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# A Review of Turning of Hard Steels using Different Cutting Tool Materials and Machining Parameters

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### Review Article

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## ABSTRACT

This paper presents the information about the state of research in hard turning and its monitoring, under three broad headings, namely (i) The science and technology of hard turning (ii) The various monitoring techniques that were developed for the process monitoring of hard turning and lastly (iii) Certain specific acoustic emission-based monitoring techniques and signal processing, employed to monitor the conventional turning operations, as it is intended to use these techniques for monitoring hard turning. Hard turning is a recent technology that involves machining of hard steels using modern machine tools. Hard machining presents challenges in terms of selection of tool insert with improved tool life and high-precision machining. Turning of hardened steels using single-point cutting tool has got considerable interest among manufacturers of ball bearings, automotive, gear, and die industry. The researchers have worked on many facets of machining of hardened steel using different tool materials and came up with their own recommendations. Researchers have tried to investigate the effects of cutting parameters, tool materials, different coatings and tool geometry on different machinability aspects like, the tool life, surface roughness, cutting forces, chip morphology, residual stresses and the tool-chip interface temperature under dry and/or semi-dry and/or flood cooling environment during machining of hardened steels while many of them have ventured to characterize the wear phenomenon. This paper presents a broad literature review on machining of hardened steels using coated and uncoated tools, studies related to hard turning, different cooling methods and attempts made so far to model machining performance(s) so as to give proper attention to the various researcher works.

## INTRODUCTION

Today, manufacturing is changing rapidly around the world as in the present context of sustainable manufacturing, the demands for most economical and environmental-friendly manufacturing processes are increasing, which have triggered the fast-commercial growth of coatings and stands out to be one of the best solutions to address the environmental problems occurring due to wet machining [1]. However, in the light of multitude influences of coatings on the contact and tribological phenomena, the choice of coating compound and its structure should be correct to the specific tool-workpiece combination and process conditions [2].

Machining of hardened steels with HSS, PCBN and ceramic tools are widely accepted as a best replacement to costly grinding operations. However, development in the cemented carbide grades, uncoated materials and coating deposition technologies have attracted many researchers in the field of machining of hardened steels using coated carbide tools as an economical alternative to costly PCBN and ceramic tools [3]. On the other side, the tool wear, especially the flank wear, which adversely affects the dimensional accuracy and product quality, is the main hurdle in the wide implementation of coated carbide tools for the machining of hardened steel in the industry. Therefore, assessment of tool wear patterns and mechanisms has been an important objective of metal cutting research. The researchers have worked on many facets of machining of hardened steel using different tool materials and came up with their own recommendations. With the advancement in cutting tool materials and machine tools, today, machining of hardened steel having hardness up-to 45 HRC is considered under soft machining and machining of hardened steels having hardness in the range of 45-65 HRC is considered under hard machining. If hard turning is applied to the manufacture of complex parts, manufacturing costs can be reduced up to 30%, and US industries exploited the advantages of hard turning for an annual gain of up to $6 billion. In aero engine manufacture, the surface integrity has established as a complex quality measure regarding not only features on the surface but also the condition of the subsurface. The integrity at the machined surface on the one hand depends on the material properties of the part and on the other hand on the machining parameters as well as the condition of the cutting edge.

## LITERATURE REVIEW

Major hard turning cutting tool materials: Material advancements for the cutting tool is one of the most critical essentials in metal cutting. Cutting tool material has always been characterized by an increase in wear resistance to machine harder, tougher, or chemically reactive materials. For example, super hard materials such as ceramic and CBN were one of the core means to enable the hard turning technology to be an alternative to grinding processes. Correlation between chemical, physical, and mechanical characteristics of cutting tool materials and their performances in cutting operations is therefore, a key issue for both tool manufacturers and users. Cutting tools must concurrently withstand heavy mechanical loads and high temperatures. Temperature in the chip/tool interface reaches more than 700ºC in some cases such as turning of high hardness alloy steel. Additionally, the friction between tool and removed chip, on one hand, and tool against the new machined surface, on the other, is very severe. Owing to this, the following main factors should be considered for a good tool design and post-manufacturing Tool material must present enough toughness to avoid fracture, especially when operation to perform implies interrupted cutting. Tool material has to present high resistance for the abrasion and adhesion wear. Material hardness must be maintained to high temperatures suffered at the chip/tool interface. Chemical and physical stability of cutting-tool substrate material must be maintained at high temperatures.

