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A Comprehensive Review on Machinability Aspects in Hard Turning of AISI 4340 Steel

S Roy, R Kumar*, R K Das and A K Sahoo

School of Mechanical Engineering, Kalinga Institute of Industrial Technology
Deemed to be University, Bhubaneswar, Odisha, India

E-mail: ramanujkumar22@gmail.com

Abstract. AISI 4340 steel is an alloy steel of nickel, molybdenum, and chromium with medium carbon content. It is known for its high toughness and the ability of further enhancement in strength by applying heat treatment condition. It is used in aircraft landing gear, oil and gas drilling, automobile industry and general engineering industries to manufacture heavy duty gears, shafts, pins, spindles, couplings, chucks etc. As it is a hard to machine material so many researchers are taking keen interest to study the effects of different machining environments and machining aspects on the machining performance of 4340-grade steel. The present paper presents a comprehensive review on important aspects associated to machining of 4340 grade steel using different cooling environments and cutting tools. Experimental and theoretical observations for tool wear, surface roughness, tool life, residual stress, machining force and cutting temperature using different types of cutting inserts under distinguish cooling environments are also been discussed.

1. Introduction

The AISI 4340 is a highly commercially utilized medium carbon low alloy steel which falls into the category of hard to cut material. In recent decades hard turning operation is mostly preferred for machining of AISI 4340 steel due to its high hardness value (45-60 HRC). It projects good balance of strength, wear resistance and toughness properties due to its alloying element for which it outcores the normal steel. [1]. It primarily treasures its application in manufacturing of aircraft landing gear, power transmission gears, shafts along with automobile industries to manufacture shafts, gears, bearings and cams which demands tight geometric tolerance, advanced surface quality and longer service life [2]. To implement AISI 4340 steel in above fields dry turning operation has been introduced which provides improved results regarding surface quality and maximum tool life [3]. The most commonly used coated tools are CVD coated carbide, PVD coated carbide, ceramic, CBN and PCBN tools. Using coated tool provides a longer life of the tool, better surface finish and lower machining temperature as compared to uncoated tool [4]. Machining under dry condition generates huge amount of heat at the tool-work specimen interface due to friction between tool and work material surface which highly affects the surface quality of work material and tool life [5]. So for the reduction of frictional force and competent removal of heat from the machining zone the use of coolant plays a vital role. During MQL technique the coolant is directly applied over the machining zone which provides easy removal of heat from the tool-workpiece interface. MQL technique not only removes the heat generated during machining but it also provides better machining performances than dry machining condition [6]. Due to heat generation at the machining zone, the surface topography of the workpiece is altered. To prevent these phenomena cryogenic cooling is being introduced. As using



cryogenic cooling the heat generation at the machining zone is very less, the change in microstructure is negligible as compared to other cooling environments. Using cryogenic cooling technique with MQL environment provided the best surface finish and longer tool life among other cooling environments [7].

In the present paper, efforts have been made to present a brief literature review on turning operation of 4340-grade steel using different coated insert under different cooling environments (dry, cryogenic and MQL). Figure 1 presents the aspects of study covered in the present review work and Table 1 describes the chemical constituent of grade 4340 steel. This literature review also describes the relationship between different machining parameters with different machining performances as surface finish, wear of the tool and tool life.

