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Optimization of Tool Wear: A Review

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Abstract: *The quality of the machined piece and tool life are greatly influenced by determination of maximum temperature of the cutting tool. Numerous researchers have approached to solve this problem with experimental, analytical and numerical analysis. There is hardly a consensus on the basics principles of the thermal problem in metal cutting, even though considerable research effort has been made on it. It is exceedingly difficult to predict in a precise manner the performance of tool for the machining process. This paper reviews work on the requirements for optimization of Tool wear so that its life could easily be predicted.*

Keywords: *Tool Wear, Taguchi, CNC, Optimization, Wear.*

I. INTRODUCTION

Research in metal cutting was started with Cocquilhat in 1851 which measured the work required to remove a given volume of material in drilling. The attempt made by Time led to the explanation of formation of chips in 1870 and further research was made by Tresca in 1873. Later in 1881, Mallock suggested that the cutting process was the shearing of workpiece to form the chip and emphasized the importance of the effect of friction occurring on the cutting tool face as the chip was removed. Further, Taylor investigated the effect of tool material and cutting conditions on tool life during rough operations. Latest fundamental work has been carried out by Ernst and Merchant in 1941 dealing with the mechanics of metal cutting process. The simplest and most widely used model for cutting was first by Ernest and Merchant (1941) and further contribution to study of Ernest and Merchant theory was done by Lee and Shaffer (1951), Kobayashi and Thomsen (1962). Large number of literature is available on the determination of chip-tool interface temperature, factors affecting the interface temperature and techniques of optimization of machining parameters including cutting speed, feed rate, cutting zone temperature, etc. Armerago (1969), Boothroyd (1981), Shaw (1984) and Trent (2000) wrote the most widely used text books. Kalpakjian, et al. (2006), and DeGarmo, et al. (1997) wrote books on more general introductory knowledge. The study machining process by experimental approach is expensive and time consuming peculiarly when a wide range of parameters is included like tool geometry, cutting conditions, and materials.

II. LITERATURE REVIEW

Jensen M.R. et al. [1] stated that an important problem in the machining of drawn parts is tool wear. They said that tool wear can be reduced by increasing the tool lifetime and by making more continuous production flow, by reducing the number of break-downs when the tools have to be re-polished. In their paper, an optimization of the shape of the draw-die profile with regard to wear was carried out using a conventional optimization method and explicit finite element. The optimized draw-die profile had almost twice the tool life compared to that of the initial circular draw-die, if the peak value of wear was used as the wear criteria. The relatively small resources used by them with their optimization approach made the tool wear design relevant for industrial use at the tool-design state.

Sullivan D.O' et al. [2] determined the temperature in a single point turning process. The total work done by a cutting tool in removing metal was determined from the force components on the cutting tool. Approximately, all of this work or energy is converted into heat which is dissipated into the chip, tool and workpiece material. The wear of the tool is related to the cutting forces. Initial experiments conducted involved the simultaneous measurement of forces and temperatures. These experiments focused on the use of embedded thermocouple (in the work piece) and using the infrared thermal camera to monitor the process. They concluded that in machining of aluminium Al 6082-T6 the decreased cutting tool forces and machined surface temperatures was resulted by increased cutting speed (V_C) and increased cutting tool forces and machined surface temperature was resulted by tool wear. They left the examination of temperature distribution at the tool chip interface for the future work.

Abukhshim N.A. et al. [3] reviewed the previous research work. Research on heat generation and heat dissipation in the orthogonal machining process is critically studied. In addition, temperature measurement techniques applied in metal cutting were also reviewed. The emphasis was on the comparability of test results obtained by a thermal imaging camera in high speed cutting of high strength alloys. Finally, latest work on these topics in metal machining was also reviewed. They reviewed the methods of temperature measurement and the analytical and numerical models for the prediction of temperature and temperature distribution in metal cutting. In metal cutting the Prediction of cutting temperatures is a major challenge. They concluded that fiber-optic pyrometers and infrared thermography techniques for temperature measurement of the high speed cutting process are more promising as compared to other methods as these techniques can measure temperature, as well as, the cooling rate easily, accurately and with fast time response. They stated that technology for consideration of interactions at the tool/chip interface is mainly based on certain assumptions and not on a precise understanding of the underlying physics. They also stated that modeling and simulation of machining processes is mainly suffering from a lack of the fundamental input data.

