Study of Chip Formation in Hard Turning of AISI 4340 Alloy Steel in Different Cutting Environments

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***Abstract* - The hardened alloy steel like AISI 4340 is known to be difficult to cut material. In order to increase the flexibility and ability to manufacture complex geometry's, hard turning was introduced where the necessity of grinding operation can be eliminated. Generally hard turning requires large quantities of coolants and lubricants. The cost of procurement, storage and disposal of coolants and lubricants increases the total cost of production.**

In the present study minimal quantity lubrication (MQL) is used for cooling in turning of hardened alloy steel AISI 4340 with CBN insert. The effect of MQL environment on chip formation is studied and compared with dry and wet environment. The experiments were conducted using Taguchi L_{18} (2' x 3^7) mixed orthogonal array. It is observed that the chip thickness in turning of hardened AISI 4340 in MQL gives the higher cutting ratio than dry and wet turning. MQL turning gives acceptable chips that can handle easily.

The cost of procurement, storage, reconditioning and disposal of coolants and lubricants can highly reduce which reduces the total cost of production considerably. This technique can form a viable alternative to conventional wet turning, as it can be implemented without any drastic alternations in existing facilities available on shop floor.

Keywords - AISI 4340 steel, Hard turning, chip formation, Taguchi method.

I. INTRODUCTION

The challenge of modern machining industries is mainly focused on the achievement of high quality, in terms of work part dimensional accuracy and surface finish, high production rate and cost saving, with a reduced environmental impact. The conventional method of manufacturing a component has the following sequences namely soft machining, heat treatment, rough turning and fine grinding. Now a days the trend is towards the lower cost, higher quality and flexibility. In order to increase the flexibility and ability to manufacture complex geometry's, hard turning was introduced where the necessity of grinding operation can be eliminated. Hard turning is the process of turning of the workpeice having hardness 45 HRC to 60 HRC. In hard turning, rough machining, final grinding can be eliminated and raw material is supplied in the final heat-treated condition. Hard turning can seriously be regarded as an alternative for grinding operations under certain circumstances. In most cases hard turning leads to substantial cost reduction in manufacturing, and therefore hard turning operations are developing wide applications in industry [1]. Commonly hard turned materials are hardened steel alloys such as tool steels, die steels and high speed steel. The hard turned parts are widely used in automotive, bearing, machine tool, die, and aerospace.

Generally hard turning requires large quantities of coolants and lubricants. The cost of procurement, storage and disposal of coolants and lubricants increases the total cost of production considerably. Conventional cutting fluid application fails to penetrate the chip-tool interface and thus cannot remove heat effectively. Addition of extreme pressure additives in the cutting fluids does not ensure penetration of coolant at the chip –tool interface to provide lubrication and cooling. However, high pressure jet of soluble oil, when applied at the chip –tool interface, could reduce cutting temperature and improve tool life to some extent. However, the advantages caused by the cutting fluids have been questioned lately, due to the several negative effects they cause. When inappropriately handled, cutting fluids may damage soil and water resources, causing serious loss to the environment. Therefore, the handling and disposal of cutting fluids must obey rigid rules of environmental protection.

For the companies, the costs related to cutting fluids represents large amount of the total machining costs. The review of the literature clears that the cost related to cutting fluids are frequently higher than those related to cutting tools. Consequently, elimination on the use of cutting fluids ,if possible, can be significant economic incentive .Considering the high cost associated with the use of cutting fluids and projected escalating costs when the stricter environmental laws are enforced. Because of them some alternatives has been sought to minimize or even avoid the use of cutting fluid in machining operations. Some of these alternatives are dry machining, machining with minimal fluid application and cryogenic cooling. Minimal fluid application refers to the use of cutting fluids of only a minute amount typically of flow rate of 50 to 500 ml/hour. The concept of minimal fluid application sometimes referred to as near dry lubrication or micro lubrication [2].

