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A REVIEW STUDY OF MQL AND DRY TURNING OF AISI 304

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***Abstract*— Austenitic stainless steels are considered as difficult to cut materials due to their high work hardening and low thermal conductivity. The common difficulties in machining of austenitic stainless steels are rapid tool wear and poor surface finish. Though the problems are there it is widely used in cutlery, sinks, tubing, dairy, food, pharmaceutical equipments, fasteners, air craft fittings, aerospace and automotive components, cryogenic vessels and components for severe chemical environments. The main reason to be used in wide verity of applications is there high strength, high corrosion resistance and excellent formability. Machining is the wide used metal shaping process. In machining rapid wear of cutting tool takes place due to high cutting temperature generated during the process. Thus to get the better workpiece quality a good control of the heat generated during machining is required. Generally cutting fluids are applied to solve the above problem. The use of cutting fluids is restricted due to their harmful health and environmental effects. A good understanding of methods of application of lubrication /cooling at cutting zone reduces the heat generation which leads to efficient and economic machining. Many researchers are finding alternatives for the excessive use of cutting fluids without affecting machinability and productivity. A newly developed economical and environmental friendly alternative to flood lubrication is minimum quantity lubrication (MQL) is a step towards 'Green manufacturing'. In minimum Quantity Lubrication a small amount of cutting fluid, in order of 500 ml/hr or less, which are about three to four orders of magnitudes lower than that used in flooded lubricating conditions, MQL technique consists in atomizing a very small quantity of lubricant in an airflow directed towards the cutting zone. In machining of AISI 304 austenitic stainless steel, the tool performance can be enhanced by using MQL and gives the best performance in terms of the surface roughness, feed forces, tool wears and cutting temperature. Minimum quantity lubrication enabled sizeable reduction in the cutting zone temperature and favorable change in the chip–tool and work–tool interactions, which helped in reducing friction, built-up edge formation, and thermal distortion of the work and wear of the cutting tool. Thus by using MQL/NDM technique in machining of AISI 304 remarkable reduction in quantity of lubricant can be obtained. In this study, a review of the literatures on use of MQL and Dry lubrication techniques in machining of AISI 304 austenitic stainless steel is conducted to understand the effects of turning parameters like speed, feed, depth of cut, tool geometry, cooling techniques on cutting temperature, surface roughness, chip generation.**

Keywords – MQL, NDM, HSM, AISI 304, HPC, Cutting fluids, Cryogenic cooling, coated carbide inserts, surface roughness, cutting temperature, chip generation, tool wear, cutting force

I. INTRODUCTION

Metal cutting also known as machining is one of the most used techniques for producing different components. In the machining processes a cutting tool removes material from a workpiece in the form of chips. Chip slides on the tool face and leaves the work piece material. Surface roughness is mainly a result of process parameters such as tool geometry and cutting conditions. In machining operation, lot of heat is generated due to plastic deformation of the work material, friction at the tool-chip interface and friction between tool and the work-piece. In recent years, high-speed machining (HSM) technology is becoming matured, HSM exhibits a higher metal removal rate, better surface finish, no critical heat of the work piece, etc. But the rapid wear rate of the cutting tool due to high cutting temperature generated during the process still remains unsolved. Generally the cutting fluid applied in the machining process is considered to act as cooling and lubricating agent, hence the cutting temperature can be reduced and the tool life and machined surface finish can be improved. The cutting fluids have many detrimental effects as it contain environmentally harmful or potentially damaging chemical constituents. These fluids are difficult to dispose and expensive to recycle and can cause skin and lung disease to the operators and air pollution. The costs associated with the use of cutting fluids is estimated to be several billion $ per year. Minimizing the use of cutting fluid also leads to economic benefits, as cutting fluids can account for a significant portion (up to 20%) of machining costs.

