting speed. High feed speed produces loose arc chips. Mathematical models developed to predict cutting force produce sound results.

Tugral Ozel et al. (2005) developed predictive model of tool wear and surface roughness in hard turning by CBN tool using neural network and regression method. Trained neural network models were used in predicting tool flank wear and surface roughness for other cutting conditions. They concluded that decrease in feed rate resulted in better surface roughness but slightly faster tool wear.

Kalos et al. (2009) studied the application of RSM for minimizing the roundness and cylindricity on turned cylindrical components of EN-8 alloy steel with carbide tool. The parameters investigated were cutting speed, feed rate and bar diameter. The response variables were roundness and cylindricity. ANOVA revealed that the cutting speed is the main influencing parameter on roundness and feed rate is the main influencing parameter on cylindricity. Roundness increased with increasing cutting speed, but decreased with increasing feed rate while cylindricity increased with increasing feed rate, but decreased with increasing cutting speed. Mathematical models developed to predict cylindricity and roundness produce sound results. Monte Carlo simulation has been applied to simulate the process for combine error.

Anirban et al. (2009) have investigated the effect of cutting parameters on surface finish and power consumption during high speed machining of AISI irons steel using Taguchi design and ANOVA. In this study, combined technique of orthogonal array and analysis of variance was employed to investigate the contribution and effect of cutting speed, feed rate and depth of cut (only three factors) on three surface roughness parameters and power consumption were studied at different metal cutting conditions. The results showed a significant effect of cutting speed on surface roughness and power consumption, while the other parameters have not substantially affected the response.

Sood et al. (2000) studied the specific energy where the power of machining is one of the parameter affecting the specific energy. There have been plenty of recent applications of Taguchi techniques to materials processing for process optimization

(Aman et al. 2007, Faleh, 2005). Statistical methods and Taguchi's technique was used for investigating machinability and optimizing power consumption. In another study, it was observed that power consumption is one of the most important parameters for condition monitoring (Faleh, 2005). The study revealed that when cutting fluid is used, cryogenic environment is the most significant factor in minimizing power consumption followed by cutting speed and depth of cut. The effects of feed rate and tool nose radius were found to be insignificant compared to other factors.

Lin et al. (2001) have formulated a statistical model for surface roughness and cutting force by regression analysis, using for turned S5sc steel. Similar investigations have been made by Risbood et al. (2003).

Taguchi method (Taguchi, 1990, Ross, 1988, Phadake, 1989) is a systematic application of design and analysis for experiments. It has proved to be an effective approach to produce high-quality products at a relatively low cost.

Daniel et al. (2004) did the experiment with the objective of optimizing surface finish in a turning operation using the Taguchi parameter design method. The study found that control factors had varying effects on the response variable, with feed rate and tool nose radius having the highest effects. The noise factors, on the other hand, were found to not have a statistically noticeable effect. The measurement of the work pieces in this confirmation run led to the conclusion that the selected parameter values from this process produced a surface roughness that was much lower than the other combinations tested in this study. The use of the Taguchi parameter design technique was considered successful as an efficient method to optimize surface roughness in a turning operation.

Nalbant et al. (2007) presented an application of the parameter design of the Taguchi method in the optimization of turning operations. Taguchi's robust orthogonal array design method is suitable to analyze the surface roughness (metal cutting) problem .It is found that the parameter design of the Taguchi method provides a simple, systematic, and efficient methodology for the optimization of the cutting parameters. The experimental results demonstrated that the insert radius and feed rate are the main parameters among the three controllable factors (insert radius, feed rate and depth of cut) that influence the surface roughness in turning AISI 1030 carbon steel.

Yang et al. (1998) used Taguchi parameter design for optimization of machining parameters for turning operations. It was found that cutting speed and feed rate are the significant cutting parameters for affecting tool life. The change of the depth of cut in the range given (0.6-1.6 mm) has an insignificant effect on tool life. Therefore, based on the S/N ratio and ANOVA analyses, cutting speed, feed rate, and depth of cut are reported to be the significant cutting parameters for affecting surface roughness. However, the contribution order of the cutting parameters for surface roughness is feed rate, then depth of cut, and then cutting speed.