Present work deals with the comparative performance of CBN tool in machining hardened alloy steel AISI 4340 in conventional dry turning and wet turning with minimal fluid application method by varying parameters such as speed and feed , depth of cut and tool geometry. The chip formation is analyzed by applying Taguchi Method and ANOVA.

II. LITERATURE REVIEW

Many authors have been studied the performance in machining of different materials with dry, wet, MQL and cryogenic cooling. The review of the literature suggests that minimal fluid application provides several benefits in machining.

A. Minimum Quantity Lubrication (MQL)

The specific function of the cutting fluid in the machining process is to provide lubrication and cooling to minimize the heat produced between the surface of the part and tool. Minimum Quantity of Lubrication (MQL) is an alternative, to reduce the tools friction and to prevent the adherence of material. In MQL small amount of lubricant is pulverized in a compressed air stream. The consumption of the fluid usually less than 300ml/hr.The advantages of MQL are -:

- less polluted,
- labor costs are reduced while disposal,
- cycle time of cleaning of machine tool/ work piece/ tool is less
- During machining the working area is not flooded so if necessary the cutting operation can be observed easily.

The positive effect of the use of fluids in metal cutting was first reported by F. Taylor, (1894) who noticed that by applying large amounts of water in cutting area, the cutting speed could be increased up to 33 % without reducing tool life. However the costs associated mainly with fluid handling, recycling and disposal are leading to alternatives such as new tool material and coating which allows dry machining and application of small quantities of fluid as mist spray. Machining cost is another relevant aspect to be considered .The costs associated with the use of cutting fluids represent approximately 17.5 % of the finished workpiece cost against 4 % spent with tooling [3].

1) Cutting Forces

P.K. Philip et al., (2001) reported the overall performance of the cutting tools during minimal cutting fluid application was found to be superior to that compared to dry turning and conventional wet turning on the basis of parameters such as cutting force, temperature and surface finish [4].

2) Surface Roughness

Surface finish is one of the important output of machining. The performance and service life of the machined/ground component are affected by its surface finish. MQL gives better surface finish than the dry and flood cutting irrespective of cutting velocity feed rate and length of cut [5].

The experimental study of Silva et al., (2005) results indicated that the MQL technique can be applied efficiently in plunge cylindrical grinding operation. The R_a value substantially reduced with use of MQL and the aluminum oxide grinding wheel provide a better surface finish than CBN wheel [6].

B. Turning of AISI 4340 steel

1) Cutting Force

L.G.Lima et.al., (2005) studied the machinability of hardened AISI 4340 of different hardness values ; 42 HRC and 50 HRC with using coated carbide and PCBN tools. It is observed that the machining forces were reduced as cutting speed was increased and increase with feed rate and depth of cut. For low feed tares and depths of cut the forces observed to 42 HRC were higher than when machining the 50 HRC steel [7].

2) Surface Surface

Federico M.Aneiro et al.,(2008) reported surface roughness values obtained in turning with coated carbide are similar to those normally obtained by normal grinding. It was also observed that feed rate was the most significant parameter affecting surface roughness [8] .

R.F. Avila et al (2001) studied the effect of cutting fluids on the machining of hardened AISI 4340 steel with different cutting fluids like fluid A(emulsion without mineral oil),fluid B (synthetic oil) and fluid C (Emulsion with mineral oil) .It was observed that the use of cutting fluid was responsible for surface finish. For a cutting speed of 200 m/min , the lowest R_a value and the narrowest scatter was provided by fluid C closely followed by dry cutting. Nevertheless, when the cutting speed was increased, the absence of cutting fluid was detrimental to the surface finish resulting in larger scatter despite the low *Ra* values at v_c = 300 m/min. At higher cutting speeds, the use of cutting fluids resulted in lower scatter in the *Ra* values [9].

L.G.Lima et.al.,(2005) observed that the surface finish of the machined part was improved as cutting speed was elevated and deteriorated with feed rate. Depth of cut was little effect on the R_a values. Best surface finish was produced by the cutting to with larger nose radius (PCBN) [8].