The concept of MQL was suggested a decade ago as a mean for addressing the issues of environmental intrusiveness and occupational hazard associated with airborne cutting fluid particles. The minimization of cutting fluid leads to economical benefits by saving lubricant costs. Workpiece, tool and machine cleaning time are reduced. The MQL technique consists of misting or atomizing a very small quantity of lubricant. The lubricant is sprayed by means of an external supply system consisting of one or more nozzles. The amount of coolant used in MQL is about 3-4 orders of magnitude lower than the amount commonly used in flood cooling condition. In MQL, lubrication is obtained via the lubricant, while a minimum cooling action is achieved by the pressurized air that reaches the tool/work interface. In MQL process, oil is mixed with high-pressure air and the resulting aerosol is supplied near to the cutting edge. This aerosol impinges at high speed on the cutting zone through the nozzle. Air in the aerosol provides the cooling function and chip removal, whereas oil provides lubrication and cooling by droplet evaporation. When the quantity of cutting fluid in MQL is very less (in ml/h instead of l/min) in comparison to flood cooling, the process is also known as Near Dry Machining. A. Attanasio et al [2] claimed that MQL reduces induced thermal shock and helps to increase the workpiece surface integrity in situations of high tool pressure Dhar et al [4] States that MQL uses the cutting fluids of very small amount-typically of a flow rate of 50–500 ml/h which is about three to four orders of magnitude lower than the amount commonly used in flood cooling condition. Varadarajan et al [5] claimed that in MQL, cooling occurs due to convective and evaporative mode of heat transfer and thus is more effective than conventional wet cooling in which cooling occurs due to convective heat transfer only. In addition, cutting fluid droplets by virtue of their high velocity penetrates the blanket of vapor formed and provides more effective heat transfer than wet cooling F. Klocke and G.Eisbletter [1997] claimed that the cost of cutting fluid is 7-17% of the total manufacturing cost of a component. The cost associated with the use of cutting fluids is mainly due to cost of procurement, storage, maintenance, and disposal. National institute of occupational safety and health [NIOSH] indicated that 1.2 million workers are exposed to the hazards of cutting fluids across the world. It is evident that workers are facing severe chronic, respiratory and skin problems. These diseases include chronic bronchitis, asthma, chest symptoms, airway irritation and skin problems. Knowing these negative aspect of cutting fluids there use should be minimized.

II. STUDIES ON MQL AND DRY LUBRICATION ASSISTED MACHINING OF AISI 304

Sharma et al [1] studied the different Cooling techniques for improved productivity in turning. He founds that the application of cryogenic cooling for turning of difficult-to-cut materials has resulted in several fold increase in tool life without compromising on the environmental conditions. With the MQL/NDM technique, there can be a remarkable reduction in machining cost, quantity of lubricant used and surface roughness by properly orienting the nozzle on flank face of the tool. Further performance of MQL can be enhanced using chip evacuation system. From view point of cost, health, safety and environment, performance of MQL technique is better with the use of vegetable oils as compared to mineral oils. Turning with HPC technique results in formation of segmented chips, better penetration at interface and thus lower cutting force, better tool life and acceptable surface finish. Attanasio et al [2] studied the effect of minimum Quantity of Lubrication on tool life in turning of 100Cr6 normalized steel pipes. He founds that lubricating the flank surface of the tip by MQL reduces tool wear and increases tool life. Lubricating the rake surface of the tip by MQL does not produce evident wear reduction. Sarikaya et al [3] studied the RSM based analysis of machining parameters in CNC turning under MQL. He founds that cooling conditions are highly effective on machined surface roughness. In the cooling conditions, MQL is a good tool in order to increase the quality for cutting operations feed rate and the cooling condition has the highest influence on machined surface roughness. Ra is influenced by feed rate and cooling conditions. Depth of cut and cutting speed has no influence on the surface roughness. Mahdavinejad and Saeedy [4] studied the influence parameters of machining of AISI 304 with and without cutting fluid. They founds that cutting speed has the main influence on the flank wear and as it increases to 175 m/min, the flank wear decreases. The feed rate has the most important influence on the surface roughness and as it decreases, the surface roughness also decreases. Also, the application of cutting fluid results in longer tool life and better surface finish. Asiturk and Neseli [5] studied the multi response optimization of CNC turning parameters via taguchi method-based response surface analysis in the machining of AISI 304 austenitic stainless steel under dry condition with coated carbide insert. They founds that the feed rate is the dominant factor affecting surface roughness, which is minimized when the feed rate and depth of cut are set to the lowest level, while the cutting speed is set to the highest level. Gandarias et al [6] studied the performance of the turning and drilling of austenitic stainless steels using two coolant techniques. They claimed that 303 steel is easy while 304 &316 are difficult to machine. Cryogenic treatment seems to improve workpiece quality parameters.

