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Prediction of tool life of different coated cutting tools during machining of Inconel 718

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Abstract - *Machining of Super alloys is tough due to its superior properties. Inconel 718 is one of the super alloy which has unusual mechanical and thermal properties. Tool wear is one of the main reasons to find out the machinability of Super alloys. Coatings are well known to improve the performance of cutting tools in machining applications. The present work includes analysis of tool wear and surface roughness. Two different kinds of wear resistant coatings (TiAlSiN and TiAlN) were deposited on the tungsten carbide flat end milling cutters for the experimental work and observed that coated tools performed better than that of uncoated tools.*

Key Words*: *Inconel, Coating, Tool Wear, Surface Roughness, Cutting Force, Chip Morphology.

1. INTRODUCTION

As manufacturing technology advances, more and more difficult-to-cut materials are used in newer applications. This indicates that there is a higher demand of the processing methods to machine difficult-to-cut materials. Inconel 718 is Nickel-based superalloy and has ability to retain its mechanical properties at high temperatures, therefore this alloy has a broad range of applications in different industries such as gas turbine, pumps, space shuttle, tooling and medical applications. Inconel 718 has a significant combination of high temperature strength, toughness and resistance to degradation in corrosive environments which make it a difficult-to-cut material [1]. Therefore, machining of Inconel 718 is not at the desired level and tool deterioration is primarily observed during its machining. Tool wear causes changes in the tool geometry and it has immediate effect on the surface produced. This indicates that we need to analyze tool wear while machining Inconel 718. Tool wear has key impact on cutting forces, surface roughness, vibrations and chatters produced during machining therefore, it is necessary to understand when tool needs to be changed.

In the recent published work, for machining of superalloys like Inconel 718 coated tools were used. The coatings like TiN, TiAlN, TiCN, TiAlCrYN, CrN and Al_2O_3 have been most common coatings used for machining of Inconel 718. Derrien et al. [2] have used TiN and CrN coated milling cutters to produce a grove in Inconel plate and TiN coated tool were seen to have least wear. Irfan et al. [3] used five different coatings such as AlTiN, TiAlN+AlCrN, AlCrN, TiAlN+WC/C and DLC to machining of Inconel and found that two coatings out of five (TiAlN+WC/C and DLC) shows better performance against formation of BUE. Jindal et al. [4] performed turning experiments to machine Inconel 718 using TiN, TiCN and TiAlN coatings at constant cutting speed, feed and depth of cut to compare the performance of coatings and found that TiAlN coated tools were seen to be stable at high temperature and proved to be a better oxidation resistant coating. Chen et al. [5] performed drilling on Inconel 718 with TiAlN-PVD multilayer coated tools and compared the results with performance of uncoated tool. It was found that TiAlN coated tool performed superiorly than uncoated tools.

Allaudin et al. [6] modelled the cutting forces and observed that cutting force increase with an increase in feed and axial depth of cut. Flank and crater wear are the two main wear mechanisms that limit cutting tool performance. Flank wear is caused when the relief face of the tool rubs against the machined surface and on other hand crater wear occurs on the rake face of the tool and affects the geometry at the chip tool interface, which in turn affects the cutting force [7]. Pavel et al.[8] performed a number of experiments to investigate effect of tool wear on surface produced and observed that as flank wear increases with cutting time, machined surface became rougher. Also according to the ISO 8688-2, the tool rejection criteria of averaged flank wear 0.3 mm is used for tool replacement during machining [9].

Tool life in turning and drilling of nickel alloys is widely investigated. Hence, tool life in milling has limited attention. Life of uncoated tools for machining of Inconel is very short as compared to the coated tools, also it is realized that very little work is done on analytical modelling of tool wear progression of the end milling cutters. Thus, the main focus of this research is to analyze the effect of progression of flank wear using nitrided tungsten carbide flat end milling cutter on surface produced.