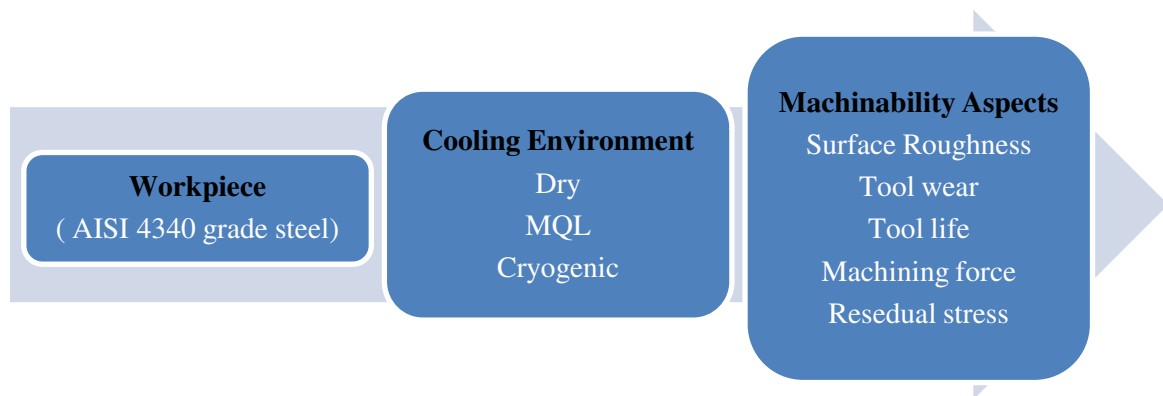


Figure 1. Schematic view of machining aspects

Table 1. Chemical constitution of 4340 grade steel [7]

Ni	Mn	S	Si	Cr	P	C	Fe
1.8	0.70	0.04	0.25	0.8	0.035	0.41	Balance

2. Cutting performance analysis in various cooling environments

In present days, due to the growing demand for an eco-friendly and cost effective machining process, green machining technique came into huge existence. Green machining technique mostly involves dry machining, MQL, spray cooling, compressed air cooling and cryogenic cooling machining environments. Many researchers investigated the role of dry, MQL and cryogenic cooling environment during turning operation of grade 4340 steel.

2.1. Dry machining environment

Due to the growing demand for machining of hard and tough steels, dry turning operation came into existence because of its better machining performances while turning difficult to machine materials. Dry turning operation is used to machine harder materials using mostly coated insert without application of lubricants or coolants [3]. Satish Chinchanikar and S.K. Choudhury observed that life of the tool was mostly affected by the hardness of the work specimen. CVD coated tool displayed longer tool life as compared to PVD coated tool. Adhesion and abrasion at the tool work specimen interface were found to be most predominant wear mechanism factor followed by notch wear and chipping of the coated layer from the tool surface [4]. Varun Sharma and P.M. Pandey studied the machining parameters which affect the residual stress generated during turning operation of grade 4340 steel. It was found that residual stress generation was only dependent on machining speed and feed rate whereas the depth of cut had the negligible effect on hoop residual stress [8]. R. Suresh et al. found that the best possible combination of low depth of cut, low feed rate and high machining speed resulted in lesser machining force and higher feed rate minimized the specific machining force. The increment in machining tool wear and machining force were found linear with increase in feed rate

and machining speed. During every machining condition the abrasion was the prime wear mechanism on the tool surface [9]. Ashok Kumar Sahoo and Bidyadhar Sahoo experimentally investigated machining under dry condition and concluded that machining speed directly controls the wear and life of the tool. Longer tool life and lower wear of the tool was achieved at lower machining speed. Best parametric combination for machining was obtained at machining speed (150m/minute), depth of cut (0.4 millimeter) and feed (0.15m/minute) [10]. R. Suresh et al. ascertain that increase in machining force was directly proportional with increase in depth of cut and feed rate during turning operation. Best machining performance was achieved at a combination of low depth of cut, low feed rate and short machining time along with high machining speed [11]. Reginaldo T. Coelho et al. observed that by using TiAlN nano coating over PCBN tool can extend the life of the tool by 38%. Machining force and surface roughness were found maximum using the uncoated tool during turning operation of grade steel [12]. Virginia Garcí'a Navas studied that as the feed increases the residual stress lean to become more tensile and the surface quality deteriorates with increase in machining feed. The residual stress was found to be less tensile at a medium machining speed range of 200 to 300 m/minutes [13].