Kulkarni et al [7] studied the dry turning of AISI 304 austenitic stainless steel using AlTiCrN coated insert produced by HPPMS technique. They founds that AlTiCrN coated tool shows lower cutting forces due to low friction coefficient and better adhesion of coating. Cutting speed has large effect on flank wear. Higher cutting speed and feed rate shows steady increases in wear. Thin chip generation was observed during dry machining. Kulkarni et al [8] carried a study on optimization of cutting parameters for turning of AISI 304 austenitic stainless steel using taguchi method. They founds that Feed has significant effect on the cutting force, coating thickness has less effect on cutting force. Increasing the coating thickness average flank wear & cutting force can be controlled. Nayak et al [9] studied the multi-objective optimization of during dry turning of AISI 304 austenitic stainless steel using grey relational analysis. They found the optimal setting of machining parameters was Vc =45 m/min, f=0.1 mm/rev, t=1.25. Selvaraj and Chandramohan [10] studied the optimization of surface roughness of AISI 304 austenitic stainless steel in dry turning operation using taguchi design method. They founds that speed, feed, depth of cut affects Ra by 51.84%, 41.99% and 1.66% respectively. Cetin et al [11] studied the performance of vegetable based cutting fluids with extreme pressure and cutting parameters in turning of AISI 304L by taguchi method. They found that in turning of AISI 304L, effects of feed rate and depth of cut are found to be more effective than cutting fluids and spindle speed on reducing forces and improving the surface finish. Performances of vegetable based cutting fluids and commercial cutting fluids are also compared and results generally show that sunflower and canola based cutting fluids performs better than the others. Ozeclik et al [12] carried the experimental investigations of vegetable based cutting fluids with extreme pressure during turning of AISI 304L. In this study the performances of the new developed VBCFs including different percentages of EP additive over commercial cutting fluids in terms of improving the surface quality, decreasing turning forces and tool wears were compared. They found that, CCF-II (8% of EP) gave the best performance in terms of the surface roughness, feed forces and tool wears. Shear stresses on surface of the material decreased and built up edge (BUE) increased with increase in EP additive rate in VBCFs. This result indicated that increasing percentage of EP additive in VBCFs had only negligible effect on the surface roughness. CSSCF gave the best performance in terms of cutting forces. The dry cutting condition, CMCF and CSSCF gave poor results in terms of tool life. This experimental research showed that CMCF and CSSCF can be replaced by the VBCFs, thus reducing the occupational health risks associated with petroleum oil based CFs and reducing the waste treatment costs due to their inherently higher biodegradability. Kaladhar et al [13] studied the performance evaluation of coating materials and process parameters optimization for surface quality turning of AISI 304 austenitic stainless steel. The experimental result shoes that, the improvement in average surface roughness is obtained when machining with PVD coated insert (1.13 µm).The nose radius have greater contribution (62.88%) when turning with PVD coated insert .Cutting speed is significant factor (37.84%) when turning with CVD coated insert. Sodavadia and Makwana [14] carried the experimental investigation on the performance of coconut oil based nano fluid as lubricants during turning of AISI 304 austenitic stainless steel. They found that Cutting temperature, tool flank wear & surface roughness are decreased significantly with Nano lubricants compared to base oil due its better lubricating properties. Coconut oil with 0.5% boric acid shows good results than other nano fluids. DeSouza et al [15] studied the characterization of the surface generated during the turning of annealed and aged AISI 303, 304 and 310 austenitic stainless steel. They found that, No significant difference was observed in roughness of the materials machined. The machining parameters affect the surface finishing in a different way. The lowest value of Ra was obtained at different cutting speeds: 94 m/minute in AISI 303 steel; 60 m/minute in AISI 304 steel and 196m/minute in AISI 310 steel. The AISI 310 steel showed the highest values of machining forces. This behavior can be associated to high work hardening of this material. The AISI 303 steel showed the lowest values of machining forces, which is widely known for its better machinability. The MnS inclusions improve chip breaking. The difference between the cutting force of AISI 304 and AISI 310 steel in the annealed condition was not significant. However, the difference between the cutting forces of these steels in the aged condition was higher. Xavior and Adithan [16] evaluated the performance of cutting fluids in machining of AISI 304 austenitic stainless steel. It was found that cutting speed had more influence on temperature (83.99%) and depth of cut had more influence on cutting force (74.65%).All other cutting parameters had considerable influence on the process parameters. From ANOVA it was also found that cutting fluids had significant influence on tool-chip interface temperature (4.64%) and on cutting force (9.31%). Nithyanandhan et al [17] carried a experiment to optimize the cutting forces, tool Wear and surface finish in machining of AISI 304 stainless steel material using taguchi method. They found that, feed and nose radius are the most important process parameters for workpiece surface roughness. Also feed and depth of cut are significant factors on MRR. Cutting speed and depth of cut have significant effect on the feed force whereas feed rate and depth of cut effects thrust force. Cutting speed and depth of cut have predominant effect on tool wear. Feed rate have less effect on tool wear. Xavior [18] carried out the experimental investigations on the machinability of AISI 304, AISI 52100 and AISI D2 steels materials. He founds that, tool material exhibits reasonable effect on the flank wear only. The tool wear rate varies for different cutting speeds. Variation in the work material considerably affects the all cutting parameters except surface roughness. For AISI 304 as speed, feed, depth of cut increases, actual machining time decreases. MRR increases as cutting parameters are increased. Grzesik [19] carried out the experimental investigation of the cutting temperature when turning with coated indexable inserts. He observed that, the average tool-chip interface temperature and heat transferred into tool-chip influenced by work material & coating. In machining of steel the use of proper coating