Review on High Speed Machining of Hard Material

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Abstract **- The challenge of modern machining industries is mainly focused on achieving high quality, in term of component accuracy, high production rate and high metal removal rate. It is necessary to change and improve existing technology and develop product with reasonable price. So, researchers have developed modern technology such as high speed machining. High speed machining is a recent technology that involves machining of advanced material using modern machine tools. Advanced materials with unique metallurgical properties such as hardened steels, super alloys, composites and ceramics have been developed to meet the demands of extreme applications. High speed machining is being widely used in the aerospace, automotive, and dies making industries. This paper presents an overview of the past research in high speed machining using hard cutting tools. Effect of high speed machining process parameters on cutting forces, heat generation during cutting, surface integrity, tool wear and chip formation have been discussed in light of the findings of the past research.**

Keywords **- High speed machining; Cutting force; Surface integrity; Cutting temperature; Tool wear; Chip formation.**

1. Introduction

High speed machining is one of the modern technologies, which in comparison with conventional cutting enables to increase efficiency, accuracy, and quality of workpiece. The first definition of high speed machining was proposed by Carl Saleman in 1931 [1]. They assumed that at a certain cutting speed which is 5-10 time higher than conventional machining.High speed machining is performed on material with hardness within the 45-68 HRC range using a variety of tipped or solid cutting inserts. These materials are difficult to machine and produce large amount of heat which leads to rapid wear of tool material. These kinds of materials can be machined by coated carbide tools such as TiAlN, TiN, TiCN, TiCON, Al_2O_3, cubic boron nitride (CBN), and polycrystalline cubic boron nitride (PCBN) [2]. The definition of high-speed machining is based on the type of workpiece material being machined. Figure 1 shows generally accepted cutting speeds in high-speed machining of various materials [4].

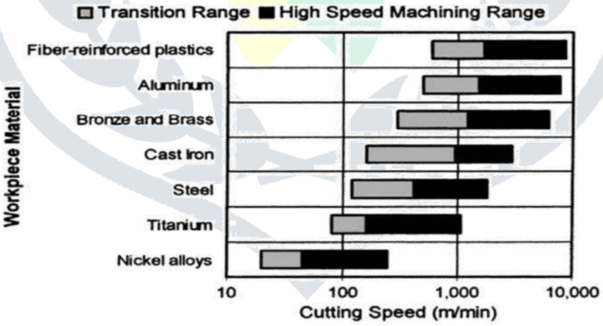

Figure 1 High-speed cutting ranges in machining of various materials

The quality of the surface plays a very important role in the performance of machining because a good quality turned surface surely improve fatigue strength, corrosion resistance, creep life [2]. Major advantage of high speed machining are high material removal rates, reduction in machining times, low cutting forces, dissipation of heat with chip removal resulting in decrease in workpiece distortion and increase part precision, developed good surface finish. The common disadvantages of high speed machining are excessive tool wear, need for specialand expensive tool holder and lastly but most importantly the need for advanced cutting tool material and coating [3]. High speed machining is being mainly used in three industry sector due to their specific requirement. The first category is industry which deals with machining aluminium to produce automotive components, small computer parts or medical devices. This industry needs fast metal removal because the technological process involves many machining operations. The second category is aircraft industry which involves machining of long aluminum parts often with thin walls. The third industry sector is die mould industry which deals with finishing of hard materials [1].

In high speed machining, the cutting speed affect on response variable such as cutting force, surface roughness, tool wear, heat generation,surface integrity, and chip formation. The methods commonly use to analysis of high speed machining are experimental, analytical and numerical methods [5]. High-hardness materials includes various hardened alloy steels, tool steels, case-hardness steels, super alloys, nitride steels, hard-chrome coated steels and heat treated powder metallurgical parts [4]. Finishing of hardened material using high speed machining using super hard cutting tools was early recognized by the automotive industry as a means of manufacturing of precisely finished transmission component.

2. Literature Review

Process parameters such as cutting speed, feed rate and depth of cut are affecting on production cost and product quality. Thus it is important to use optimization technique to determine optimal levels of these parameters so as to reduce the production cost and to achieve the desired product quality simultaneously. Therefore, if an increase in productivity is desired then an increase in these three cutting parameters is required. But, there are limits to these cutting parameters since they also have an effect on the tool life, tool wear, surface quality, surface integrity, cutting force, and heat generation. Keeping this in view, many researchers have investigated effect of these parameters pertaining to the high speed machining. The following sections present the findings of some of the research studies involving these parameters with reference to high speed machining.