3) Chip Formation

The form of the chip produced is one of the major parameter influencing productivity in metal cutting industry. According to Kaldor et.al, (1979) there are two types of chip forms 1) acceptable chips and 2) unacceptable chips , based on the convenience of handling. Acceptable chips do not interface with work or tool and do not cause problems of disposal. Unacceptable chips interrupt regular manufacturing operation, as they tend to tangle around the tool and workpiece and pose safety problems to operators. These chips can lead to unexpected surface finish and tool wear. Chip formation mechanism in turning of hardened steel AISI 4340 is influenced by the machining process and cutting environment. The main factor which largely governs the chip formation is the cutting environment which governs the temperature condition in the shear zone [10].

III. EXPERIMENTAL WORK

In the present work an attempt has been made to study the effect of minimal quantity lubrication (MQL) turning of hardened alloy steel AISI 4340 by CBN insert on cutting force components, surface finish and its comparison with dry and wet turning. In addition to the cutting environments the process parameters used in the work are cutting speed, feed rate, depth of cut and tool related parameter as nose radius. The response variables selected to achieve better machining and tool performance are chip form and chip thickness ratio. The experiments were conducted using standard L_{18} (2^1 x 3^7) Taguchi mixed Orthogonal Array.

A. Workpiece Material

The workpiece material used is hardened alloy steel AISI 4340 with diameter 50 mm and 150 mm working length. The material is hardened upto 45 HRC by tempering heat treatment.

B. Cutting Tools and Tool Geometry

For turning CBN insert which contains 50% CBN and TiC binder is selected. The insert is having grade MT KB 5625 which was clamped on tool holder PCLN L 2525 M12. Two Cubic Boron Nitride (CBN) cutting tool inserts are used for turning operations. Both are having chamfered and honed tool geometry. One is having tool nose radius 0.4 mm and other having 0.8 mm.

1) Specification of insert

ISO designation: CNGA 12 04 08 S 0 1025 and CNGA 12 08 08 S 0 1025
Grade : KB 5625
Make : Kennametal India Ltd.
Tool Geometry : Chamfered and honed
Material : Cubic Boron Nitride (CBN)

2) Specification of tool holder

ISO designation : PCLNL 2525 M 12
Make : Kennametal India Ltd.
Principal cutting edge angle : 95°
Orthogonal rake angle : -6°
Clearance angle : 0°

C. Cutting Fluid and it's Application

Since the quantity of cutting fluid used in this method is very low (5 ml/min), specially formulated cutting fluid is used. The base oil is commercially available mineral oil. The oil is properly formulated by adding additives such as surfactant, evaporator, emulsifier; stabilizer etc agents. The oil is available commercially in formulated form. A special fluid supply system is designed to maintain the fluid supply as 5 ml/min as shown in Fig.1. It consist of a lubricator which is used in pneumatic system to regulate the fluid supply. This lubricator has the capacity of 0.5 litre. The inlet port of the lubricator is connected to the compressor which supplies the air with 6 bar pressure. The mist air coming out from the lubricator is used as cutting fluid. The lubricator knob is adjusted such that the oil flow rate is 5 ml/min.

D. Machine Tool

A high speed precision CNC Lathe (Jobber XL Make, Model NH 22) having 7.5 HP electric motor and 5000 rpm was used for experimental work.

The cutting parameters like feed rate, cutting speed, depth of cut are changed in three different levels and cutting environmental conditions are also changed in three levels like dry, wet and MQL. The nose radius of the insert is changed in two levels. The inserts are having two different nose radii and the tool geometry is chamfer and honed.