Many researchers has been undertaking into measuring the temperatures generated during cutting operations. Investigators have attempted to measure these cutting temperatures with various techniques (see figure 1 based on [4])

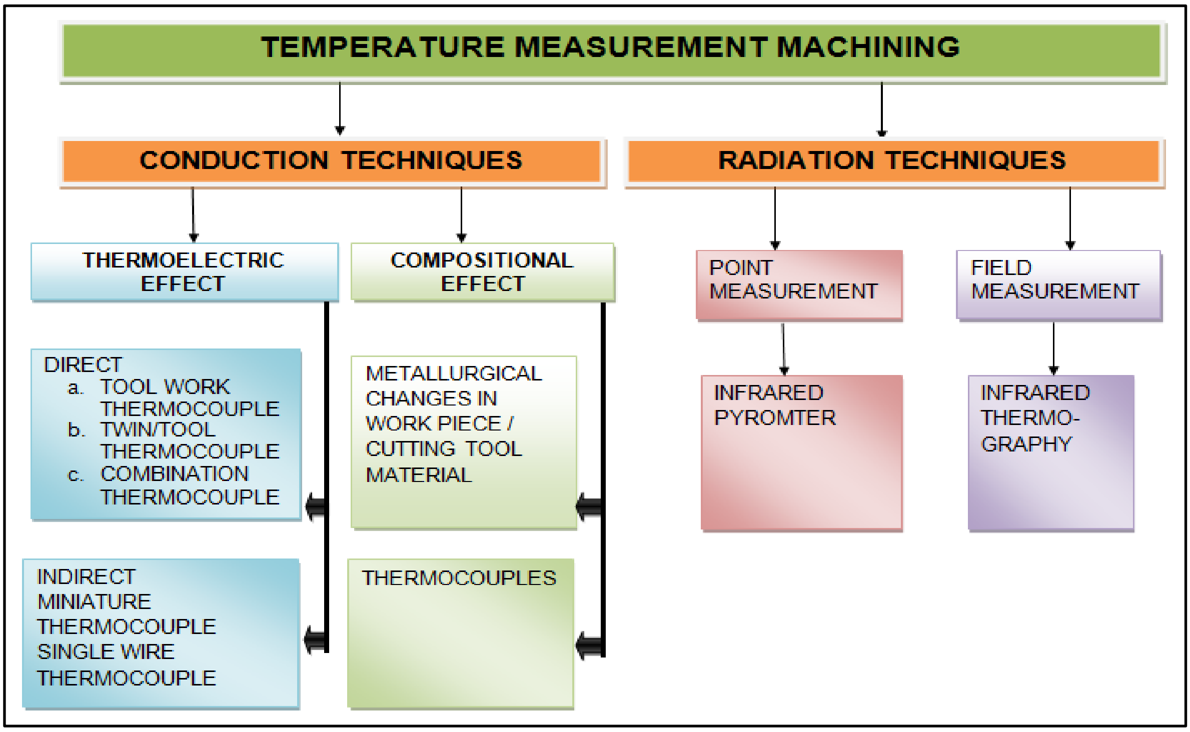

Figure 1: Temperature measurement in machining [4]

Lazoglu Ismail et al. [5] predicted the tool chip temperature in continuous and interrupted machining. They presented a numerical model based on the finite difference method to predict tool and chip temperature fields in continuous and interrupted machining and time varying milling processes. By modeling the heat transfer between the tool and chip at the tool-rake face contact zone Continuous or steady state machining operations like orthogonal cutting were studied. They determined Heat balance equations in partial differential equation forms for the chip and for the tool. The solutions of the steady-state tool and chip temperature fields were taken by finite difference method. The chip thickness was discretized along the time to determine the transient temperature variation in the case of interrupted machining.

