Comparative Performance Evaluation of Uncoated and Coated Carbide Inserts in Dry End Milling of Stainless Steel (SS 316L)

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ABSTRACT
Investigate of wear of coated and uncoated carbide end mill cutters (K20) was done. This study was done on austenitic stainless steel (SS316L) with the use of combination of different speeds and feeds. 4 µm thick coating of AlCrN which is done by PVD method on carbide tools proved to better when machining is done on SS316L, as compare to uncoated tools. Wear as well as surface roughness is found to be increased with the help of coated tools. For surface roughness feed is found to be the most dominant factor at constant depth of cut. Al based coatings provide chemical inertness, hardness and good wear résistance due to the formation of Al_2O_3 layer on the tool surface at high temperatures. ISO criterion (0.3 mm flank wear) was used to measure the tool life of end mill cutters. Almost double tool life is achieved for coated tools as compare to uncoated one, may be due to fact that coatings provide better wear resistance even at high temperature at cutting zones which is due to high speed cutting. The combination of high speed and high speed was found to be the worst combination as far as flank wear is considered, as at high speeds higher stresses are developed on tool and tool edge. Good surface finish is observed for coated tools, specifically when combination of high speed and low feed is used. SEM analysis is done so as to investigate tool wear of end mill cutters. Finally it was found that uncoated carbide inserts can not be used to machine SS316L at high speeds and feeds, and coating of AlCrN is proved to be suitable for the same

Key words: Coating, Carbide end mill, SS316L, Tool life.

1 INTRODUCTION
The cutting tools need to be capable to meet the growing demands for higher productivity and economy as well as to machine the exotic materials which are coming up with the rapid progress in science and technology.

Success in machining can be achieved by the proper selection of cutting tool. The selection of tool depends on the tool material, geometry and the cutting parameters. The mode of tool failure is very harmful not only for the tool but also for the job and the machine tool. Hence, this kind of tool failure needs to be prevented by using suitable tool materials and geometry depending upon the work material and cutting condition. But failure by gradual wear, which is inevitable, cannot be prevented but can be slowed down only to enhance the service life of the tool. As milling is an interrupted cutting process, the forces coming on the tool are more severe. Hence, while selecting the tool material for milling one should take care that it should be tough and able to withstand forces coming on to it [1].

Progress in cutting tool materials from the carbon steels through the high speed steels, super high speed steels, carbides and ceramics, is concerned with attaining increased wear resistance and increased red hardness. A corresponding reduction in strength or toughness is inevitable as wear resistance and red hardness properties increase. Tool wear plays an important role as far as cutting ability and surface finish of the machined surface is concern.

Stainless steel is very difficult to cut material due to high plasticity and tendency to work harden, along with lower thermal conductivity which inflicts high thermal impact within the chip-tool contact zone, which significantly increase the cutting tool wear rate. This is the reason that very few researchers have handled this material.

Gu et al. found that in milling steel, the tool wear was sensitive to the speed and feed rate. Machining at high feed rate could cause high stress acting on the tool and thus tool edge to chip. They also found that attrition wear occurring at low speeds was due to the unstable built-up edge (BUE) formed at the chip–tool interface. (Ref paper of WYH LIEW).

Liew et. al.[12] found that while machining AISI 420SS coated tools exhibit higher wear resistance that uncoated one, highest flank wear was found at the flank face near the DOC zone. Abrasive wear take place a low cutting speeds as the work material is hard enough to plough into the tool. Endrino et. al.[10] have reporte his study on cutting SS with the use of Al based coating, having higher oxidation resistance due to formation of aluminum oxide surface layers. The nano-crystalline AlTiN coating outperformed the fine-grained AlTiN coating within the post running-in (stable) wear stage that almost doubled the tool life. As for the AlCrN-based coatings, the AlCrNbN coating with (200) texture performs significantly better than the AlCrN coating.

Shau et. al.[11] have reported the work on end milling of 3% Co–12% Cr heat resistance stainless steel. They have found that small rake angles give longer tool life and large rake gives steady machined surface integrity. Coating effectively decreases the formation of adhesive layer on tool and no BUE observed on inserts.

Abou-El-Hussein et al.[12] has done the experiments using AISI304 stainless steel. They had observed that increase in cutting speed caused a dramatic reduction in tool life and feed variation at high cutting speeds had small affect on tool life.