2.1 Studies on cutting force

The force acting on the tool is important aspect of machining. Knowledge of the cutting forces are needed for the estimation of power requirements, the adequately design of machine tool elements, tool-holders and fixtures for vibration free operations. Many force measurement devices like dynamometers have been capable of measuring tool forces with increasing accuracy. By measuring the cutting forces, one is able to understand the cutting mechanism such as the effects of cutting force, the machinability of the workpiece, the process of chip formation, and tool wear. The cutting force in even unsteady state conditions is affected by many parameters. The variation of cutting force with time has a typical characteristic. Cutting forces can be resolved into three components i.e. thrust force, feed force, and cutting force.

Pawade and Joshi [5] analysed multi-objective optimization of cutting force and surface roughness in the high speed turning of Inconel 718. A commercially available low cubic boride nitride (CBN) content inserts were used as cutting tool.Results showed that depth of cut had statistical significance on overall turning performance. They concluded that an increase in the value of predicted weighted GRG from 0.1160 to 0.2071 confirms the improvements in the performance of high speed turning process using optimal values of process parameters.

Aouici et al. [6] experimentally studied the effects of hard turning process parameters such as cutting speed, feed rate, workpiece hardness, depth of cut on surface roughness and cutting force. AISI H11 steel had a hardness of 40, 45, 50 HRC, machined using a CBN tool. Results showed that the cutting force components are influenced principally by the depth of cut and workpiece hardness.

Ozel et al. [7] carried out experimental investigation on the effects of cutting edge preparation geometry, workpiecehardness and cutting conditions on the surface roughness and cutting forces in the finish hard turning of AISI H13 steel. The results indicated that cutting force is influenced not only by cutting condition but also cutting edge geometry and workpiece surface hardness.

Lalwani et al. [8] carried out experimental investigation of process parameters influence of cutting forces and surface roughness in finish hard turning of MDN 250 steel. Results showed that cutting speed hasno significant effect on cutting force and surface roughness. Cutting force model: the depth of cut is most significant factor with 89.05% contribution in the total variability of model whereas feed rate has a secondary contribution of 6.61% in the model.

Fang and Wu Q [9] investigated a comparative experimental study of high speed machining of two materials- titanium alloy Ti-6Al-4V and Inconel 718. The results show that of both materials: while cutting speed increases then cutting force, thrust force and feed force are increases.

Ekanayake and Mathew [10] carried out experimental investigation of high speed end milling. The experimental results are cutting force increases with increasing feed and depth of cut does not show a specific trend with increasing cutting speed. This could be complex effect of temperature and strain rate on the flow stress of the material. From the observations, the chamfer insert is used high speed machining, because they are generated lower cutting force.

Kurt et al. [11] investigated the effects of chamfer angle on the cutting forces and stresses by PCBN cutting tools in finish hard turning of AISI 52100 bearing steel. They found that the chamfer angles (20° and 30°) have a great influence on the cutting forces and Von Mises tool stresses distribution.

2.2 Studies on surface integrity

The surface integrity of machined part after high speed machining gives further information about the physical properties of machined surface. Surface integrity includes the existence of micro-cracks, surface finish, untempered and over tempered mertensite, phase transformation, residual stresses imposed by the machining process, the pull-out of carbide from the grain boundary,plastic deformation and change in microhardness. Residual stress on the machined surface and subsurface is known to influence the service quality of a component, such as fatigue life, tribological properties, and distortion. The findings of some of the research studies pertaining to the effect of cutting parameters on surface integrity are presented below.

Peng et al. [12] studied the effect of machining on microstructural and residual stresses respectively. High speed turning of Inconel samples under different cutting conditions. It was concluded that mechanical force and heat generation are most significant process parameters affecting on microstructural and residual stresses.

Batalha et al. [13] have developed residual stresses modeling for hard turning and its correlation with cutting forces. Results showed that the feed rate and depth of cut are most significant factors on the circumferential residual stresses introduced in surface tests. The residual stresses are so much more compressive as larger feed rate and smaller depth of cut.