Sutter G. et al. [6] presented an experimented setup for the measurement of temperature field in high speed machining. Their paper presented an experimental setup during an orthogonal machining operation with 42 CrMo 4 steel. The technique of temperature measurement was developed on the principle of pyrometer in the visible spectral range by using an intensified CCD camera with very short exposure time and interference filter at 0.8 micrometer. They obtained the temperature gradients in an area close to the cutting edge of the tool, along the secondary shear zone. It was established that their experimental arrangement shown in Figure 2 was quite efficient and can provide fundamental data on the temperature field in material during orthogonal high speed machining. They showed experimentally that, for a cutting speed of 20 m/s a hot spot was located near the tool-chip interface at a distance of 300-350 μm of the tool tip. This value corresponds to about the two-thirds of the depth of cut. The reaching temperature is around 825°C. The temperature in the chip increases with increasing of the cutting speed. Their result showed that, with an increase of the cutting speed from 20–30 m/s the dependence of the temperature on the cutting speed was more noticeable. They even showed that, the temperature appeared to stabilize for the cutting speeds larger than 40 m/s. A similar tendency was observed with the increasing in the depth of cut and for a cutting speed fixed to 40 m/s by their experimental technique. The temperature in the chip was nearing a saturated value about of 840°C during the process of an un-deformed chip thickness larger than 0.5 mm.

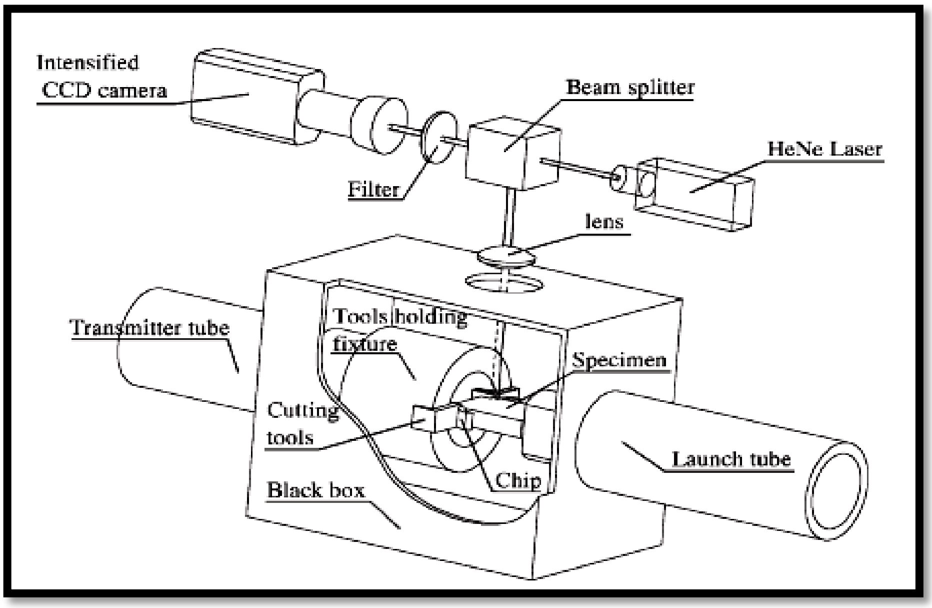

Figure 2: Experimental Apparatus's scheme used by **G. Sutter et al.** [6]

Dogu Yahya et al. [7] designed a numerical model to determine temperature distribution in orthogonal metal cutting. In their study, they developed a thermal analysis model to determine temperature distribution in orthogonal in metal cutting using FEM. Their model was used to calculate the temperature distribution as a function of heat function of heat generation. Assuming that all the work required for cutting is converted to the sensible heat energy the amount of heat generation was calculated by them. Accurate predictions of temperature field over the entire cutting zone were given by the developed model. It was also found that at the half of the contact length from cutting edge, the maximum temperatures for relatively smaller cutting speeds occurred for the analyzed cases. It was clear that the outer surface of the material will be subject to higher heat removal and sudden temperature drop.