E. Design of Experiment

In this study, Taguchi's design of experiment was used to determine optimal machining parameters for minimum cutting force and minimum surface roughness value in MQL turning of AISI 4340 with CBN insert. The experiments were conducted using standard L_{18} (2^1 x3^7) Taguchi mixed

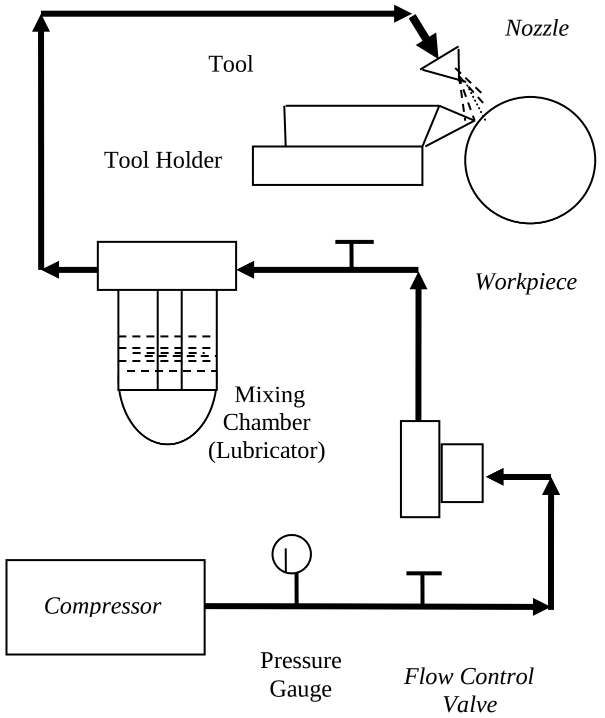


Fig. 1. Schematic line diagram of experimental set up showing Minimal Fluid Delivery Unit

orthogonal array. According to the array eighteen experiments were conducted as per selected orthogonal array. Table no.I shows the orthogonal design matrix and coded values used during experiment.

F. Selection of input Factors and their levels

It is therefore seen that there are various factors which directly or indirectly influence the performance of cutting tool and cutting force magnitude in turning of hardened AISI 4340 steel with CBN insert.

1) Input Factors

In this experiment study, five parameters as cutting speed, feed rate, and depth of cut,
tool nose radius and supply of coolant were selected as input factors for the present work. Table no. II shows the input factors and their levels.

TABLE 1 SELECTED STANDARD L_{18} (2^1 x3^7) ORTHOGONAL ARRAY WITH CODED AND ACTUAL VALUES USED FOR THE EXPERIMENT.

Expt. No. (Sample No.)	Coded Values								Actual Valus				
	A	*B*	*C*	*D*	*E*	*e**	*e**	*e**	*A*	*B*	*C*	*D*	*E*
1	1	1	1	1	1	1	1	1	0.4	0.25	100	0.08	Dr
2	1	1	2	2	2	2	2	2	0.4	0.25	120	0.09	W
3	1	1	3	3	3	3	3	3	0.4	0.25	140	0.1	M
4	1	2	1	1	2	2	3	3	0.4	0.35	100	0.08	W
5	1	2	2	2	3	3	1	1	0.4	0.35	120	0.09	M
6	1	2	3	3	1	1	2	2	0.4	0.35	140	0.1	Dr
7	1	3	1	2	1	3	2	3	0.4	0.5	100	0.09	Dr
8	1	3	2	3	2	1	3	1	0.4	0.5	120	0.1	W
9	1	3	3	1	3	2	1	2	0.4	0.5	140	0.08	M
10	2	1	1	3	3	2	2	1	0.8	0.25	100	0.1	M
11	2	1	2	1	1	3	3	2	0.8	0.25	120	0.08	Dr
12	2	1	3	2	2	1	1	3	0.8	0.25	140	0.08	W
13	2	2	1	2	3	1	3	2	0.8	0.35	100	0.08	M
14	2	2	2	3	1	2	1	3	0.8	0.35	120	0.1	Dr
15	2	2	3	1	2	3	2	1	0.8	0.35	140	0.08	W
16	2	3	1	3	2	3	1	2	0.8	0.5	100	0.1	W
17	2	3	2	1	3	1	2	3	0.8	0.5	120	0.1	M
18	2	3	3	2	1	2	3	1	0.8	0.5	140	0.09	Dr

e* =empty column

A – Nose Radius (mm)	1. 0.4	2. 0.8	
B – Depth of Cut (mm)	1. 0.25	2. 0.35	3. 0.5
C-- Cutting Speed (m/min)	1. 100	2. 120	3. 140
D-- Feed (mm/rev)	1. 0.08	2. 0.09	3. 0.1
E-- Enviromental condition	1. Dry - Dr 2. Wet - W 3. MQL- M		