The optimization of turning operations based on the Taguchi method with multiple performance characteristics is proposed by Nian et al. (1998). The orthogonal array, multi-response signal-to-noise ratio, and analysis of variance were employed to study the performance characteristics in turning operations. Three cutting parameters namely, cutting speed, feed rate, and depth of cut, were optimized with considerations of multiple performance characteristics including tool life, cutting force, and surface finish.

Nihat Tosun (2006) used the grey relational analysis technique and determined the optimum drilling process parameters. Various drilling parameters such as feed rate, cutting speed, drill type and point angles were considered and optimized by the grey relational grade obtained from the grey relational analysis for multi-performance characteristics (surface roughness and the burr height).

Kao et al. (2003) obtained grey relational grade using grey relational analysis while electrochemical polishing of the stainless steel. Optimal machining parameters were determined by the grey relational grade as the performance index. They observed that the performance characteristics such as surface roughness and passivation strength are improved.

Palanikumar et al. (2006) optimized the turning parameters such as cutting speed, feed rate, depth of cut and machining time based on the multiple-performance characteristics including material removal rate, tool wear, surface roughness and specific cutting pressure by using grey relational analysis method.

Brahmankar et al. (2009) used new combination of response surface method and grey relational analysis to optimize electro-discharge machining parameters with multi-performance characteristics. A metal matrix composite Al/Al2O3P/10% has been machined at various combinations of machining parameters such as pulse on time, off-time, and wire speed and wire tension. Empirical models have been developed to predict the cutting rate, surface roughness, and kerf width of the machined composite material by RSM method. They observed that improvement in cutting rate was more than 100% compared to the initial level experiments, with reasonably smooth surfaces and narrow kerf width.

Chang et al. (2007) used grey relational analysis to set two stage experiments to determine cutting parameters for optimizing the side milling process with multi performance characteristics. Yang et al. (2006) employed grey relational analysis method to determine optimal machining parameters setting for the end milling of high-purity graphite under dry machining conditions.

However, when calculating the values of grey relational grade, most of the researchers determine the weighting values of various performance characteristics based on their own subjective estimation. The drawback of this approach is that it does not give actual weighting of various performance characteristics. To overcome this limitation, Jean et al. (2004) and Peng et al. (1999) used fuzzy logic to calculate weighting for determining grey relational grade to optimize a problem involving multi-performance characteristics.

This research work specially introduces a desirable solution for a multi performance characteristic problem-grey relational analysis for optimizing combination of turning parameters and principal component analysis for determining the corresponding weighting values of various performance characteristics. Pearson (1901) proposed Principal component analysis (PCA) which was subsequently developed as a statistical tool by Hotelling (1993). The principal component analysis approach preserves as much original information as possible by significantly simplifying a large number of correlated variables into fewer uncorrelated and independent principal components.

Lu et al. (2008) applied grey relational analysis coupled with principal component analysis for optimization design of the cutting parameters in high-speed end milling process performed on SKD61 tool steel. The major performance characteristics are tool life and metal removable rate, and the corresponding cutting parameters are milling type, spindle speed, feed per tooth, and radial depth of cut and axial depth of cut. Moreover, the principal component analysis is applied to evaluate the weighting values corresponding to various performance characteristics so that their relative importance can be properly and objectively described. The results of confirmation experiments reveal that grey relational analysis coupled with principal component analysis can effectively be used to obtain the optimal combination of cutting parameters.

Arshad et al. (2010) used grey relational analysis coupled with principal component analysis for optimization design of the process parameters in in-feed center less cylindrical grinding process performed on EN-52 austenitic valve steel. The major performance characteristics are surface roughness, out of cylindricity of the valve stem and diametral tolerance, and the corresponding center less cylindrical grinding parameters are dressing feed, grinding feed, dwell time and cycle time. Moreover, the principal component analysis is applied to evaluate the weighting values corresponding to various performance characteristics so that their relative importance can be properly and objectively described. The results of confirmation experiments reveal that grey relational analysis coupled with principal component analysis can effectively be used to obtain the optimal combination of center less cylindrical grinding parameters.

Santanu et al. (2003) applied analytical hierarchy process (AHP) for estimation of the state of the cutting tool in the machining of medium carbon steel workpiece with coated carbide inserts based on cutting force measurement. It is found that the estimated state of tool wear matches closely with the directly observed state of tool wear.