After all the discussion done by various researchers it was found that no one has handled SS above 150 m/min, using end milling cutter. Also there is no sufficient data available about the effect of feed, as well as surface finish of the machined surface. In this work, we have investigated the effect of speed and feed on the tool life of coated and uncoated carbide inserts, while machining austenitic SS316L. Feed was found to be the most influencing cutting parameter as far as surface finish of the machined surface is concern. High speed used with low feed gives good surface finish, but higher feed values are proved to be unfavorable for both tool wear as well as surface finish. Even coated tools do not allow cutting of austenitic stainless steel at high speed and feed, at different combinations of speed and feed coated tools gives almost double tool life than uncoated tools.

2. WORKPIECE SPECIMEN AND CUTTING TOOL MATERIALS

Austenitic stainless steel SS316L (composition C 0.3%, Mn 2%, Si 0.75%, S 0.03%, Cr 18%, Mo 3%, Ni 14%, N 0.10%) was used as a work piece material. SS316L is used for exhaust manifolds, furnace parts, heat exchangers, jet engine parts, pharmaceutical and photographic equipment, valve and pump trim, chemical equipment, digesters, tanks, evaporators. It consists of higher corrosion resistance, along with good pitting resistance and resistance to most chemicals. They are non hardenable and can be readily formed and drawn. SS316L posses poor weldability as compare to other grades of stainless steel.

Cutting tools used for the machining was an end mill tool holder of 16 mm diameter having 2 flutes, along with cemented carbide indexable inserts of grade K20. Specifications of uncoated tool XDHT 090308 THM (Kennametal's make) are as shown in fig 1. It is the most commonly used grade, readily available, and less costly. On the other hand, though M grade is suitable for stainless steel, it is not readily available. It requires special manufacturing for stainless steel and it is costly.

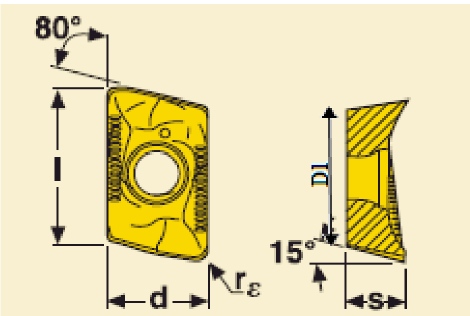


Fig. 1 Cutting tool (Insert) dimensions

3 EXPERIMENTAL PROCEDURES

The cutting tests were performed on CNC milling machine (HASS, U.S.A.). Cutting speed was used in the range of 100-200 m/min, and the feed in the range of 0.02-0.04 mm/tooth. Depth of cut was kept constant at 1 mm. End mill cutter having 16 mm diameter with carbide inserts was used to cut SS316L. Inserts were PVD coated using AlCrN coating from Oerlikon Balzer Coating Services (I) Limited. The coating specifications for coated tool are as follows:

Table 1 Coating specifications

Sr. No.	Parameter	Value/Name
1	Coating material	AlCrN
2	Microhardness (HV)	3200
3	Coating thickness	4 μm
4	Max. Service Temperature	1100 °C
5	Coating Technique	PVD (Iron Plating)

Design of experiments was done with different levels of speed and feed as follows:

Table 2 Design of experiments

Expt. No.	Parameters		
	Cutting Speed (m/min)	Feed (mm/tooth)	DOC (mm)
1		0.02	1.0
2	100	0.03	1.0
3		0.04	1.0
4		0.02	1.0
5	150	0.03	1.0
6		0.04	1.0
7		0.02	1.0
8	200	0.03	1.0
9		0.04	1.0

4 END MILLING OF SS316L

Austenitic stainless steel was machined using CNC mill. The cutting conditions were selected as per the literature survey as well as recommended by the tool supplier. The close-up view of cutting tests is as shown in Fig 2.