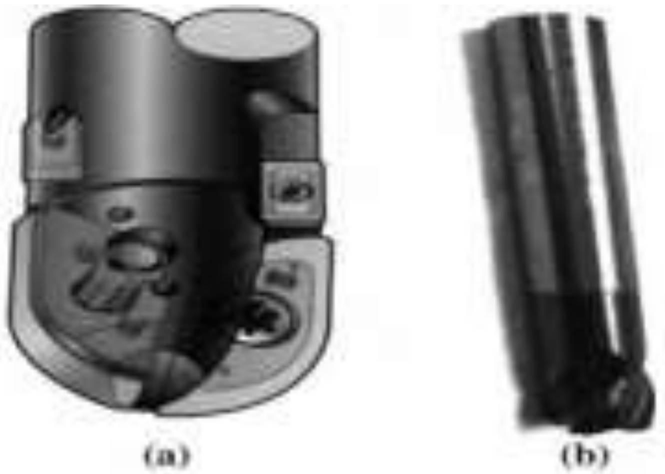
Before explaining the main features of each material, a remark of the company type elaborate in tool fabrication is a thought-provoking fact. Thus, in the current tool market two types of company are possible: firstly, the producers of basic tool materials, usually big international companies such as CeraTizit, Krupp, Sumitomo, General Electric, De Beers, Sandvik, Kennametal, Iscar and others, which also manufacture the complete cutting-tool systems including tool holders, inserts or integral cutting tools. Currently these companies represent the 80% of the total world market. Secondly, there are small and medium companies that start from calibrated material rods, supplied by some of the former companies, and give form and geometry to cutting tools. This is the case of integral end mills, drilling tools and tailor-made tools. The natural markets for these companies are either very specific roles or special tailor-made tools built with user requirements (Figure 1).

**Figure 1.** Solid reamer tool for routing carbon-fibre-reinforced plastics, by Kendu®, made of submicrograin tungsten carbide (top), and with TiAIN (Titanium aluminium nitride) coating applied by Metal Estalki® (bottom).

High-speed tool steel and their requirements are defined by The American Society for Testing and Materials in Specification A600-79 as, High-speed tool steels are so named primarily because of their ability to machine materials at high cutting speeds. They are complex iron-base alloys of carbon, chromium, vanadium, molybdenum, or tungsten, or combinations thereof, and in some cases substantial amounts of cobalt. The carbon and alloy contents are balanced at levels to give high attainable hardening response, high wear resistance, high resistance to the softening effect of heat, and good toughness for effective use in industrial cutting operations [4-6]. This group of high-alloyed steels was developed at the early years of the 20th century. Basically, they are high-content carbon steels with a high proportion of alloy elements such as tungsten, molybdenum, chromium, vanadium and cobalt. The mean hardness is 75 HRC. The T series includes tungsten, the M series molybdenum, whereas vanadium produces the hardest of the carbides giving rise to the super-high-speed steels. The maximum working temperature of HSS is about 500ºC. Currently, HSS produced by Powder Metallurgy (HSS-PM) offers a higher content of alloy elements and a combination of unique properties: higher toughness, higher wear resistance, higher hardness and higher hot hardness. HSS and HSS-PM are excellent substrates for all coatings such as TiN, TiAIN, TiCN, solid lubricant coatings and multilayer coatings. HSS-PM has many advantages in high-performance applications such as rouge milling, gear-cutting tools and broaching, and also in cases of difficult tapping, drilling and reaming operations. HSS-PM is used too in disc and bandsaws, knives, cold-work tooling, rolls, etc.

Hard metal grades are classified under the standard ISO 513 [2] into six groups, M, P, K, N, S and H, following a numerical scale for each of them. On the other hand, in the USA the C-x scale is used instead. The original concept of both classifications was to rate tungsten carbides according to the job that they had to do, and this led to a little clear scale in which no cobalt binder amount or grain size is specified. As consequence, tungsten carbide from different manufacturers may have identical designation but may vary considerably in performance (Figures 2A and 2B).