Selection of Response Variables

It is seen from past work that the performance of cutting tool is evaluated in terms of surface finish, cutting force. Hence chip formation and chip thickness ratio are selected as response variables for this study. Other machining parameters were kept constant during the experiment.

As we know that the chip thickness ratio and chip formation are depends on quantity of coolant supply and other cutting parameters. It is necessary to correlate the machining parameters, which produce machined component with low surface roughness and chip formation. Being oblique cutting process, three force components namely axial (feed), radial (thrust) and cutting force were also selected in this study.

TABLE II INPUT FACTORS AND THEIR LEVELS

Factors	Machining parameter	Unit	Level		
			1	2	3
Variable	Tool Nose Radius	mm	0.4	0.8	
	Cutting Speed, V	m/min	100	120	140
	Feed Rate, f	mm/rev	0.08	0.09	0.1
	Depth of Cut, d	mm	0.5	0.75	1.0
	Environmental condition		Dry	Wet	MQL
Fixed	Tool geometry (clearance angle= 0° -, 80° rhombus shape, nose radius = 0.8 mm, back rake angle = -6°, approach angle=95°, side cutting edge=5°)				
	Tool material (CBN inserts)				

G. *Experimental Procedure*

The cylindrical workpiece of alloy steel 4340 having dia. 50 mm and length 150 mm was mounted on rigid CNC lathe machine with tail stock support. A CBN insert with MT KB 5625 grade was clamped on tool holder PCLN L 2525 M12 that was mounted on the top plate of the Kistler dynamometer. The forces were measured online and recorded on computer with Kistler dynamometer and dynaware software. Chip thickness was measured with micrometer.

The experiments were performed randomly as per the L_{18} orthogonal array (see Table III). Before starting first experiment the workpiece was prepared for experiment and the turning length was selected as 30 mm. Then the machining parameters were selected according to the first experiment data on CNC lathe machine. For every new experiment, the next 30 mm of the work piece was used. Thus on a work piece of 150 mm three experiments were conducted .After each set of three experiments new workpice of same dimensions was used. After completing the experiment the roughness value was measured by Mitutoyi surface Tester.

TABLE III RANDOMIZATION

Run Order	Sample No.	Control Factor Levels allotted to columns				
		A	B	C	D	E
1	17	2	3	2	1	3
2	9	1	3	3	1	3
3	5	1	2	2	2	3
4	13	2	2	1	2	3
5	10	2	1	1	3	3
6	3	1	1	3	3	3
7	7	1	3	1	2	1
8	18	2	3	3	2	1
9	6	1	2	3	3	1
10	14	2	2	2	3	1
11	11	2	1	2	1	1
12	1	1	1	1	1	1
13	16	2	3	1	3	2
14	8	1	3	2	3	2
15	4	1	2	1	1	2
16	15	2	2	3	1	2
17	12	2	1	3	2	2
18	2	1	1	2	2	2

IV. RESULT AND DISCUSSION

The analysis of experimental data was performed in order to determine the effect of cutting speed, feed rate, nose radius, depth of cut and cutting environment on the magnitude of cutting force components, surface roughness and chip formation. Statistical analysis was performed using MINITAB 15 software. The analyzed results are presented using mean effects plots.

A. Statistical Analysis of chip thickness ratio

The chip thickness ratio is the index of the frictional conditions existing at the tool chip interface. A higher chip thickness ratio implies better lubrication at the tool chip interface and formation of chips of thinner sections. It is observed from the ANOVA (see Table IV) that the no one parameter is statistically significant at *95%* CI. The cutting environment shows less statistical significance (93 % CI) on the chip thickness ratio.