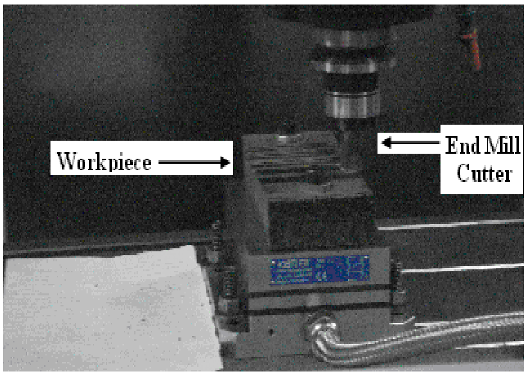


Fig. 2 Close-up view of experimental setup

4.1 Wear Measurement

Various cutting conditions as per the design of experiments were used for machining. After every pass flank wear of carbide inserts were measured by using Nikon Measuring Microscope (MM-40/L3U). Under the microscope, the worn out area of flank was seen at 10X magnification and the scale on the lens was used to measure the amount of flank wear. The insert was kept below the magnification lens, parallel to the base of machine as shown in Fig 3. Tool wear criterion as per ISO i.e. 0.3 mm flank wear was used for tool life of end mill cutters. All the nine experiments were carried out for coated as well as uncoated carbide indexable inserts.

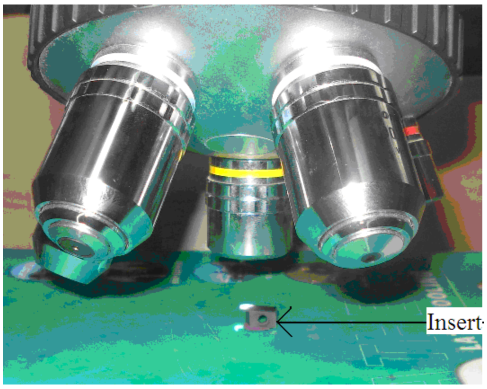


Fig. 3 Set-up for wear measurement

4.2 Surface roughness measurement

After every pass surface roughness of machined surface was measured. Surface roughness was measured by using surface roughness tester, manufactured by Mitutoyo surftest SJ-301. For surface roughness measurement cut-off length of 0.25 mm was used, along with diamond stylus. The set-up of measurement is as shown in fig 4.

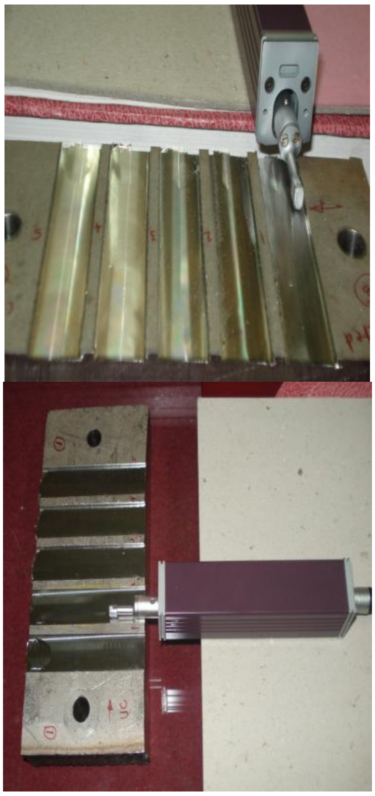


Fig. 4 Views of surface roughness measurement

5 RESULTS AND DISCUSSION

After completing the milling tests, the parameters such as wear and surface roughness are measured. The values obtained are related to the input parameters like cutting speed and feed at constant depth of cut for both uncoated and coated inserts. Effect of feed at different speeds is discussed on flank wear and surface roughness of machined surface for both types of tools. Fine and rough milling is compare for coated and uncoated end mill tools. SEM analysis is done for flank wear of inserts. All tools were used for machining until they reach upto 0.3 mm flank wear (as per ISO criterion). Some of the tools may fail early due to rupture at cutting edges. This is due to the fact that, at high feeds, higher forces are developed on the tools edges.

5.1 Effect of feed on flank wears for uncoated and coated inserts

The effect of feed on flank wear can be observed by plotting the graph of feed Vs flank wear. Keeping the cutting speed constant, the graph (fig 5) is plotted with varying feed. When a speed of 100 m/min was used, uncoated tools shows less wear at initial stages but wear increases when feed reaches to 0.03 mm/tooth, then it remains almost constant upto the feed value of 0.04 mm/tooth. When machining is done with coated tools reverse results are observed. Even at high feed values flank wear is less as compare to uncoated tools. This may be due to high toughness and excellent oxidation resistance of coating used on tools. Flank wear of different can be seen in Table no 2.