**Figure 2.** (A) Ball-endmill with inserts, and (B) integral bull-nose endmill.



Ceramics are very hard and refractory materials, withstanding more than 1500°C without chemical decomposition. These features recommend them to be used for the machining of metals at high cutting speeds and in dry machining conditions. Unfortunately, they are fragile, and ceramics without any reinforcement are only indicated for turning of continuous shapes. In milling the continuous impact at each tooth entrance in the machined part implies a high risk of chipping and tool failure. Ceramic materials are moulded from ceramic powders at pressures more than 25 MPa, to be later sintered at approximately 1700°C. Ceramic tools are based primarily on alumina ($Al_2O_3$), silicon nitride ($Si_3N_4$) and sialon (a combination of Si, Al, O and N) [2]. Alumina tools can contain additions of titanium, magnesium, chromium or zirconium oxides distributed homogeneously into the alumina matrix to improve toughness.

The ceramics reinforced by a non-homogeneous matrix of silicon carbide (SiC) whiskers ($Al_2O_3$+SiCw) are focused on the milling operation. Whiskers are fine-grained silicon carbide crystals similar to hairs. The whiskers form 20%-40% of the total ceramic, improving the tool toughness a lot, making them suitable for milling operations. Whisker-reinforced ceramics are successfully applied on hard ferrous materials and difficult-to-machine super alloys, especially in the case of the nickel-based alloy Inconel 718. Ceramics are a very productive option in a lot of applications, but special care must be taken when machining is programmed. Tools must be kept hot throughout the operation (dry condition is the best) and shocks on tool edges at tool entrances and exits from the work piece must be avoided. In turning, the ramping technique is highly recommended to reduce the notch wear in the cylindrical roughing of austenitic materials [2].

PCD (Polycrystalline Diamond) and PCBN (Polycrystalline cubic boron nitride) are extra-hard materials. There are several grades in the PCD and PCBN groups. As a rule of thumb, PCD is suitable for tools focused on machining abrasive non-ferrous metals, plastics and composites. Otherwise, PCBN finds applications in the machining of hardened tool steels and hard cast irons [2].

## DISCUSSION

Cutting force is basically the product of specific cutting energy coefficient ($N/mm^2$), depth of cut (mm), and feed (mm/rev). Cutting force is generally resolved into three components, namely feed force ($F_x$), thrust force ($F_y$), and cutting force ($F_z$). Many force measurement devices like dynamometers have been developed which are capable of measuring tool forces with increasing accuracy. Power consumed in metal cutting is largely converted into heat near the cutting edge of tool, and many of the economic and technical problems of machining are caused directly or indirectly by this heating action. By measuring the cutting forces, one is able to understand the cutting mechanism such as the effects of cutting variables on the cutting force, the machinability of the workpiece, the process of chip formation, chatter, and tool wear. It has been observed that engineering calculations used for obtaining the force values give some errors when compared to experimental measurements of the forces and developed a theoretical model to predict cutting forces for machining hard materials and the predicted results from the model were found to be in good agreement with those measured from an experiment of hard machining of an AISI 4140 steel heattreated bar using ceramic inserts and studied the effect of the cutting parameters (cutting speed, feed rate and depth of cut) on the cutting force components during turning AISI 1045 steel using coated carbide inserts under dry condition. The results of their study indicated that the three components of the turning force decreased slightly as cutting speed was elevated and increased linearly with feed rate and depth of cut. Furthermore, the analysis of variance indicated that the three components of the force were not significantly affected by cutting speed; however, they were significantly affected by feed rate and depth of cut, investigated the effect of cutting parameters on cutting forces during dry and wet turning for heat treated medium carbon steel. The results revealed that the machining forces for the dry turning were higher than that of the wet turning. They also suggested that for precision machining, dry turning is by far a better cost safer and cleaner option than wet turning. The experimental study to investigate the turning of hardened AISI 6150 heat treatable steel using Polycrystalline Boron Nitride (PCBN) tools to explore the effects of the cutting parameters (cutting speed, feed and depth of cut) on the cutting forces. They found no effect of the depth of cut on the force components for the selected ranges of depth of cut. The behavior of austenitic stainless steel when machining at very high cutting speeds in dry turning. The results of their study indicated that the material used in the study undergoes a significant change in its behavior when machined at cutting speeds above 450 m/min that favored the machining operation. Further, the results also revealed that the main component of cutting forces reached a minimum value at this cutting speed and presented a specific study of the application of solid lubricants in turning of AISI1040 steel with carbide tool. It was observed from their experimental results that the cutting forces slightly increased or remained same with increase in cutting speed in dry and coolant conditions, but slightly increased while using solid lubricants. However, cutting forces were significantly less in all the solid lubricant conditions compared to dry and coolant machining. The influence of machining process variables on the cutting force components in finish turning of KhVG hardened steel (60–62 HRC) using CBN tool. They found that the minimum magnitude of the cutting force fluctuations could be achieved under the following cutting parameters setting: cutting speed=2 m/s, depth of cut=0.1 mm, and feed rate=0.166–0.208 mm/rev. The experimental data to construct model using neural networks in hard turning of adamite steel using coated carbide insert and reported the following results: (i) approaching angle influences cutting force and feed force positively but thrust force negatively, (ii) speed influences thrust force and feed force positively but tangential force negatively, (iii) feed rate influences tangential force, feed force, and thrust force positively and (iv) depth of cut influences tangential force, thrust force, and feed force positively. The model for predicting cutting forces in hard turning of 51CrV4 using CBN tool with a wiper cutting edge and for validation of the results, they compared the cutting forces predicted by the model with experimental measurements and found that most of the results agreed quite well [7-10].