Saglam Haci et al. [8] studied the effect of tool geometry and cutting speed on main cutting force and tool tip temperature. They investigated the temperature generated on the tip of the tool in turning and cutting speed on cutting force components and the effects of rake angle and entering angle in geometry of tool in their paper. The experiments were conducted on a CNC lathe to derive the data used for investigation. Each test was conducted with a sharp uncoated tool insert, while keeping the depth of cut and feed rate constant, during the tests. They found that the cutting speed was effective on the tool tip temperature, while the rake angle was effective on all the cutting force components. They found that, the deviation in temperature was 54%, while the average deviation between calculated and measured values of main cutting force was 0.26% in 64 numbers of experiments.

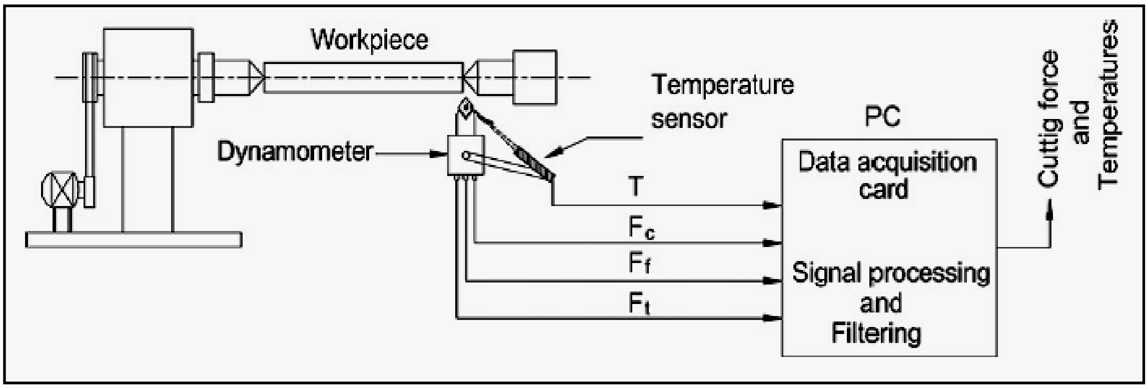

Figure 3: Experimental setup used by **Saglam et al.** [8].

They experimentally found that the main cutting edge subjected to maximum loading and unloading as it enters and leaves the cutting zone abruptly at 90^o of entering angle by using the experimental setup shown in Figure 3. They also found that the impact of load was not exerted on cutting tool when it has an entering angle different then 90^o, because the cutting edge enters and leaves the workpiece gradually. Hence, they concluded that at 60^o to 70^o the optimum entering angle was obtained. They showed that, the cutting forces were reduced and the temperature was increased when the cutting speed was raised. They also showed that, the cutting forces were decreased, for the increased positive rake angle. Their result of cutting forces and temperature evaluated together resulted that the optimum rake angle should be 12^o. Their results of analysis of variance evaluated, that the cutting speed was effective on tool tip temperature while, the rake angle had a significant effect on cutting forces components. They verified their conclusions by the correlation coefficients.

Ueda Takashi et al. [9] determined the temperature of a signal crystal diamond tool in turning. They in precision turning, investigated experimentally and theoretically the temperature on the rake face of a single crystal diamond tool. They used FEM to calculate the temperature distribution in the tool and in the work piece numerically. Two-color pyrometer with an optical fiber was used by them to measure the temperature on the rake face of a single crystal diamond tool in precision turning and then they calculated numerically using FEM. They showed that, regardless of the size of the object, the two-color pyrometer is capable of measuring the temperature when the temperature of the object is constant.