Navas et al. [14] studied the effect of final surface stress on the AISI 4340 steel. The surface residual stresses have been measured by the help of X-ray diffraction. Process parameters are cutting speed (200 – 300 m/min), cutting feed (0.075 – 0.200 mm/rev), two different nose radius (0.4 and 0.8 mm), two different surface states one coated with CVD and other without coating and two different geometries of the chip breaker. The results indicated that residual stresses are more tensile due to an increase in cutting temperature with increase in feed. The cutting speed is not significant parameter for residual stress.

Kacal and Yildirim [15] carried out experiment on high speed hard turning of AISI S1 cold work tool steel. The results show that good surface roughness obtained with CBN tools. A surface roughness value of approximately 0.2 µm was obtained.

Bhattacharya et al. [16] investigated the effect of cutting parameters on surface roughness and power consumption during high speed machining of AISI 1045 steel using Taguchi design and ANOVA. The result shows that the cutting speed is significant parameter affecting on surface roughness and power consumption.

Singh and Venkateswararao [17] have investigated the effects of cutting conditions and tool geometry on surface roughness in the finish hard turning of AISI 52100 bearing steel with mixed ceramic inserts made up of aluminium oxide and titanium carbonnitride (SNGA). Results showed that the feed is dominant factor determining the surface finish followed by cutting speed and then tool rake angle. They developed a mathematical model for surface roughness by using response surface methodology.

Vikram and Ratnam [18] developed an empirical model for surface roughness in hard turning based on analysis of machining parameters and hardness values of various engineering materials. The process parameters like cutting speed and feed are primary influencing factors of surface finish. The results indicate that feed is the dominant factor affecting on surface roughness followed by cutting speed and material hardness.

Akhyar et al. [19] analysed optimization of cutting parameters in turning Ti-6Al-4V extra low interstitial with coated and uncoated cemented carbide tools underhigh cutting speed with dry cutting condition. Taguchi's robust design method is suitable to optimize the surface roughness in turning Ti-6Al-4V ELI. The significant factors of surface roughness in turning Ti-6Al-4V ELI were feed rate and tool grade, with contribution of 47.14% and 38.88% respectively.

Gunay and Yucel [20] analysed optimization of cutting conditions for the average surface roughness obtained in machining of high alloy white cast iron (Ni-Hard) at two different hardness levels. The effects of the cutting parameters and tool material on surface roughness were evaluated by the analysis of variance. The statistical analysis indicated that the cutting speed and feed rate are significant parameters affect on surface roughness for Ni-Hard materials with 50 HRC and 62 HRC.

2.3 Studies on cutting temperature

The metal cutting is an intricate process. When metal cutting process starts then plastic deformation occurs and produced heat between primary share zones. It could be assumed that all the required cutting energy is converted to heat. The generation of the heat during machining increases the temperature in the cutting zone which affects the strength, hardness, wear resistance and tool life of the cutting tool and cause difficulty in controlling the dimensional accuracy and surface integrity. The findings of some of the research studies pertaining to the effect of cutting parameters on heat generation and cutting temperature are presented below.

In 1954 Lowen and Shaw's [21] developed analytical prediction model for the measurements of cutting temperature during machining. They concluded that the cutting temperature is the function of cutting speed and feed rate.

$$\theta t = V \times 0.5 \times t$$

Where, θt = Average cutting temperature

V = Cutting speed

T = Underformed chip – thickness

Rech [22] found out that various coating deposited on a carbide insert has shown the sliding properties of the TiN and N+MoS_2 coating compared with uncoated tools in the context of high speed dry turning of steel. TiN and N+MoS_2 coatings reduce tool-chip contact area, reduce thickness of secondary shear zone, and reduce temperature at tool - workpiece interface.

Majumdar et al. [23] carried out experimental investigation of the heat generation during metal cutting processes and its effects on cutting force and tool wear. Results showed that when cutting speed increases from 29.6 m/min to 155.4 m/min then tool temperature increases from 709.36 K to 1320 K. The model also describes significant effect of conduction and convection losses in heat dissipation and temperature rise in the tool.

Abukhshim et al. [24] used finite element analysis for estimate the amount of heat flow into the cutting tool in high speed turning of AISI 4140 high strength alloy steel using uncoated cemented carbide. Results showed that tool-chip contact temperature increases with increase in cutting speed and this could be attributed to the trend of heat fraction flowing into the tool.

Ren et al. [25] determined cutting temperature during hard turning of high chromium hard facing materials using PCBN tools. They found that the average cutting temperatures ranged from 600 to 700 °C. Cutting temperature increased with higher cutting speed and feed rate.