UC: Uncoated
C: Coated

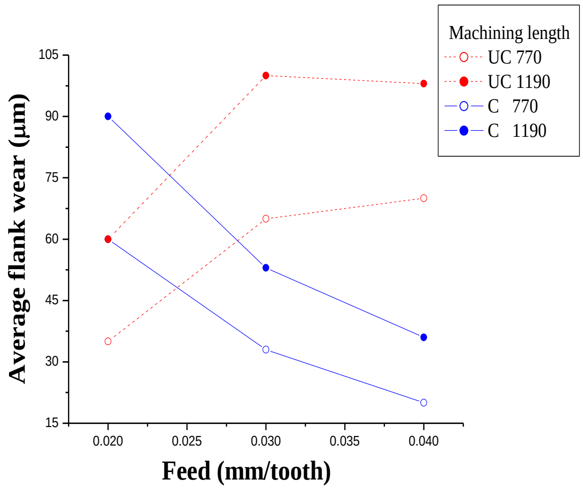


Fig. 5 Effect of feed on average flank wear of both inserts at cutting speed of 100 m/min

Table 3 Effect of feed on average flank wear of both inserts at cutting speed of 100 m/min

Feed (mm/tooth)	**Machining length (mm)**			
	770		1190	
	Average flank wear (µm)			
	UC	**C**	**UC**	**C**
0.02	35	60	60	90
0.03	65	33	100	53
0.04	70	20	98	36

Similarly when a speed of 150 m/min was used, wear observed at a feed of 0.02 and 0.04 mm/tooth (low and high values of feed) were higher. But at feed rate of 0.03 mm/tooth flank wear observed was less as compare to other feed values.

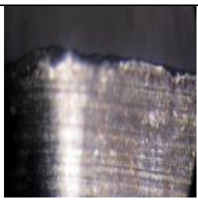
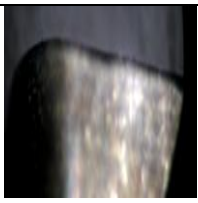
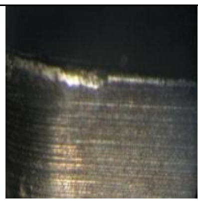
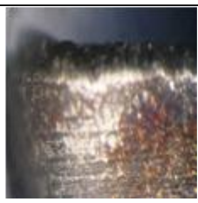
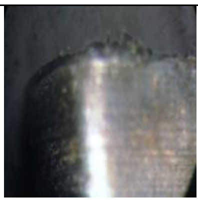
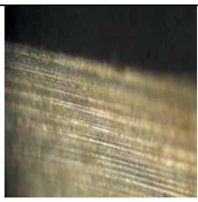
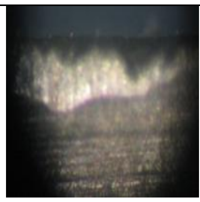
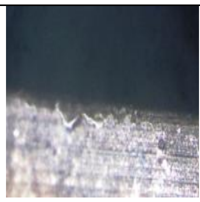
Feed (mm/tooth)	**Machining length (mm)**			
	770		**1190**	
	Average flank wear (µm)			
	UC	**C**	**UC**	**C**
0.02				
0.04				

Fig. 6 Flank wear pattern at cutting speed of 100 m/min.

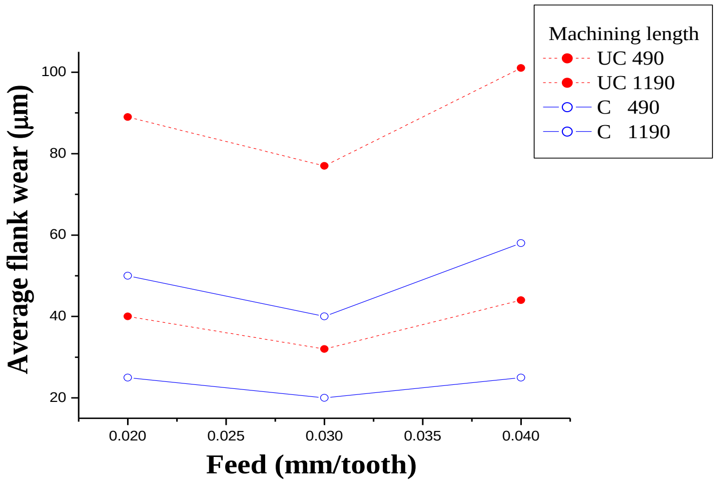


Fig. 7 Effect of feed on average flank wear of both inserts at cutting speed of 150 m/min