2.2. *Minimum quantity lubrication*

A huge amount of heat is being generated during dry turning operation at the machining zone due to the friction between tool and work specimen surface. So to achieve improved surface quality and minimize the heat generation, the use of coolant becomes very necessary. Thus MQL technique is used to fulfill all the demands which were not achieved during dry turning operation [5,6]. N.R. Dhar et al. experimentally found that the machining performance using MQL was best as compared to dry and flooded condition during turning operation of 4340-grade steel. Using MQL environment also resulted in better surface finish, longer life of the tool and lower wear of the tool surface [14]. According to Kedare et al. MQL technique can become the best alternative for traditional flooded cooling method during milling operation of grade steel because of it consumes lesser coolant. MQL technique provided both economic and ecological benefits as the coolants are eco friendly and its consumption during machining was found only 900 ml/hour which is very minimal when compared with conventional cooling methods [15]. Sanjeev Kumar et al. compared the machining performance during turning operation of AISI 4340 grade steel using different machining environments (dry, wet and MQL). Using MQL environment resulted in around 7%-10% increase in surface finish and greatly reduced the wear of the tool tip [16]. D.V. Lohar and C.R. Nanavaty tried to evaluate the machining performance of MQL condition during turning operation of AISI 4340 grade steel. Experimental results showed that while using MQL environment, the machining force and machining temperature got reduced by around 40% and 36% respectively as compared to dry machining condition. Surface finish was also found to be better as compared to other machining conditions [17]. Nikhil Ranjan Dhar et al. found that using MQL environment during turning operation reduces the wear of the tool, enhances the surface quality of the workpiece and increases the life of the tool. MQL also provided benefits like reduction of machining temperature and maintaining the sharpness of machining edges [18]. L. R. Silva et al. found that using MQL technique significantly reduced the diametric wear and surface roughness value. As compared to other traditional cooling methods, reduction in tangential machining force during machining of grade steel was maximum using MQL environment [19].

2.3. *Cryogenic environment*

Cryogenic environment further decreases the heat generated at the machining zone and the work specimen microstructure is hardly affected during the machining operation. So using cryogenic environment allows high speed machining even using higher machining parameters [7]. Mirghani I. Ahmed researched to increase the effectiveness of cryogenic cooling environment by modifying the tool holder. It was observed that using customized tool holder during cryogenic environment was extra effective when the coolant out flow was directed away from the machining edge of the cutting insert.

Table 2. Summary of types of coolant and its effects on machining performances

Ref.	Year	Cooling environment	Process parameters			Response
			Cutting Speed (m/min)	Feed (mm/rpm)	Depth of cut (mm)	
4	2013	Dry	100,300	0.1,0.2,0.3	1.5	Wear mechanism, machining force, surface roughness, tool life
8	2016	Dry	10 - 90	0.1 - 0.3	0.1 - 0.5	Residual stress, hoop residual stress
9	2012	Dry	140,200,260	0.10, 0.18, 0.26	0.6, 0.8, 1	Surface roughness and Tool wear
10	2012	Dry	150	0.15	0.4	Wear mechanism, machining force
11	2012	Dry	80,140,200 260	0.10,0.18,0.26	0.8,1,1.2	Machining force, tool wear, surface roughness
12	2007	Dry	150	0.07	0.2	Machining force, surface roughness, tool life
13	2012	Dry	200,255,300	0.075,0.1,0.125	0.4	Residual stress, thermal stress, surface roughness
14	2006	MQL	110	0.16	1.5	Tool wear,surface roughness
16	2017	MQL	75,100,125,	0.1,0.125,0.15	0.2,0.4,0.8	Surface quality
17	2013	MQL	40,80,120	0.05,0.075, 0.10	0.5,1.0	Cutting force, cutting temp, surface finish
18	2007	MQL	63, 80, 95, 110,128	0.1, 0.13,0.16, 0.2	1, 1.5	Tool wear, surface roughness
19	2005	MQL	20	1	0.1	Surface roughness, tool wear
21	2017	Cryogenic	50,150,250	0.045,0.90.135	0.2,0.4,0.6	Surface roughness