1) Effect of nose radius on chip thickness ratio

It is seen from the factor effects plots (Fig. 8) that the nose radius has the linear effect on chip thickness ratio. The chip thickness ratio increases from 0.48 with the 0.4 mm nose radii to 0.51 with nose radii 0.8 mm.

2) Effect of depth of cut on chip thickness ratio

As depth of cut increases from 0.25 mm to 0.35 mm, there is decrease in chip thickness ratio from 0.51 to 0.46. Further as depth of cut increases from 0.35 mm to 0.5 mm there is rise in the chip thickness ratio from 0.46 and it reaches up to 0.51.

3) Effect of cutting speed on chip thickness ratio

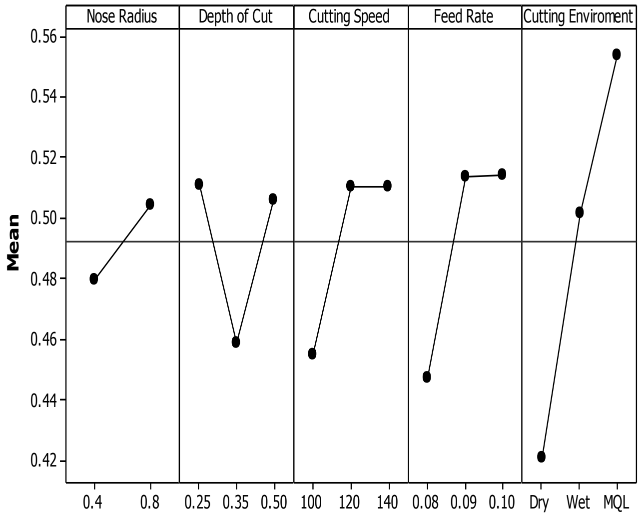
It is observed from main effects plots (Fig. 2) that, as cutting speed increases from 100 m/min to 120 m/min, chip thickness ratio increases from 0.45 to 0.51. But, as cutting speed increases from 120 m/min to 140 m/min the chip thickness ratio almost remains constant.

4) Effect of feed rate on chip thickness ratio

It is observed that the feed rate has the similar effect on chip thickness as that of cutting speed. As the feed rate increases from 0.08 mm/rev to 0.09 mm/rev, the chip thickness ratio increases from 0.44 to 0.51. But further increase in feed rate from 0.09 mm/rev to 0.1 mm/rev, the chip thickness ratio almost remains constant.

TABLE IV ANOVA FOR CHIP THICKNESS RATIO

Source of variance	Sum of Squares (SOS)	Degrees of Freedom (DOF)	Variance (MS)	F Ratio α = 5%	P Value
Nose Radius (R)	0.00278	1	0.00278	0.37	0.561
Depth of Cut (d)	0.0100	2	0.005016	0.66	0.541
Cutting Speed (V)	0.0122	2	0.006109	0.81	0.479
Feed Rate (f)	0.0177	2	0.00883	1.18	0.357
Cutting Enviroment(Ev)	0.0537	2	0.0268	3.56	0.079
Error	0.060	8	0.00755		
Total	0.1569	17			
S = 0.8689	R.Sq = 61.50 %		R –Sq(adj) = 18.19 %		



. Fig. 2. Main effects plots for chip thickness ratio

5) Effect of cutting environment on chip thickness ratio

The chip thickness ratio is the index of the frictional conditions existing at the tool chip interface. A higher chip thickness ratio implies better lubrication at the tool chip interface and formation of chips of thinner sections. It is observed that the chip thickness ratio in MQL is much better than that of in dry and wet turning**.** During MQL the cutting fluid is fragmented into tiny globules, which is reached upto tool-chip interface. The high velocity results the better penetration of cutting fluid to the underside of the chip (Fig. 3) .This creates its passage to reduce the friction between tool and chip. The reduction in friction results in increase in chip thickness ratio. Such condition is not prevailed in wet turning because there is no such fragmentation phenomenon since velocity and pressure in wet turning is less than MQL. Hence in case of wet turning chip thickness ratio is less followed by dry turning.

