Recent developments in turning hardened steels – A review

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Abstract - Hard materials ranging from HRC 45 – 68 such as hardened AISI H13, AISI 4340, AISI 52100, D2 STL, D3 STEEL Steel etc., need super hard tool materials to machine. Turning of these hard materials is termed as hard turning. Hard turning makes possible direct machining of the hard materials and also eliminates the lubricant requirement and thus favoring dry machining. Hard turning is a finish turning process and hence conventional grinding is not required. Development of the new advanced super hard tool materials such as ceramic inserts, Cubic Boron Nitride, Polycrystalline Cubic Boron Nitride etc. enabled the turning of these materials. PVD and CVD methods of coating have made easier the production of single and multi layered coated tool inserts. Coatings of TiN, TiAlN, TiC, Al2O3, AlCrN over cemented carbide inserts has lead to the machining of difficult to machine materials. Advancement in the process of hard machining paved way for better surface finish, long tool life, reduced tool wear, cutting force and cutting temperatures. Micro and Nano coated carbide inserts, nanocomposite coated PCBN inserts, micro and nano CBN coated carbide inserts and similar developments have made machining of hardened steels much easier and economical. In this paper, broad literature review on turning of hardened steels including optimizing process parameters, cooling requirements, different tool materials etc., are done.

1. Introduction

In the modern world with fast developing technologies, manufacturing industries are striving hard to survive with economical and shorter time production methodologies. Based on the functional requirements, some parts demands high hardness. Conventional procedure for machining these hard materials is

(a) Annealing the work piece.
(b) Turning the work piece to near net shape.
(c) Performing the required hardening processes.
(d) Finally grinding the material to the required dimension.

Finish grinding process involves in removing the material in micron level and consumes more time.

Until 1970, turning these types of hard materials are considered as difficult process. Recent developments in the designing of rigid machineries, tool holders, newer super hard tool materials, work pieces are directly turned to correct dimensions after hardening, thus eliminating annealing process, the need to turn the work piece to near net shape and finish grinding process. The direct turning of hard material is made feasible by the arrival of newer super hard tool materials such as
cemented carbide, Cubic Boron Nitride (CBN), Polycrystalline Cubic Boron Nitride (PCBN), coated carbide inserts, CBN coated carbides, micro and nanocomposite coated tools. Also, Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD) coating technologies have made hard turning an easier process.

Implementation of hard turning results in reduction in set up time, process steps and increased productivity yielding more cost saving. Other major advantage of hard turning is that it can be machined without or minimum lubrication. Handling of the lubricants also adds cost to the process and excluding the lubricant makes the process more economical. Absence of lubricants makes hard turning an environment friendly system. The recent developments in turning hardened steels are reviewed in this paper, the areas of research done, scope for further research are discussed.

2. Cutting tool materials

A cutting tool material must possess the following qualities.

(a) Hardness greater than work piece material.
(b) Hot hardness – Retain the hardness at elevated temperatures.
(c) Toughness – Should not fracture or chip during cutting operation.
(d) Wear resistance – Able to resist wear leading to longer tool life.
(e) Chemical affinity – Should not react with work piece material and coolant.
(f) Impact resistance – Withstand impact loads.

None of the cutting tool materials incorporates all these characteristics. Based on the specific requirements trade-offs occur in tool materials.

The history of tool material starts from carbon tool steels followed by High speed steel (HSS), cemented carbide, ceramics, cermets, coated carbides, coated ceramics, Polycrystalline Diamond, Cubic Boron Nitride (CBN), Polycrubic Boron Nitride, CBN coated carbide tools.

In 1923 Osram Lamp Works developed cemented carbide tool a composite material having tungsten carbide (WC) as the hard aggregate and Co as the metallic binder. Introduction of cemented carbide tools increased the cutting speed to approximately 4 times the speed of high speed steel. The addition of TiC to cemented carbide increased the tool life. Later TaC, VC, Cr3C2 and other carbides were added to cemented carbide based on the requirement and the performance of cemented carbide has increased.