The freshly modified tool holder resulted in better surface quality, reduction in coolant consumption and longer life of the tool even at higher machining speed [20]. Sanchit Kumar Khare and Sanjay Agarwal found that the depth of cut and machining speed were the most influencing factors on the surface roughness. Experimental results proved that cryogenic environment generated better surface quality than dry machining environment [21]. Khalid A Al-Ghamdi et al. studied the machinability of AISI 4340 steel under cryogenic cooling environment using CO₂ snow as coolant. It was observed that machining speed and feed rate were the prime factors affecting the machining performances and longer life of the tool was only ensured at a lower combination of machining parameters (machining speed and feed rate) [6]. The different types of the coolant used by the various researchers and its effect on the machining performance are mentioned in Table 2.

3. Performance analysis of different cutting tools

Modern machining operation demands for machining tools with enhanced properties, especially to achieve improved surface quality. The relationship between physical, chemical and mechanical properties of machining operation acts as the key factors for both uses and the machining tool manufacturers. Many researchers studied the performance of ceramic, CBN and coated carbide tools during machining of 4340-grade steel [9]. Satish Chinchankar and S.K. Choudhury came to a conclusion that the life of the tool was mostly affected by workpiece hardness, depth of cut and machining speed. The longer service period of the tool was obtained using CVD coated tools nose wear and flank wear was found to be the prime wear mechanism for wear of the tool surface [4]. Ashok Kumar Sahoo and Bidyadhar Sahoo found that TiN coated tool have longer service period as compared to ZrCN and uncoated carbide tool during turning operation. From the experimental results it was proposed that hard turning of grade 4340 steel using ZrCN and TiN can be done ever at a higher machining speed of 150 m/minutes [10]. Many researchers investigated on the wear mechanism and surface roughness of the workpiece during turning operation using different types of coated tools. They came with a conclusion that machining parameters and the nature of the coated material over the tool surface mainly influences the surface quality of the workpiece [21,22,23,24]. Anshuman Das et al. experimentally found that using coated cermet tool during turning operation helped in reducing wear of the tool, machining temperature and machining force as compared to uncoated carbide tool [25].

Summary of investigation on machining tools during turning operation is presented in Table 3.

Table 3. Summary of various machining tools during turning operation

Ref	Year	Tool	Workpiece hardness (HRC)	Response	Findings
4	2013	CVD coated carbide, PVD coated carbide	35 and 45	Wear mechanism, machining force, surface roughness, tool life	CVD coated tool performed better at lower speed, PVD coated tool performed better at higher speed
9	2012	(TiN/TiCN/Al ₂ O ₃) CVD coated cemented carbide	48	Surface roughness and Tool wear	Machining speed and feed rate highly influence machining force
10	2012	Uncoated carbide, CVD coated carbide	47±1	Wear mechanism, machining force	Longer tool life and better surface quality using coated tool,
14	2006	SNMM 120408 carbide	–	Tool wear, surface roughness	Reduction in tool wear, longer tool life, better surface finish using MQL

16	2017	K5625 CBN tool	45	Surface quality	Surface finish enhanced by 7-10%
17	2013	TNMA160404 Grade PB250 CBN	45 ~ 55	Cutting force, cutting temp, surface finish	Improvement in Ra, Decrease in machining force and temperature
18	2007	SNMM 120408 carbide	–	Tool wear, surface roughness	Improvement in tool life, tool wear and surface finish
21	2017	HSS T-42, S-400	–	Surface roughness	Surface roughness was better in cryogenic
23	2013	MT KB 5625 CBN	45	Machining force, Surface finish	Machining environment and depth of cut highly effect the machining force
31	2006	TiN (CVD) coated, PCBN compact	53	Surface roughness, tool wear, life of the tool	Machining performance of PCBN was found better than TiN (CVD) coated tool
32	2014	TiC mixed alumina ceramic	35, 45, 55	Surface roughness, machining temperature, machining force	Machining force increases with increase in depth of cut, feed and specimen hardness
33	2008	CBN grades 7020 and 7050	56	Wear of the tool, life of the tool	Tool life was longer in interrupted machining as compared to continuous machining
34	2009	PCBN, silicon carbide reinforced ceramic	56	Life of the tool, wear of the tool	Surface finish was better using PCBN tool