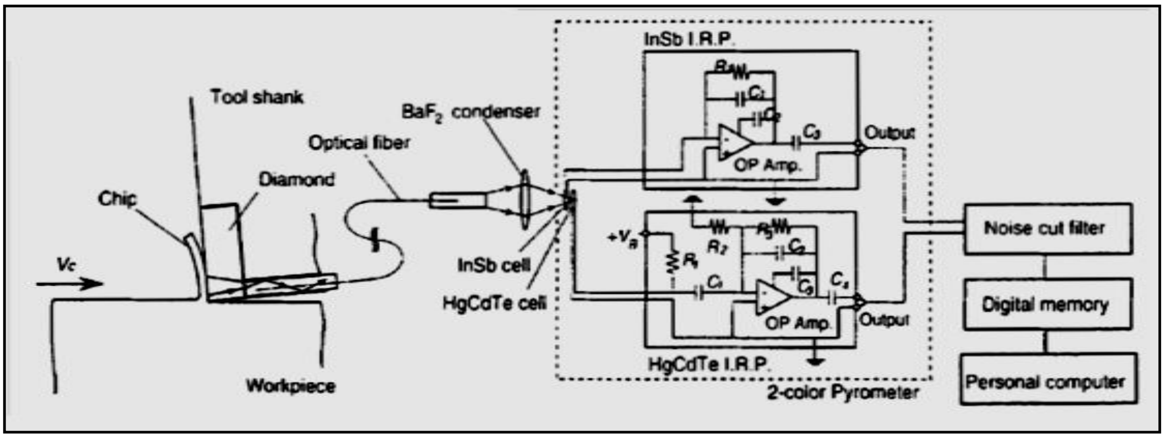

Figure 4: Experimental setup used by **Ueda Takashi et al.** [9]

They experimentally concluded that, it is possible to estimate the maximum temperature from the measured temperature, when the object has a surface of known temperature distribution. They also concluded that, when the object has a surface of known temperature distribution, it is possible to estimate the maximum temperature from the measured temperature and the increase in cutting speed increases the temperature on the rake face. Their measured values of temperatures in the experiment agreed well with their calculated results numerically using FEM.

Tanikic et al. [10] studied the metal cutting process parameters modeling using artificial neural network (ANN) and hybrid, adaptive neuro fuzzy systems. The main aim of their experiment was to conduct the qualitative analysis of metal cutting processes, and also identifying and resolving the frequently occurring problems, while improving the productivity of metal cutting by reducing the manufacturing costs. The infrared camera was used to measure and monitor the temperature at the chip tool interface. They also, modeled the measured data by using ANN and neuro fuzzy system. Their work concluded that, the implementation of artificial intelligence based systems in metal cutting process is possible. In the end, they proposed the global system for predicting the state of cutting tool along with sub-systems for cutting temperature, cutting force and arithmetic mean deviation prediction.