For hard turning, alumina based ceramics plays an important role. Though alumina has most of the required properties such as high hot hardness, increased wear resistance and chemical inertertis, it is highly brittle leading to shorter tool life [1]. To overcome this, alumina based ceramic tools are generally reinforced with TiC, TiN, (W, Ti)C, Ti(C, N), ZrO2, TiB2, SiCx, SiCp [2].

PCBN tools are very expensive as it needs high temperature and pressure in the manufacturing compacting process. In consequence, an alternate tool material, with near equivalent quality but with less price have gained importance. Fulfilling both requirement ceramic tools replaces the costly PCBN [3, 4, 5].

Abhijeet et al. [6] compared CBN-TiN composite coated WC – Co insert with PCBN tool in turning hardened AISI 4340 steel. Though PCBN tool performance was better than CBN-TiN composite coated WC-Co tool in terms of tool life, cutting force, CBN-TiN composite coated tool takes an edge as it is cheaper than the PCBN tool.

In 1986, Brandt [7] observed better flank wear resistance in mixed alumina ceramic tool when compared to oxide alumina ceramic tools. Later Senthil kumar et al. [8] experimented EN 24 steel with hardness HRC 40 to HRC 45 with two types of cutting tools, Ti(C,N) mixed alumina ceramic cutting tool and Zirconia toughened alumina ceramic cutting tool. Comparing these two tools, the author found that with respect to adhesive wear Zirconia toughened alumina ceramic cutting tool was better and best surface finish was recorded by Ti(C,N) mixed alumina ceramic cutting tool.

Luis Henrique Andrade Maia et al. [9] have made study on AISI 4340 hardened steel with uncoated, AlCrN coated and nano AlCrN coated WC inserts. The author utilized acoustic emission methodology to collect wear rate and power spectral density (PSD) technique and auto-covariance coupled PSD
technique to analyze. In his study he found that compared to uncoated WC insert and ordinary AlCrN coated WC insert, nano structured AlCrN coated WC insert performed superiorly.

Usage of Polycrystalline cubic boron nitride (PCBN) cutting tool in hard turning is attributable to its ultra high hardness, lower chemical affinity towards work piece and extreme wear resistance[10 -19]. Researchers have indicated that highly precision, rigid machine and rigid tool clamping are required to use CBN tools as it is brittle in nature and chips easily [20, 21]. Many researchers have made research about the composition, wear and tool temperatures of CBN cutting tools [22 -24]. Prior studies in turning AISI 52100 hardened steel revealed that low content CBN tools generates good surface finish compared to high content CBN tools [22, 24].

Pradeep Kumar and Chauhan [25] experimented hard turning of hardened AISI H13 die tool steel using CBN tools and investigated cutting forces and surface roughness of three work pieces with different hardness values (45 HRC, 50 HRC and 55 HRC). The authors considered five parameters cutting speed, depth of cut, feed rate, nose radius and hardness of work piece for their study. They concluded that turning work piece with higher hardness lead to better surface finish. Larger nose radius, high cutting speed resulted in reduced surface roughness and increase in cutting speed reduced the cutting force.

Shalaby et al. [26] investigated about the tool life and cutting forces in Hard turning of D2 tool steel with three different tools mixed alumina ceramic tool, PCBN tool and coated PCBN tool. He concluded that mixed alumina ceramic tools resulted in less cutting forces and increased tool life compared to PCBN tools, this can be accredited to its less chemical affinity to work piece, thermal stability. But, the brittle nature limits its application.

Ranjit Babu B. G and Sonachalam M [27] experimented turning of AISI 52100 hardened steed using nano coated tool insert and optimized the process parameters using Taguchi technique. Vereschaka A. A et al.[28] successfully developed nano-scale multilayered composite coatings on cutting tool using chemical vapor deposition (CVD) and physical vapor deposition (PVD) and stated that nano coated tool have more wear resistance. Escobar C et al.[29] investigated tribological and wear behavior of Hafnium Nitride (HfN) and Vanadium Nitride (VN) nano multilayer coated tool. The authors concluded that turning work piece with nano multilayer coated tool shows high tribological performance and have high wear resistance. Also the nano coated tools have 24% higher tool life than uncoated WC tool.

Several researches are going on to develop newer cutting tool material, nano coated and nano composite coated tool insert aiming at reducing the tool wear, cutting force, surface roughness and increasing the tool life, metal removal rate and productivity. Emerging researchers have an ample of scope in developing newer tool material.