Federi et al. [26] studied effect of the cutting parameters on tool temperature, tool wear, cutting forces and surface roughness. While machining hardened steel with multilayer coated carbide tools astandard K-type of thermocouple inserted near the rake face of the tool was used to measure the interface temperatures. The experimental results show that the temperature near the rake face increases significantly when the depth of cut charges from 0.2 to 0.4 mm.

2.4 Studies on tool wear and tool life

The prediction and control of tool wear is one of the most essential problems emerging in the design of cutting operations. The useful life of a cutting tool may be limited by a variety of wear processes such as crater wear, flank wear, built up edge, notching and nose wear. Tool life generally indicates the amount of satisfactory performance or service rendered by a fresh tool or cutting point till it is declared failed. Tool life is always expressed by span of machining time in minutes, no of pieces of work machined, and total volume of material removed total length of cut. Many researchers focused their studies on the prediction of the tool wear and toll life during high speed machining.

Mahfoudi et al. [27] carried out experimental investigation of high speed turning on hard material with PCBN inserts to analysis tool wear. An experimental result shows that crater wear is the most important phenomenon controlling in high speed turning process by modifying tool geometry. It is recommended to select the wear criterion [KT] = 0.07 mm in order to avoid the domain of catastrophic wear according to wear curves.

Senthilkumar et al. [28] carried out experimental investigation of surface roughness and flank wear in finish turning and facing of Inconel 718 using taguchi technique. The percentage error between experimental and predicated result is 4.67% for turning process and 2.63% for facing process. Results showed that cutting speed and depth of cut are the dominant factors of turning process while cutting speed and feed are dominant factors of facing process.

Das et al. [29] analysed optimization of cutting parameters on tool wear and workpiece surface temperature in turning of AISI D2 steel. The taguchi parameter design is an effective way of determining the optimal cutting parameters for achieving low tool wear and low workpiece surface temperature. The experimental results showed that percentage contributions of depth of cut (60.85%) and cutting speed (33.24%) in affecting the variation of tool wear are significantly larger as compared to the contribution of the feed (5.70%).

Aruna et al. [30] investigated the effect of feed rate and cutting speed on the tool wear and surface roughness in finish turning of Inconel 718. Results showed that less tool wear and good surface finish are obtained using ceramic tool. The tool failure occurs at cutting speed of 200 m/min and feed rate of 0.15 mm/rev. They concluded that basically the flank wear and depth of cut notch wear are tool failures observed in high speed conditions.

Morea et al. [31] carried out experimental investigation of PCBN tool is the dominant tool material for hard turning applications due to its high hardness, high wear resistance, and high thermal stability. The experimental results showed that the flanks wear is mainly due to abrasive actions of the martensite present in the hardened AISI 4340 alloy. The crater wear of the CBN-TiN coated inserts is less than that of the PCBN inserts because of the lubricity of TiN capping layer on CBN-TiN coating.

Khrais and Lin [32] carried out experimental study on wear mechanisms and tool performances of (TiAlN) PVD coated inserts during machining of AISI 4140 steel at high speed for both dry and wet machining. The turning test was conducted with variable high cutting speeds ranging from effect on TiAlN coating under high speed machining. Micro-wear mechanisms identified in the tests through SEM micrographs include edge chipping, micro-abrasion, micro-fatigue, micro-thermal, and micro-attrition. These micro-structural variations of coating provide structure–physical alterations as the measures for wear alert of TiAlN coated tool inserts under high speed machining of steels.

Sahin [33] was compared tool life of CBN and ceramic inserts in turning hard steels using the Taguchi method. The effects of cutting parameters such as cutting speed, feed rate, and tool hardness on tool life was determined by signal to noise ratio and ANOVA. Results showed that the effects of cutting speed, tool hardness and feed rate on tool life were 41.63%, 32.68% and 25.22% respectively.

Bhatt et al. [34] carried out experimental investigation on the wear mechanisms of uncoated tungsten carbide and coated tools (single-layer (TiAlN) PVD and triple-layer (TiCN/Al2O3/TiN) CVD) in oblique finish turning of Inconel 718. The experimental results shows that the abrasive and adhesive wear are the most dominant wear mechanisms, controlling the deterioration and final failure of the tungsten carbide tools by the triple layer CVD coated tools.