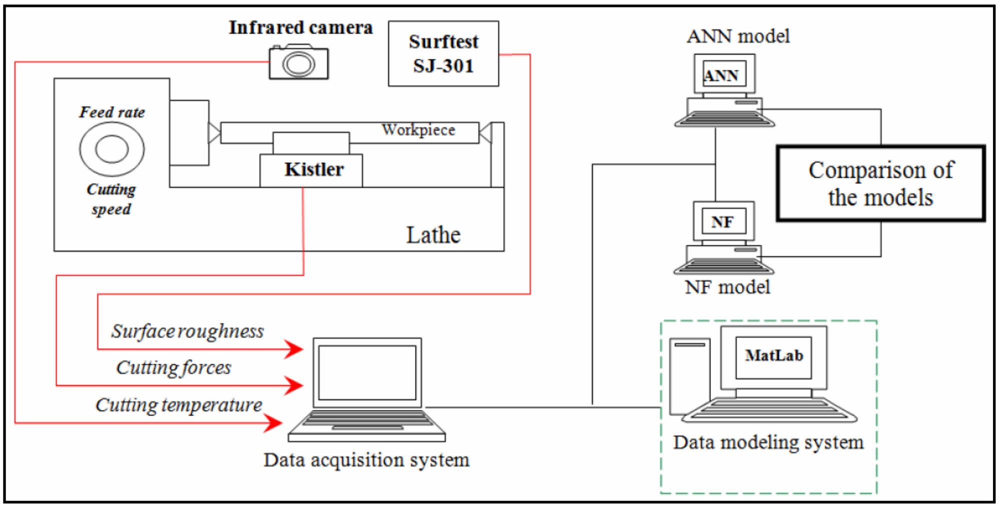

Figure 5: Component relations and information flow of material handling system

Fata [11] proposed the method of embedded thermocouple for temperature measurement along with infrared pyrometer. The experiments are conducted for dry and orthogonal machining condition with simultaneous measurement of temperature by embedded thermocouple and infrared pyrometer. With the help of these experiments a relation was established between tool temperature and cutting parameters such as cutting speed, feed rate and depth of cut. The results so obtained showed that if cutting speed, feed rate and depth of cut are increased then the tool temperature also increases which reduces the life of the cutting tool. These investigations revealed that the most effective cutting parameter in tool temperature rise is the cutting speed, especially at high range of cutting conditions. It also showed an increase in feed rate and depth of cut will lead to an almost straight line with low slope on the graph of tool temperature when plotted against them.

Adnan Jameel et al. [12] focused their study on the temperature generated at two heat zones namely primary heat zone (shear zone) and secondary heat zone (tool chip interface zone). They proposed two new objective functions for optimizing the cutting temperature problems and this system used particle swarm optimization (PSO) methodology to determine the optimal temperature. Their experiments showed that major amount of energy is converted into heat in the shear zone while the heat generated at the tool chip interface zone is due to the rubbing action at that interface. They concluded that heat distribution pattern is dependent on the size and thermal conductivity of the tool-work material and the cutting conditions. Specifically the results were obtained for mild steel work and carbide insert cutting tool in dry turning operation. Their study concluded that main cutting force, feed rate and depth of cut greatly influence the shear zone temperature while chip thickness and friction force have low effect. They also concluded that, the chip tool interface temperature increased with increase in feed rate and main cutting force while it decreased with increase in the depth of cut. Their whole study of paper concluded that feed rate has a huge effect on shear zone and chip tool interface zone temperature as compared to other parameters. Their study also concluded that till date the nearly all of optimization algorithms concentrated to optimize parameters are other than cutting temperature and according to their studies there are few papers focusing on the cutting temperature optimization.

Shirpurkar P.P. et al. [13] attempted to review the literature on optimization of machining parameters in turning processes by using different tool inserts. During their review of different conventional techniques employed for optimization of parameters were also studied by them. These techniques include geometric programming, geometric plus linear programming, non-linear programming, goal programming, sequential unconstrained minimization technique and dynamic programming. Later the latest optimization techniques were also discussed by them, specifically Taguchi technique, genetic algorithm, fuzzy logic and ant colony technique. These techniques were successfully applied in the industrial applications for optimal selection of process control variables. The paper concluded that Taguchi approach has the potential for savings in experimental time and cost on product or process, development and quality improvement and therefore is widely used in industries. According to their review, in most of the industries the skill, experience and mentality of the operators are the primary factors affecting the turning process parameters and surface roughness on the job/work piece. Therefore to attain minimum surface roughness it was very necessary to optimize the turning process parameters. Their review concluded that the latest optimization techniques like Taguchi technique, genetic algorithm, Fuzzy logic and response surface methodology are being applied successfully in industrial applications for optimal selection of process variables in the area of machining.

Yen et al. [14] stated that the tool wear on the tool–workpiece and tool–chip interfaces in metal cutting (i.e. crater wear and flank wear) are strongly influenced by the relative sliding velocity and cutting temperature at the interface. Their study's overall objective was to develop a methodology to tool life in orthogonal cutting and predict the tool wear evolution using FEM simulations. To approach their goal, the methodology proposed by them had three different parts. In the first part, a tool wear model for the specified tool–workpiece pair was developed by them via a calibration set of tool wear cutting tests in conjunction with cutting simulations. In the second part, they modified the commercial FEM code, which was used to allow tool wear calculation and tool geometry updating. The last part was experimental validation of the developed methodology.