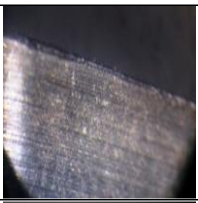
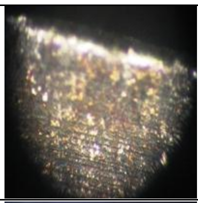
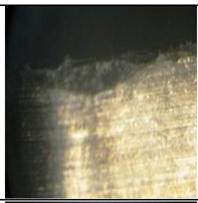
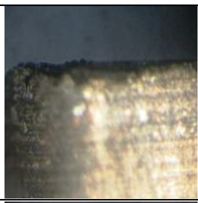
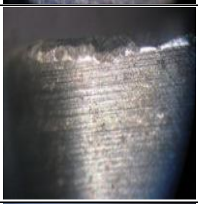
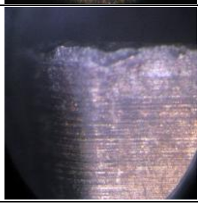
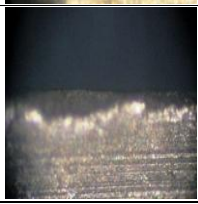
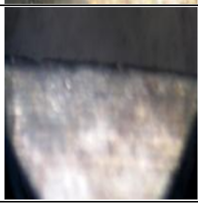
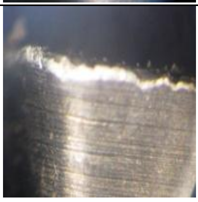
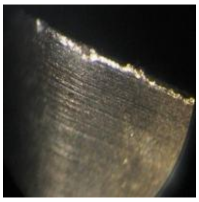
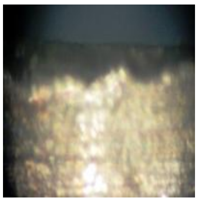
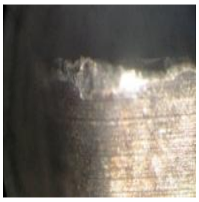
Feed (mm/tooth)	**Machining length (mm)**			
	490		**1190**	
	Average flank wear (µm)			
	UC	**C**	**UC**	**C**
0.02				
0.03				
0.04				

Fig. 8 Flank wear pattern at cutting speed of 150 m/min

Also maximum tool life was measured for this combination of speed and feed. Effect of feed on flank wear and wear pattern at a speed of 150 m/min can be observed on fig 7 and fig 8. Further when speed is increased to higher values i.e. 200 m/min, which don't allow the tool to last long. Coated tools at high feed rates get failed early than uncoated tools. This may be due to catastrophic failure. Also, after this uncoated tool doesn't last too long at high speeds due to high temperature produces at tool edge.

5.2 SEM analysis of flank wear of tools

Tools used at different conditions of speed and feed have last long for different amount of tool life. SEM analysis is shown in fig for certain inserts with their tool life.