Noordin et al. [35] carried out experimental investigation on hard turning of martensitic stainless steel using wiper coated tool at various cutting speeds and feeds. It was found that low cutting speed and low feed produces the longest tool life. The combination of high cutting speed and feed was found to be unfavorable for hard turning of stainless steel. Wiper coated carbide tool achieved very fine surface finish, much better than the theoretical values and within the strict range of finish machining criteria.

Hossein and Yahya [36] analysed high speed end milling of AISI 304 stainless steel, which has poor machinability, with multilayered (TiN/TiCN/TiN) carbide inserts. They concluded that the tool life is inversely proportional to the cutting speed. The feed variation at high cutting speeds has small effect on tool life.

2.5 Studied on chip formation

Machining is the process of removing the material in the form of chip by means of wedge shaped tool. The most common manufacturing process in industry ismetal cutting. Finite element method (FEM) has become the main tool for simulating metal cutting processes. The chip can be continuous, segmented, or discontinuous; depending on the cutting parameters. Temperature also affects tool life, work piece surface finish, chip morphology, and power consumption. Many researchers focused their studies on the prediction of the chip formation during high speed machining.

Umer et al. [37] carried out the finite element chip formation analysis for high speed milling operation. The analysis of the result revealed that, the comparison between simulated and experimental results indicate that, high speed milling operation using flat bottom end mill can be simulated using a 2D FEM model with reasonable degree of accuracy. The cutting forces do not show a marked difference when increasing speed from 200 to 600 m/min for H13 tool steel. Increase of feed rateincreases both cutting forces. At lower feed rate the chip curls earlier i.e. at low angle of rotation of the cutter.

Jeevannavar and Hussain [38] carried out experimental study on thermo-mechanical numerical simulation model of plane-strain orthogonal metal cutting condition with continuous chip formulation is presented using the finite element method software ABAQUS/Explicit. The developed model has proved to be able to predict chip morphology in a workpiece that undergoes a typical high speed machining. The FEM simulation technique used for orthogonal cutting process is an accurate and doable analysis as long as flow stress behavior of work material obtained realistically and friction at the chip tool interface is modeled correctly.

Ng and Aspinwall [39] investigated the effect of steel hardness and cutting speed on chip formation. Homogenous deformed segmental chips occurred when machining at 75 m/min with 28 HRC workpiece hardness and the chip grain structure was uniform. Inhomogeneous deformed segmental chips occurred when machining at 150 m/min with 42 HRC workpiece hardness. Results showed that higher shear angle is associated with lower cutting force. Work piece hardness and formation of a particular chip type was dependent on the percentage of brittle/hard matrix present in the workpiece and associated strain rates. When cutting speed and workpiece hardness increased then shear zone thickness and chip thickness decreased.

Poulachon and Moisan [40] carried out experimental study on hard turning: chip formation mechanisms and metallurgical aspects. The results obtained by four stages of the formation of a saw tooth chip. Each shape of the chip formation could be observed on each micrograph of quick stop test. The influence of the increase in hardness during the plastic deformation of the material and the analysis of it is variation allows the effect of strain hardening and theoretical softening occurs at higher and lower cutting speeds.

3. Conclusion

This paper has presented an overview focusing mainly on turning of hardened steels that are used by ball bearings, automotive, aircraft and die-making industries. On the basis of the research findings reported in the available literature reviewed and presented in this paper, the major observation gleaned from the literature are the following:

- High speed machining, the taguchi method and ANOVA have proved to be efficient tools for controlling the effect on cutting force, tool wear and surface roughness.

- The cutting forces are influenced not only cutting conditions but also cutting edge geometry.
- The feed rate and depth of cut are the most significant factors of residual stresses. As well as feed rate, cutting speed, hardness of the material are dominant factors of surface roughness.
- The cutting speed is most significant factor of cutting temperature, especially in high range of cutting conditions.
- Flank wear and depth of cut notch (DOCN) wear are the dominant factor of tool wear. When cutting speed increases then tool life decreases. The longer tool life was observed in case of CBN/TiC cutting tools.
- Saw toothed chips are always formed during the machining of hardened steel. Cutting tool wear and cutting forces are major influencing factors of chip morphology.
- The complex phenomena involved in high speed machining can be studied through simulation and modeling using techniques such as FEM, ANN etc. and the results of the models can be validated with experimented results.

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