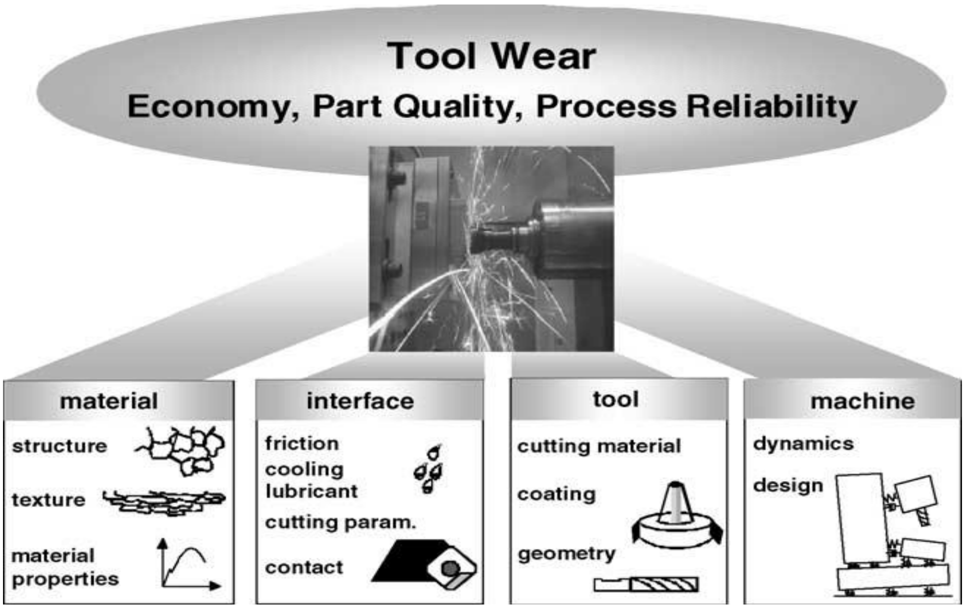

Figure 6: Four major functional elements influencing tool wear in machining processes. [14]

The maximum wear rate was clearly located on the tool rake face as shown in Figure 7. Nevertheless, they predicted small wear rates on the flank side of the tool edge radius, which were about one order of magnitude smaller than the rake face wear rates. They showed that the experimental results for uncoated carbide tools depicted that crater wear and flank wear on the tool face occur simultaneously at a similar wear rate [15].

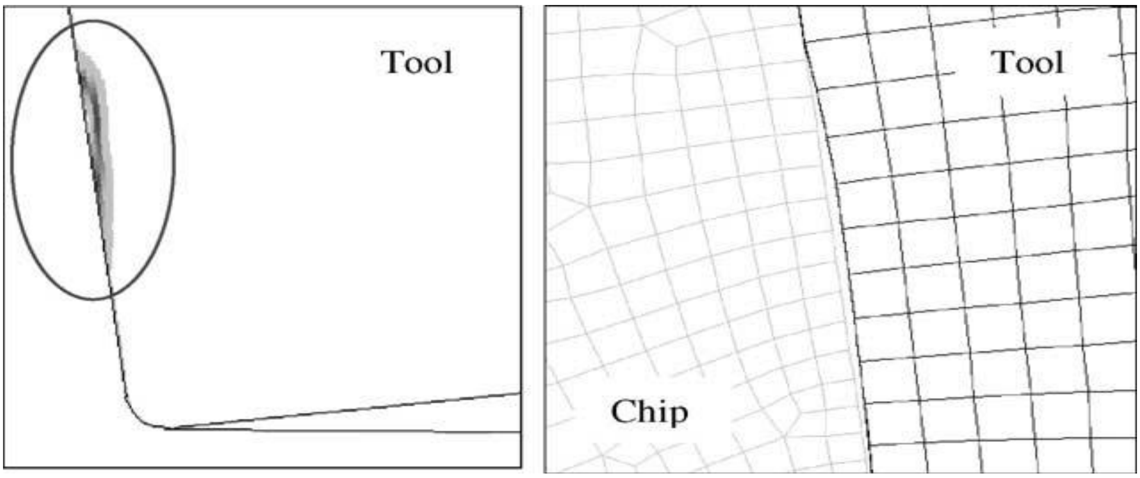

Figure 7: Result of wear rate (left) and updated rake face geometry (right) for an uncoated sharp tool. [14]