4. Analysis of Surface roughness

Surface roughness is an important index for machinability of any cutting operation. As in every manufacturing industry surface finish is given maximum priority, many researchers investigated on machining parameters which affect the surface roughness of the work specimen [14]. Sanchit Kumar Khare and Sanjay Agarwal investigated on machining parameters which affect the surface roughness during turning operation of 4340 grade steel using cryogenic cooling environment. Experimental results suggested that surface roughness was mostly dependent on the machining speed and depth of cut [21]. Sanjeev Kumar et al. experimentally found that using MQL environment during turning operation resulted in 7-10% enhancement in surface finish as compared to other cooling environments. The reduction in machining temperature and lower wear of the tool were the prime factors for improvement in the surface quality of the work specimen [16]. Using MQL environment resulted in thinner chips formation during machining operation which reduces the frictional force produced between the tool-chip interface, which added further enhancement in surface quality of the workpiece [17, 23]. Bailey et al. observed that initially the surface roughness increases continuously with increase in machining speed for some extent and then it became independent of machining speed with further increment in machining speed. Sudden damage on the machined surface arises due to discontinuous chip formation during machining operation [24]. Nilrudra Mandal et al. studied the surface roughness produced during turning operation of 4340-grade steel using coated alumina tool. During experiment best surface finish was obtained at a machining parameter combination of machining speed 420 m/minute, depth of cut 0.5 millimetre and feed rate 0.24 mm/revolution [26].

Machining insert nose geometry along with feed rate was found to strongly affect the surface roughness values in the turning operation [27]. Most of the researchers found that during turning operation of 4340 grade, the main machining parameters which alter the surface roughness were machining speed, depth of cut and feed rate [28,29,30].

5. Conclusion

In this review paper efforts are being made to present a brief description on turning operation of AISI 4340-grade steel using different machining tools in different cooling environment (Dry, MQL and Cryogenic). This paper also depicts the affect of different machining parameters and cooling environments on surface roughness of the work specimen. Due to the growing demand for eco-friendly and cost efficient machining process, many researchers are taking a keen interest in new cooling environments so the comparison between different cooling conditions are presented in this review paper.

- Best possible combination of low depth of cut, low feed rate and high machining speed resulted in smaller machining force and higher feed rate minimized the specific machining force. The increment in machining tool wear and machining force were found linear with increase in feed rate and machining speed. For every machining condition the abrasion was the major wear mechanism on the tool surface.
- During turning operation with TiN and ZrCN coated carbide tool, longer tool life and lower wear of the tool was achieved at lower machining speed. Best parametric combination for machining was obtained at machining speed (150 m/min), depth of cut (0.4 mm) and feed (0.15 m/min).
- CVD coated insert displayed longer tool life as compared to PVD coated insert. Adhesion and abrasion on the tool work specimen interface were found to be most predominant wear mechanism factor followed by notch wear and chipping of coated layer from the tool surface.
- Using MQL cooling condition resulted in the better surface finish, lower wear of the tool and longer tool service life as compared to dry machining condition. Cryogenic cooling environment displayed maximum heat removal rate from the machining zone during turning operation and best cooling condition was achieved under hybrid (Cryo + MQL) environment for short machining time.
- Machining environment highly controls the quality of the machined surface and it was found to be mostly dependent on machining speed followed by feed and depth of cut.

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