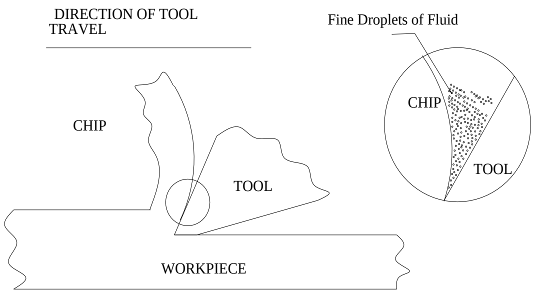
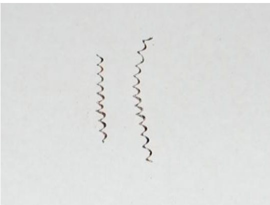


Fig.3. Penetration of cutting fluid to underside of the chip.

B. Analysis of Chip Formation

It is observed that tightly coiled chips are formed during wet turning and during MQL that could handled easily where as long snared chips are prevalent during dry turning. The chips formed during MQL were similar to that during wet turning in spite of fluid application rate which only 0.05 % of that in wet turning. It is clear that MQL promotes acceptable chips that can handle easily. Figure No. 4 to 6 shows the photographs of chips for eighteen experiments.

Chip changes its form from continuous to saw tooth type when the cutting speed crosses the threshold value and enters in the high-speed machining range. The deformation is non-homogeneous and twin deformation regions are formed, one is with pure deformation and other is no deformation at all, therefore pure narrow, concentrated shear band formation results and chips are saw tooth type. When the machining was done MQL environment the chips were continuous long and tightly coiled curly chips with silvery glazy type. But while machining in wet environment the form of chips is similar to MQL environment. These chips are yellowish brown. In dry cutting environment, the temperature in cutting zone increases due to which , the chips were too long and snarled ribbon type. These chips show blue radish brown colour and burnt type due to higher temperature. These chips do not break easily because of its ductility at high temperature. Hence these chips wound the workpiece and spoil the machined surface. Sometimes the chips clogs between the cutting edge and the machined surface which reduces cutting action, increases friction and results increase in higher forces.

Environment condition - Dry	
Nose Radius =0.4 mm	Nose Radius =0.8 mm
 Expt.No.7  Expt.No.6-	 Expt.No.18-  Expt.No.14-

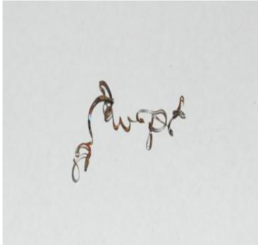
 Expt.No.1	 Expt.No.11

Fig. 4. Photographs of Chips during dry turning

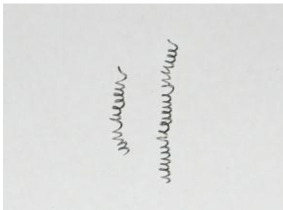
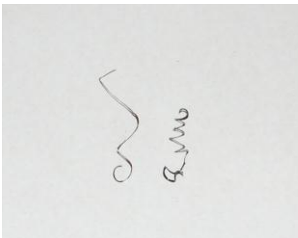
Environment condition - Wet	
Nose Radius =0.4 mm	Nose Radius =0.8 mm
 Expt.No.8	 Expt.No.16
 Expt.No.4-	 Expt.No.15
 Expt.No.2	 Expt.No.12