structure leads to reduction of friction between the rake and chip which result in decrease in heat generation and lowers the tool chip interface temperature. Klocke et al [20] studied the metal forming and machining process with combination of PVD tool coatings and biodegradable lubricants. He founds that, the test using newly developed biodegradable lubricants shows that synthetically refined native esters offers great potential for use in cold forming and machining. High polar surface energy combines with high pressure stability to form suitable lubricant film, just like hard coatings, can lead to wear reduction. Klocke et al [21] studied the advanced system for environmentally friendly machining with PVD-coated tools and native ester. He founds that uncoated cemented carbides can be used at low cutting speed and increase in the cutting speed is possible by coated carbide tool. The combination of PVD coated carbide insert and synthetic Easters as a lubricoolant is marked by an excellent machining result great performance potential. Hong and Broomer [22] studied the economical and ecological cryogenic machining of AISI 304 austenitic stainless steel .They states that Cryogenic machining can be more profitable and helps to achieve great productivity than emulsion cooling. This is done by injecting small amount of liquid nitrogen to the tool chip interface but not to the work piece. It improves machining productivity and reduces the production cost. Khan and Ahmad [23] carried the experiments to study the cryogenic cooling technique for improving tool life. They founds that, the modified tool used for applying cryogenic coolant provides an effective means for cooling the cutting edge during machining and can increase tool life to more than four times. Cryogenic cooling is more effective at a higher feed rate rather than at a higher depth of cut. Machining at a lower cutting speed and using cryogenic coolant, very little wear was observed on the tool flank. Application of this cryogenic cooling was found to be more effective at higher cutting speeds. It was also observed that cryogenic cooling is efficient at a higher feed rate rather than a higher depth of cut. Dananchezian et al [24] carried the experiments on cryogenic turning of AISI 304 stainless steel with modified tungsten carbide inserts. They founds that cryogenic cooling reduces the cutting temperature by 44-51% over the wet machining which improves cutting force, surface roughness & tool wear. The modified insert used for applying cryogenic coolant decreases cutting force to maximum of 16% over wet machining. Cryogenic machining reduces Ra by 22.34% over wet machining. Cryogenic machining using liquid nitrogen reduces tool wear as compared to wet machining. Khan et al [25] proposed a new approach of applying cryogenic coolant in turning AISI 304 austenitic stainless steel. They founds that, cryogenic cooling improved the tool life but did not improve the surface finish. A special device has been designed which can be fixed at any convenient position on tool or tool post for applying cryogenic coolant. Patil et al (2015) [26] studied the effect of cutting parameters on surface roughness and hardness of AISI 316 austenitic stainless steel in CNC turning under conventional cooling condition. He founds that the feed rate has the highest influence on surface roughness. Ra is influenced by feed rate with PCR of 75.76% and depth of cut and cutting speed has negligible influence on the surface roughness at the reliability level of 95%. Depth of cut has the highest influence on hardness. Hardness is influenced by depth of cut with PCR of 90.93%. Cutting speed and feed rate have negligible influence on the hardness. The hardness values of the micro-hardness profile revealed that the hardness of the turned specimen goes on decreasing from the surface to the depth of the specimen. Waychal and Kulkarni (2015) [27] studied the effect of various machining parameters on surface roughness and power consumption during machining of AISI 304 stainless steel in turning operation. They founds that the depth of cut and speed were the main influencing factors on the surface roughness. It improved with increase in cutting speed. Nithyanandhan et al (2014) [28] carried the study to optimize the effect of process parameters on tool wear of tungsten carbide insert when machining of AISI 304 stainless steel materials. They founds that the feed and nose radius is the most significant process parameters on work piece surface roughness. However, the depth of cut and feed are the significant factors on MRR. Cutting speed and depth of cut have significant effect on feed force whereas feed rate and depth of cut are factors that significantly influences on thrust force. The depth of cut and cutting speed has predominant effect on tool wear. Feed rate have less significant effect on tool wear. But, in case of cutting force modeling, all the three parameters have significant effect. Rawat et al (2014) [29] carried out the experimental study to find the effects of cutting parameters on cutting force in dry turning of ss316l using taguchi method. They founds that as the cutting force gets increased with increase in the cutting velocity and increase in feed rate. Whereas the depth of cut gets increased cutting force gets decreased. M.A. Xavior (2012) [30] studied the effect of machining parameters on surface roughness, cutting temperature and tool wear in machining of AISI 304 stainless steel using alumina inserts. They founds that cutting speed was found to have a significant effect on the machined surface roughness values. With increasing cutting speed, surface roughness values decreased .As the feed rate increases surface roughness increases and as nose radius increased surface roughness decreases. The cutting temperature gets increased with increased in cutting speed irrespective of cutting fluid used. For the combination of low feed rate and lesser cutting speed, the cutting zone temperature is very low. For any cutting speed, lower temperature value is observed for a lesser depth of cut and as the depth of cut is increased the temperature also increases accordingly. As the wear increase with the time, chatter marks are observed on the workpiece. More heat was developed in the machining zone and the chips produced are in the red hot a condition which confirms that two-third of the heat is carried away by the chips. Rodriguez et al (2011) [31] studied the influence of cutting parameters and material properties on cutting temperature when turning stainless steel. They founds that the cutting temperature increases when the values of cutting speed, feed, depth of cut, and material maximum strength are increased and that the cutting temperature decreases with the increase of material strength, thermal conductivity.