The initial results of tool wear simulations obtained by them using the developed method tend to underestimate the wear rates associated with the flank wear and crater wear, when the tool life was compared with the measured data obtained at the same conditions. They concluded that the reason to underestimate the wear rates associated with the flank wear and crater wear may be partially due to the fact that the two wear constants in Usui's wear model were directly borrowed from the literature [16].

Thamizhmanii et al. [18] applied Taguchi method under optimum cutting condition for finding out the optimal value of surface roughness in turning SCM 440 alloy steel. They detected that the tool chattering and machine tool vibrations were the causes of poor surface finish whose effects were ignored by them for analysis. The authors concluded that that depth of cut of 1 to 1.5 mm can be used to get lowest surface roughness, and the only significant factor was depth of cut which, contributed to the surface roughness.

Kilickap [19] investigated the use of the Taguchi method and the Response Surface Methodologies (RSM) for minimizing the burr height and the surface roughness in drilling Al-7075. The optimization results showed that to minimize burr height, the combination of low cutting speed, low feed rate and high point angle were necessary. At the combination of lower cutting speed and feed rates and at higher point angles the lowest values of surface roughness were obtained. In his paper he presented an application of response surface methodology (RSM) and Taguchi method for selecting the optimum combination values of drilling parameters affecting the burr height and surface roughness in dry drilling of Al-7075. He also concluded that to perform trend analysis of the surface roughness and the burr height with respect to various combinations of drilling parameters Taguchi method is the most successful technique. The analysis of experiments perfumed by him has shown that Taguchi method can be successfully used to verify all the optimum cutting parameters.

III. Summary

Experiments revealed that, the tool wear can be reduced by increasing the tool lifetime and by making more continuous production flow. The total work done by a cutting tool in removing metal was determined from the force components on the cutting tool. If cutting speed, feed rate and depth of cut are increased then the tool temperature also increases which reduces the life of the cutting tool. The chip tool interface temperature increased with increase in feed rate and main cutting force while it decreased with increase in the depth of cut. This review concluded that the decreased cutting tool forces and machined surface temperatures was resulted by increased cutting speed (V_C). It also revealed that, increased cutting tool forces and machined surface temperature was resulted by tool wear and the temperature in the chip increases with increasing of the cutting speed. Experiments also showed that, the temperature appeared to stabilize for the cutting speeds larger than 40 m/s and the temperature in the chip was nearing a saturated value during the process of an un-deformed chip thickness larger than 0.5 mm. It is now clear from the above that the outer surface of the material will be subject to higher heat removal and sudden temperature drop. The cutting forces were decreased, for the increased positive rake angle. The implementation of artificial intelligence based systems in metal cutting process is possible. The latest optimization techniques like Taguchi technique, genetic algorithm, Fuzzy logic and response surface methodology are being applied successfully in industrial applications for optimal selection of process variables in the area of machining. The maximum wear rate is located on the tool rake face. The crater wear and flank wear on the tool face occur simultaneously at a similar wear rate.

IV. Future Scope

The future work may require validation of the proposed methodology [14] for selected cutting conditions, different from those in the calibration set by predicting tool wear curves, and comparing the results with the experiments. It may also require use of other wear rate models available in the literature (e.g. Takeyama and Murata's wear model [17]). From the above review one can optimize the turning process parameters like depth of cut, speed, feed, nose radius, material and type of tool, and even work piece material etc using Taguchi method for maximizing the tool life and minimizing the surface roughness by experimental setup. Taguchi technique will help to finalize the number of levels with orthogonal array and thus finalizing the number of experiments. Also the signal to noise ratio will help to observe the behavior of quality characteristics of work piece.

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