3. Tool geometry
One of the major factors in tool life is cutting edge geometry, a tool with poor edge geometry fails quickly [30-31]. To accomplish high productivity with economy, cutting tool geometry has to be optimized. Heat generated in the cutting process is related to the cutting edge geometry. Cutting edge significantly affects the surface integrity of the work piece [22, 32-35]. As a whole, cutting tool edge preparation influences on the performance and reliability of the cutting tool.

Tugrul Ozel et al.[36] studied the effects of cutting edge geometry on surface roughness and cutting forces in turning of hardened AISI H13 steel and concluded that cutting edge geometry on surface roughness is significant and also cutting edge geometry influences the cutting forces. The author also states that honed edge geometry produces better surface finish. Authors Muammer Nalbant et al. [37] and Huges et al. [38] in their study stated that, in metal cutting process, cutting tool edge geometry significantly influences tool wear, tool life, chip formation, surface roughness, cutting force and cutting temperature.

In hard turning, tool geometry influences the following tool wear, surface finish, chip form, residual stress, cutting forces, heat generation, white layer and variations in micro hardness [39] as shown in the fig. 1.
Variation in tool geometry is one of the prime factor in enhancing surface integrity and tool life. The probable variations that can be made in the cutting tool are shown in the fig. 2. [39]. From the above literature study, it is obvious that by adopting proper tool cutting geometry variation, productivity is much improved in turning of hardened steel.

4. Minimum quantity lubrication
Generally hard turning is done in dry condition as it is believed that, due to high temperature it reduces the cutting force and in turn the power consumption of the machine tool. At the same time, surface integrity and tool life are affected by dry cutting. Recent survey on European automotive industries exposed that the cost of cooling lubricant nears 20% of the total manufacturing cost [40], which is more than the cost of cutting tools (7.5%). This factor forces the need to reduce the consumption of cutting fluids. Also, the governmental initiatives on environmental aspect, lead to a tighter regulations to force the industries to take pollution preventing measures to achieve eco-friendly manufacturing.

Finding a solution to satisfy both the extreme conditions of dry cutting and flooded wet cutting, emerges the concept of Minimum Quantity Lubrication (MQL). The usage of lubricant in MQL is very less, in the order of 50 to 500 ml/hour. This near dry lubrication is environmental friendly and reduces the hazards caused by the flooded cutting fluids in the shop floor. MQL reduces the handling cost of lubricant leading to reduction in cost and time.

As a recent advancement, using nano-lubricants in MQL proved to be an effective method to minimize the friction between the contact surfaces in machining. Nanoparticles dispersed in the coolant oil...
easily penetrate into the rubbing surface and gives better elasto-hydrodynamic lubrication effect [41]. Mohd Sayuti et al. [42] succeeded in using SiO$_2$ nano-lubricant in turning of AISI 4140 hardened steel. The author reports minimum tool wear and better surface finish achieved in the study.

5. Cryogenic cooling

Turning hard material involves high speed machining generating more heat, ending in shorter tool life and poor surface finish. Increase in tool work interface being the main cause for reduced tool life. The heat generated is removed by flooded coolant or minimum quantity lubrication (MQL) and thus reducing tool wear and increasing tool life. The use of cutting fluids is nowadays restricted due to the adverse health and environmental hazards, and also high cost of coolant, handling and disposal cost directed the researchers to look for other methods of cooling. Alternate to the traditional and MQL methods, usage of cryogenic fluids like liquid nitrogen (LN$_2$) emerged as new technology. Liquid nitrogen is inert, odorless, non-toxic, non-combustible gas satisfying the environmental requirements and also capable of achieving very low temperature (-196 °C).

The method of spraying liquid nitrogen directly on the cutting area, while machining, yielded better tool life [43, 44]. Many researchers reported reduction in cutting temperature [45-47] as the main advantage resulting in higher surface integrity and tool life. Increase in tool life [48-49] is observed by several authors as there is reduction in tool wear due to cryogenic cooling. Ghost et al. [49] investigated the effects of cryogenic cooling in machining of A2 hardened tool steel by alumina ceramic tool.