Fig. 5. Photographs of Chips during wet turning

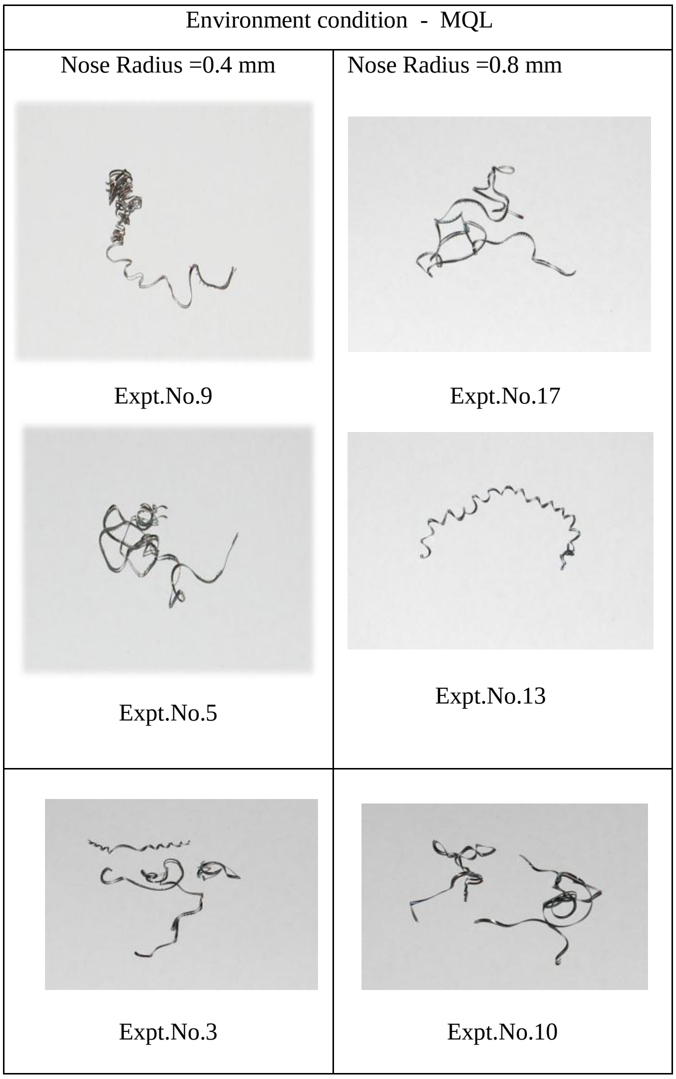


Fig. 6. Photographs of Chips during MQL turning

V. CONCLUSIONS

The experiments and analysis were carried out to express the effect of cutting environment on chip formation in hard turning of hardened alloy steel AISI 4340 by CBN insert. From the experimental investigations based on Taguchi's method and the analysis with MNITAB 15 considering the limits of the variables employed, the following conclusions are drawn –

- It is observed that the chip thickness in turning of hardened AISI 4340 in MQL is minimum followed by wet and dry turning. Hence MQL turning gives the higher cutting ratio than other two which is helpful for reduction in friction at the tool- chip interface and formation chips of thinner sections.
- It is observed that tightly coiled chips are formed during wet turning and during MQL that could handled easily where as long snared chips are prevalent during dry turning. The chips formed during MQL were similar to that during wet turning in spite of fluid application rate which only 0.05 % of that in wet turning. It is clear that MQL promotes acceptable chips that can handle easily.
- Chip changes its form from continuous to saw tooth type when the cutting speed increases. It also observed that at higher cutting speed the chips becomes more ductile and continuous in nature because of increased temperature of the shear zone. However as the depth of cut increases, the chip becomes more and more segmental or discontinuous in nature. The chip thickness ratio is related to cutting process parameters and cutting environment and it will always be less than unity and often in the range 0.2 to 0.6.
- As the minimal rate of fluid application is as low as 5 ml/min a major portion of the fluid is evaporated. The remaining is carried away with work and chips is too low. The cost of procurement, storage, reconditioning and disposal of coolants and lubricants can highly reduce which reduces the total cost of production considerably.
- As in MQL turning the rate of fluid application is very low and major portion of it is evaporated. The handling and disposal of cutting fluids should not require to obey rigid rules of environmental protection. The use of minimal fluid lubrication for machining is one step towards increasing careful for man kind and our environment.
- This technique can form a viable alternative to conventional wet turning, as it can be implemented without any drastic alternations in existing facilities available on shop floor.

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