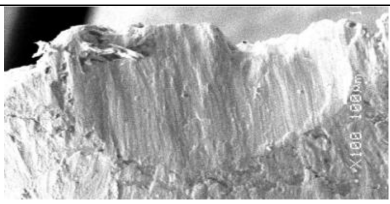
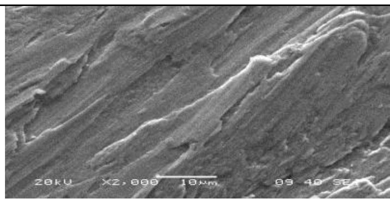
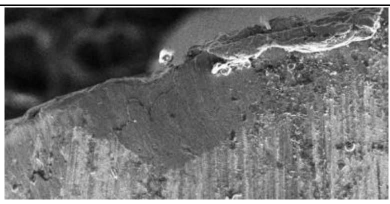
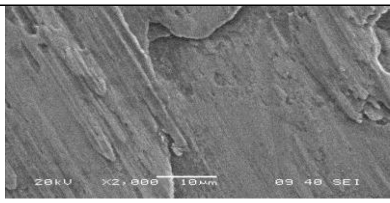
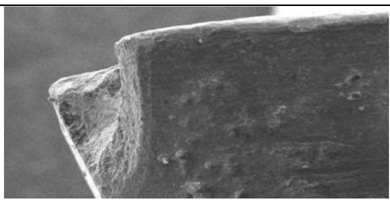
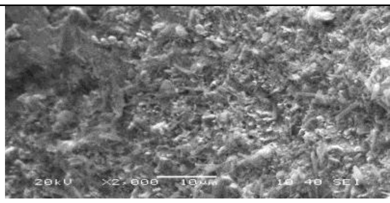
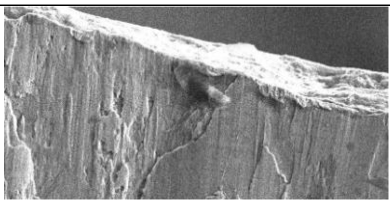
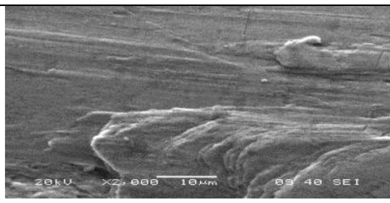
SR NO.	CUTTING CONDITIONS	SEM (100 X)	SEM (2000X)
1	**Vc =** 100 m/min **F =** 0.04 m/tooth **Coated (LSHF)**		
2	**Vc =** 100 m/min **F =** 0.02 mm/tooth **Coated (LSLF)**		
3	**Vc =** 200 m/min **F =** 0.04 mm/tooth **Coated (HSHF)**		
4	**Vc =** 20 0m/min **F =** 0.02 mm/tooth **Coated (HSLF)**		

Fig. 9 SEM analysis

5.3 Performance of inserts in rough and fine milling

The performance of milling cutter in two groups of cutting conditions for milling SS 316L is shown below:

Table 4 Fine and Rough Milling parameters

Milling conditions	Cutting speed (m/min)	Feed (mm/tooth)
Rough milling	150	0.04
Fine milling	200	0.02

From Fig 5.4 (a) it can be revealed that for fine milling coated tool failure occur may be due to catastrophic failure at a machining time of 11 minutes, in comparison uncoated tool runs for a machining time of approximately 18 minutes.
For rough milling, it can be seen from Fig. 5.4 (b) that coated tool runs for long time of machining i.e. 17 minutes as compare to uncoated tools i.e. 11 minutes.

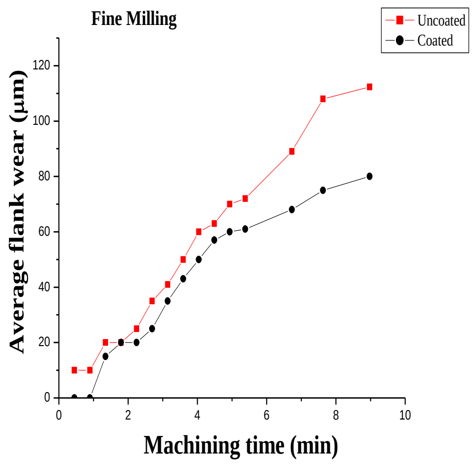


Fig. 10 Growth of average flank wear during fine milling

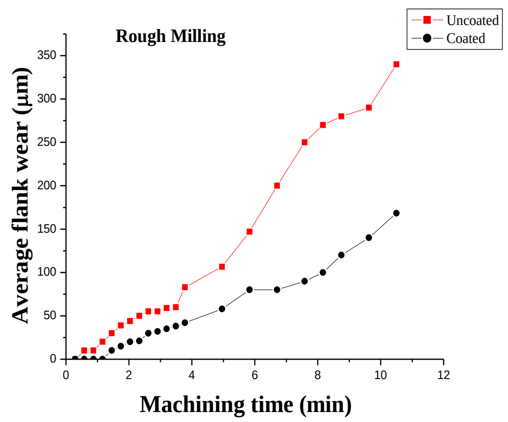


Fig. 11 Growth of average flank wear during rough milling

5.4 Effect of speed and feed on surface roughness of machined surface

Feed is found to be the most effective parameter as far as surface roughness is considered. Results for the effect of feed on surface roughness of machined surface are plotted as graphs of machining length Vs surface roughness. For surface roughness conclusions different combinations of speed and fee were chosen as below:

5.4.1 Low speed (100 m/min) and low feed (0.02 mm/tooth)

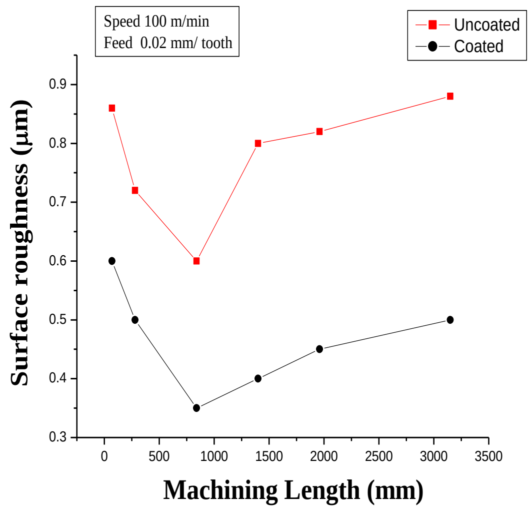


Fig. 12 Effect on surface roughness during low speed and low feed machining

5.4.2 High speed (200 m/min) and high feed (0.03 mm/tooth)

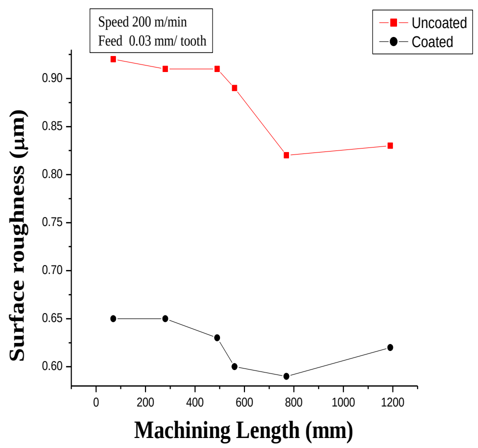


Fig. 13 Effect on surface roughness of both inserts during high speed and high feed machining

5.4.3 Low speed (100 m/min) and high feed (0.03 mm/tooth)

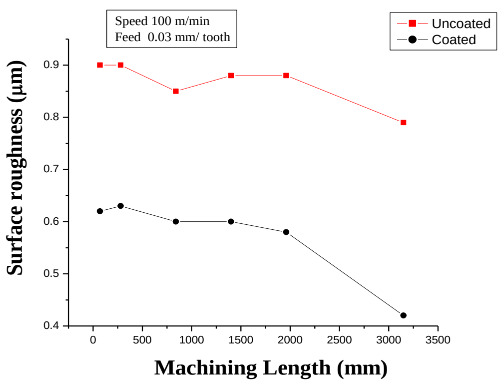


Fig. 14 Effect on surface roughness at low speed and high feed machining

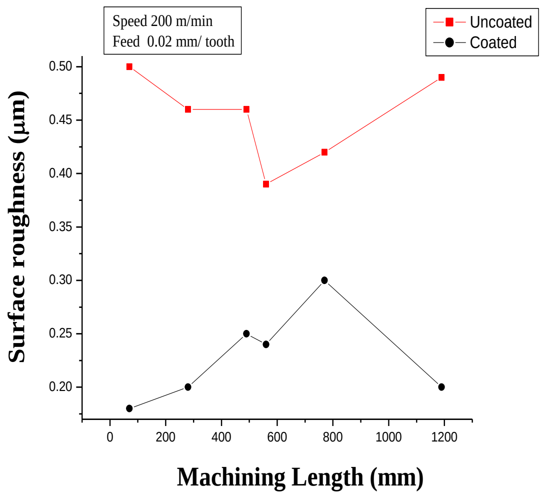


Fig. 15 Effect on surface roughness at high speed and low feed machining

Coated tools show better surface finish than uncoated tools. This is due to the reason that when uncoated tools are used for machining, the work material adhere on to the machined surface because of more tool wear. So for uncoated tools the surface defect occurs at a short distance which causes to increase the Ra value. For coated tools wear is less so Ra value appears for longer distance i.e. reduces Ra values.