Rao (2006), presented combined multiple attribute decision-making method in evaluation of machinability of work materials for a given machining operation. He suggested that the global machinability index helps to evaluate and rank the work materials for a given machining operation.

Kumar et al. (2000) applied Taguchi method and the utility concept for quality (multi-objective) optimization. The utility concept employs the weighting factors to each of the signal to noise (S/N) ratios of the performance characteristics to obtain a multi-response S/N ratio for each trial of an orthogonal array.

Based on the literature given above the present work was planned. En-31 steel was turned with tungsten carbide tools under different levels of cutting speed, feed rate, and depth of cut, nose radius and concentration of solid lubricants mixed with SAE-40 base oil based on 24+8 and 25+8 design. En-31 steel is 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. (Kalpakjian, 1997). Tungsten carbide inserts were used due to its low cost (economic reason) and superior properties as a cutting tool material for optimizing the minimum quantity lubrication parameters during machining of En-31 steel (Kalpak Jian, 1997).

In the pilot experiments different concentrations of three solid lubricants (1%, 2%, 3%, 4%, 5%, 10%, 12%, 13%, 15%, 17%, 20%, and 23%) were applied and the percentage of solid lubricant that gave minimum (stable) cutting forces was 10% to 20% solid lubricant + SAE -40 oil as optimum. Therefore minimum and maximum percentage of concentration of solid lubricants mixed with SAE-40 base oil have been selected in this work is 10% and 20% respectively. 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), (Venugopal, 2004). They have properly applied solid lubricant i.e. graphite powder and MoS2 powder during milling, grinding and metal forming process. They reported that solid lubricant assisted machining is a novel concept to control the machining zone temperature without polluting the environment.

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 to be 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 MQL 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 and cooling properties of minimum quantity lubricant (solid-liquid).

In the development of predictive machinability models five turning parameters at three levels were used. The suitable values for the cutting conditions for this work were selected based on pilot experiments and specification of lathe machine used. These five parameters were cutting speed, feed rate, and depth of cut, tool nose radius and % of concentration of lubricants (MQL). The output parameters used as performance indicators were chip-tool interface temperature, cutting forces, surface roughness, tool wear rate and chip thickness. These parameters are considered as response variables under dry, wet and minimum quantity of lubrication machining. Effect of tool geometry (tool nose radius) was also considered apart from the effect of main cutting parameters (cutting speed, feed rate and depth of cut) on the responses. Most researchers used three main cutting parameters and studied the effect of these parameters on responses (Feng et al. 2002, Hari Singh et al. 2007, Bardie et al. 1997), but the combined effect of tool nose radius and the cutting parameters has not been studied properly. Therefore, in this work an effort has been made to study the combined effect of tool nose radius and the cutting parameters on responses during turning En-31 steel with tungsten carbide inserts under dry, wet and QL(solid- liquid) condition.

As emphasized earlier design of experiment is a powerful analysis tool for modeling and analysis of the influence of process variables over some specific parameters which is an unknown function of these process variables. Factorial design (2^4+8) and (2^5+8) used in this work is a composite design. This has been proposed by Box and Hunter (1978). There are numerous advantages associated with the use of factorial design in conducting these experiments. It is more efficient than the conventional method one-factor-at-a-time experiments commonly employed by researchers, and also enables the study of both, the main and interaction effects among the factors. Factorial design will give a combination, near to the minimum or maximum, where as the one-factor-at-a-time procedure will not.

2^4+8 factorial design for dry machining represents 24 experiments. Eight experiments represent an added center point, repeated eight times to estimate the pure error.

2^5+8 factorial design for solid-liquid minimum quantity lubrication machining represents forty experiments for each lubricant. Eight experiments represent an added center point, repeated eight times to estimate the pure error. This method classifies and identifies the parameters to three different levels (viz low, middle and high). In this experimentation, 24 experiments were carried out at these levels under dry and flooded coolant machining separately. Similarly 40 experiments were carried out at these levels under solid-liquid minimum quantity lubricant machining for each lubricant. Model equations for cutting temperature, cutting forces, surface roughness, chip thickness and tool wear rate under dry, wet and MQL machining as well as chip micro-hardness under dry conditions were obtained by using the analysis of variance technique, F-test and coefficient of determination.