This paper has presented an overview focusing mainly on turning of hardened steels that are used by ball bearings, automotive, gearand mold and die industries. On the basis of the research findings reported in the available literature reviewed and presented in this paper, following conclusions can be drawn: Producers of machined components and manufactured goods are continually challenged to reduce cost, improve quality, and minimize setup times in order to remain competitive. Hard turning presents embryonic benefits as well as interests in preference to conventional cylindrical grinding; (a) by without losing the product quality in connection with more flexible, less expensive, and more eco-friendly production, and (b) by employing appropriate and very hard futuristic tool materials under critical machining condition. Cutting tool geometry and materials, work piece hardness, cutting parameters, and cooling methods significantly affect the energy consumption, cutting forces, surface residual stress, surface roughness, surface integrity, tool wear and tool life. The suggestion obtained through study and prediction of the tool wear during machining can be used as a source for the effective design of cutting tools and determination of cutting conditions that will leading to the formulation of the tool change strategies. The multifaceted phenomena involved in hard turning can be studied through simulation and modeling using techniques such as FEM, ANN, MINITAB, MATLAB, TAGUCHI, CREO etc. and the results of the models can be validated with experimental results. The actual surface finish produced by a turning tool is influenced by two groups; namely (a) those of a theoretical nature (ideal roughness) and (b) those of a practical nature (natural roughness).

## CONCLUSION

it is concluded that the information gathered through extensive literature review has been presented in a modular way in this paper. The review has been organized in terms of role of machining parameters on machining of hard steel, cutting force, heat generation, and temperature evolution during machining, surface integrity, and tool wear during hard machining, etc. The information presented are immensely useful to the researchers in identifying solutions to the several machining problems to mention some: (I) to identify strategies with regard to tool edge geometry, cutting parameters, etc. for specific work material hardness so as to obtain better surface integrity and surface finish; and (II) to identify prevalent wear mechanisms and appropriate tool material for specified machining situations. Thus, it is concluded that the information collected through comprehensive literature review has been presented in a modular way in this paper. The review has been planned in terms of role of machining parameters on machining of hard steel, cutting force, heat generation, and temperature evolution during machining, surface integrity, and tool wear through hard machining, etc. The information presented are enormously useful to the researchers in finding solutions to the numerous machining problems to remark some: (a) to find strategies with respect to tool edge geometry, cutting parameters, etc. for specific work material hardness so as to gain improved surface integrity and surface finish; and (b) to find predominant wear mechanisms and suitable tool material for specified machining conditions.

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