5.4.4 High speed (200 m/min) and low feed (0.02 mm/tooth)

Combination of high speed and low feed gives good surface finish. But combination of low speed and high feed seems to be unfavorable criterion, as gives higher surface roughness. Due to the use of high speed and high feed both coated and uncoated tools fails very early, giving rough finish due to tool rupture.

6 CONCLUSIONS

Following conclusions can be drawn from the present investigation:

1) Effect of cutting speed and feed on average flank wear
- Increase in cutting speed and feed resulted into increase in average flank wear for both coated and uncoated milling cutters. At higher cutting speed temperature is high and increase in feed results in high cutting forces along with high stresses and temperature.
- Effect cutting speed is more dominant on average flank wear as compared to feed, due to high temperature at high cutting speeds.
- Machining with coated tools give less average flank wear due to excellent resistance to high temperature oxidation.

2) Milling performance during rough and fine milling
- Rough milling showed higher values of average flank wear than fine milling, due to high feeds, high stresses and temperatures.
- Even at rough milling conditions coated tools give less average flank wear due to lower chemical affinity of coating material.

3) Effect of cutting speed and feed on surface roughness
- Change in feed is more dominant factor on surface roughness than speed, as increase in feed causes increase in temperature and also increases tendency of built-up edge formation.
- Coated tools showed better surface finish than uncoated due to less coefficient of friction and lower thermal conductivity of coating.

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REFERENCES

[1] ASM Handbook – Vol. 16, Machining", 9th Edition, 1989, ASM International.

[2] Trent E.M., Metal Cutting, Butterworths-Heinmann, 2000.

[3] D.S. Rickerby, A Matthews, "Advanced Surface Coatings- A Handbook of Surface Engineering", Chapman and Hall, New York, 1991.

[4] Machinability, Module 3, Version 2, ME IIT, Kharagpur, Lesson 14

[5] Bunshah R.F., Handbook of Hard Coatings, Noyes Publications, New Jersey, 2001.

[6] Zhang S., Zhu W., TiN coating of tool steels: a review, Journal of Materials Processing Technology, 39, 1993, pp. 165 – 177.

[7] A. Bhattacharya, Metal cutting – Theory and Practice, New Central Book Agency, Calcutta, 1996.

[8] Minoru , Noriside Kimura, Naoya Omori, Yoshio Fukuyas, "Development of coated insert grade ACECOAT AC610M/AC630M for SS machining" SEI Technical Review, No. 61, Jan, 2006.

[9] W.Y.H.Liew, "Wear progression of carbide tool in low speed end milling of SS", Wear, 265(2008) pp. 155-166.

[10] J.L.Endrino, "Hard AlTiN, AlCrN PVD coatings for machining of SS", Surface and Coatings Technology, 200(2006) pp. 6840-6845.

[11] H.Shao, "Machinability study on 3%Co–12% Cr stainless steel in milling" , Wear, 263(2007) pp. 736–744.

[12] K.A. Abou-El-Hossein, "High-speed end-milling of AISI 304 stainless steels using new geometrically developed carbide inserts", Journal of Materials Processing Technology, 162–163 (2005) pp 596–602.

[13] J.A. Ghani, "Performance of P10 TiN coated carbide tools when end milling AISI H13 tool steel at high cutting speed", Journal of Materials Processing Technology, 153-154 (2004) pp.1062-1066.

[14] Y.L.Su, "Design of a TiN coated WC milling cutters", Journal of Material Processing Technology, 88(1999) pp. 233-236.

[15] G.E.D'ERICO, "A study of coatings for end mills in high speed cutting", Journal of Materials Processing Technology, 92-93(1999) pp. 251-256.

[16] G.S.Fox, "Improvement of duplex PVD coatings for HSS tools," Surface and Coatings Technology, 160(2002) pp. 99-107.

[17] M. Sokovic, "Wear of PVD coated solid carbide end mills in dry speed cutting", Journal of Material Processing Technology 157-158 (2004) pp. 422-426.

[18] M. Sokovic, "Wear of PVD coated solid carbide end mills in dry speed cutting", Journal of Material Processing Technology 157-158 (2004) pp. 422-426.

[19] G. Boothroyd, Fundamentals of Machining and Machine Tools, Marcel Dekker, Inc., First edition.