Comparing to flooded and dry cooling systems cryogenic cooling excelled in performance. Sunil Magadum et al. [50] evaluated the tool life and cutting forces in machining EN -24 steel having hardness 45 HRC with coated carbide insert in cryogenic cooling environment. The authors found that tool life increased up to 38.60% and the cutting forces are reduced up to 15.42%.

Garcia Navas et al. [51] studied about the surface integrity of AISI 4150 steel while turning in dry, wet and cryogenic cooling conditions and concluded that cryogenic cooling resulted in increased tool life and good surface integrity. Several authors are still doing research in cryogenic cooling and there is a lot of scope for further research.

6. Laser assisted hard turning

Laser assisted hard turning involves in heating the workpiece using laser and removing the material simultaneously. Heating the workpiece with laser beam takes place first and is followed by the cutting tool by a short gap. The material is softened by the laser irradiation and the tool that follows removes the material easily.

Ding H and Shin YC studied about laser assisted machining of hardened steel [52]. Laser assisted turning has its own limitations, that for removing the material a high power laser is required to induce the thermal softening and integrating a laser beam into the machine have become the challenging tasks.

7. Laser tempering based turning

The above process of laser assisted turning is decoupled into two steps in the laser tempering based turning, first the surface of material is softened by laser treatment through tempering process and then after cooling to room temperature, the material is removed by turning. Since the outer layer of the material is soft due to tempering, higher material removal rate can be achieved with the hard CBN tool. Otherwise a low cost ceramic tool can be used for turning.

Satyanarayanan Raghavan et al. [53]. experimented laser assisted turning of AISI 52100 hardened steel (63 HRC) with two cutting tools (a) Mixed alumina ceramic tool and (b) CBN tool and made the following conclusions. Ceramic tools can be used in place of high cost CBN tools resulting in almost same tool life and metal removal rate. In turning the hardened steel based on laser tempering high cutting speeds is possible leading to high metal removal rate. The authors also reported lower cutting forces in laser tempering based turning process.
8. **Acoustic emission controlled hard turning**
Several studies about tool wear were reported, and when the tool wears, it has to be replaced by a new tool. The time of changing the tool plays a major role in the production industries. To change a tool at right time needs monitoring of the tool wear. Monitoring the tool wear can be done in two ways, online or continuous method and offline or intermittent method.

Tool wear is accurately monitored by offline method, otherwise called direct method, but practically it has its limitations such as cutting fluid usage, illumination and possibility of accessing. Online or indirect methods of measuring are not accurate but practically possible to measure it. Some of the direct or offline methods of measuring tool wear are

(i) Optical
(ii) Radioactive and
(iii) Electrical resistance.

Indirect or online method involves in measuring the parameters such as cutting force, surface roughness, sound, vibration, temperature and acoustic emission (AE).

8.1 **Acoustic emission (AE)**
The spontaneous release of energy from the work material, when it undergoes a change from its original condition produces sound. Metal removing, corrosion, wear, shear are some of the acoustic emission generating processes. Acoustic Emission is one of the foremost techniques in monitoring tool wear [9].

Li X [54] explained acoustic emission as a wave of tension travelling through the material when there is a sudden release of tensile energy. Hase A et al.[55] correlated AE signals with wear mechanisms. It is evident from the literature survey that AE monitored hard turning will be helpful in the advancement of the hard turning technology and budding researchers have plenty of scope in developing this area.

9. **Conclusion**
It is evident from the review that, introduction of latest tools, cooling methods, monitoring systems, newer modeling techniques, tool geometry hard machining process attained new high in technological development. Still there is a possibility of developing newer tools with micro and nano coating technology resulting in more tool life, less economic and increased productivity. Dry and cryogenic cooling system have led to the pollution free environment, increased performance and reduced cost. Ultrasonic assisted turning, and AE monitored machining have given more control over the production process leading the metal cutting industries to a new higher level of performance.

In spite of these developments, turning of hardened materials such as D2, D3, M7, M35, M42, O1, O2 tool steels, which have hardness value above 60 HRC pose a challenge to manufacturing industries and there is a lot of scope in doing further research in the field of turning hardened materials.

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