III. CONCLUSIONS

- AISI 304 is hard to machine material because of its high strength and low thermal conductivity.
- The common difficulties in machining of AISI 304 austenitic stainless steels are rapid tool wear and poor surface finish.
- AISI 304 austenitic stainless steel is widely used in various applications because of its high strength, excellent corrosive resistance and excellent formability.
- The machining of AISI 304 is done with flooded lubrication system, which is not beneficial for employee health, disposal of coolant and overall machining cost.
- In machining of steel with MQL, the use of proper coating structure leads to reduction of friction between the rake surface and chip which result in decrease in heat generation and lowers the tool chip interface temperature.
- In machining of steel, coating material type, number of coating layers, coating methods affects the coefficient of friction and thermal conductivity .
- To get the improved productivity, longer tool life and better surface finish the application of cooling technique is most important factor.
- A good understanding of methods of application of lubrication /cooling at cutting zone reduces the heat generation which leads to efficient and economic machining.
- MQL is the technique that could reduce many cutting problems coming from high consumption of lubricant like high machining cost, environmental & worker health problems and can provide improved productivity, longer tool life and better surface finish hence, it is important to study it in detail.
- MQL provides reduced tool wear, improved tool life and better surface finish as compared with wet and dry machining.
- MQL/NDM technique gives remarkable reduction in quantity of lubricant used.
- Surface roughness is most important parameter for judging machinability.
- In machining of AISI 304 austenitic stainless steel, the tool performance can be enhanced by using MQL.
- In machining of AISI 304 austenitic stainless steel MQL gave the best performance in terms of the surface roughness, feed forces, tool wears and surface quality.
- Minimum quantity of lubrication enabled sizeable reduction in the cutting zone temperature and favorable change in the chip–tool and work–tool interactions, which helped in reducing friction, built-up edge formation, and thermal distortion of the work and wear of the cutting tool.
- MQL and dry machining are less polluted, environmental friendly hence a step towards green manufacturing.

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