1.1Tool Material and Work Material Properties

In this subsection, work material properties are widely listed. By observing difficulties in machining of work material some of the coatings are also suggested. Inconel 718 is hardened by precipitation of secondary phases (gamma and gamma double prime strengthened) into metal matrix and has good weldability. Table I gives elemental composition of this alloy along with some of the important mechanical and thermal properties. Nickel and chromium contributes more in the composition of Inconel 718 [19].

Table -1: Process Parameters for Milling of Inconel 718

Parameters	Level I	Level II
Cutting Speed (m/min)	25	75
Feed (mm/tooth)	0.06	0.12
Depth of Cut (mm)	0.2	0.6

Table -2: Coatings for Machining Inconel 718

Coatings	Hardness (HV)	Service Temperature(°C)	Coefficient of Friction	Colour
TiAlSiN (Type-I)	3300	900	0.44	Bronze
TiAlN (Type-II)	3000	800	0.35	Violet-Grey

Table -3: TOOL GEOMETRY

Geometric Parameter	Recommended Values
Number of Flutes	2
Helix Angle	30 Degree
Rake Angle	17 Degree
Cutting Tooth Diameter	8 mm
Shank Diameter	8 mm
Shank Type	Cylindrical
Cutting Length	16 mm
Overall Length	63 mm

Table -4: MATERIAL PROPERTIES OF INCONEL 718

Work material	Inconel 718
Chemical composition	(Ni 54.95%,Cr 17.90%,Ti 0.92, Al 0.52%, Co 0.03%, Fe 16.50%, Si 0.68%, Cr 0.92%, Nb 0.54%, Si 0.08%,
Hardness (HV)	412/331
Yield Strength (MPa)	1034
UTS (MPa)	1276
Elongation, 50 mm %	10-12
Poissons ratio	0.284
Thermal conductivity, $Wm^{-1}K^{-1}$	15
Density, g cm^{-3}	8.47

1.2 Selection of Coating for Machining Inconel 718

Coating plays very vital role in machining of difficult to cut materials like Inconel 718. There are ample types of coatings available for milling cutter but their selection is based on the type of material to be machined. Form the literature we captured some coatings that may be used for machining of Inconel 718 and properties of these coatings are listed below in Table 3-4.

1. **TiAlSiN (Type-I):-**TiAlSiN is a coating with nano-structure matrix formed by adding Si to TiAlN coating. It is also called nc-TiAlNSiNx. With its nano-structure, it has higher hardness, wear resistance and oxidation resistance than conventional coatings. Especially, this coating can be superbly adapted to dry machining and high speed machining in harsh environments.

   Primary Applications

   High Speed Milling, Drilling, Turning, Cutting, etc .

2. **TiAlN (Type-II):-**It can also be called as AlTiN depending on the composition of Ti and Al. TiAlN or AlTiN coatings are suitable for use in "Difficult-to-cut" materials machining (Hard Milling/Hard Turning) and extreme environments such as high temperature and high pressure conditions. It is generally applied in dry machining and high speed millings where heat is generated. When properly applied, it enhances the speed and the feed, ultimately improving productivity.

   Primary Applications

   Milling, Drilling, High Speed Machining, Die Casting, High Temperature Forging.

2. EXPERIMENTAL SETUP AND PROCEDURE

The setup comprises of a vertical milling Centre HARDINGE VMC 600 II, a milling dynamometer (Kistler 9257A) for cutting force measurement along with the data acquisition module, a Pertometer to measure surface roughness and a Rapid-I to measure tool wear. A flow diagram of the series of events occurring while performing the experiments is shown in Figure 1. Milling of Inconel 718 with nitride milling cutter was performed in the vertical milling Centre. After each run of 50 mm, the milling cutter was taken to observe flank wear in Rapid-I. Here, flank wear was measured and images were recorded. Soon after the wear measurements were done, the milling cutter was taken back for next run if that tool is in good condition. Cutting force measurement were taken simultaneously during milling.

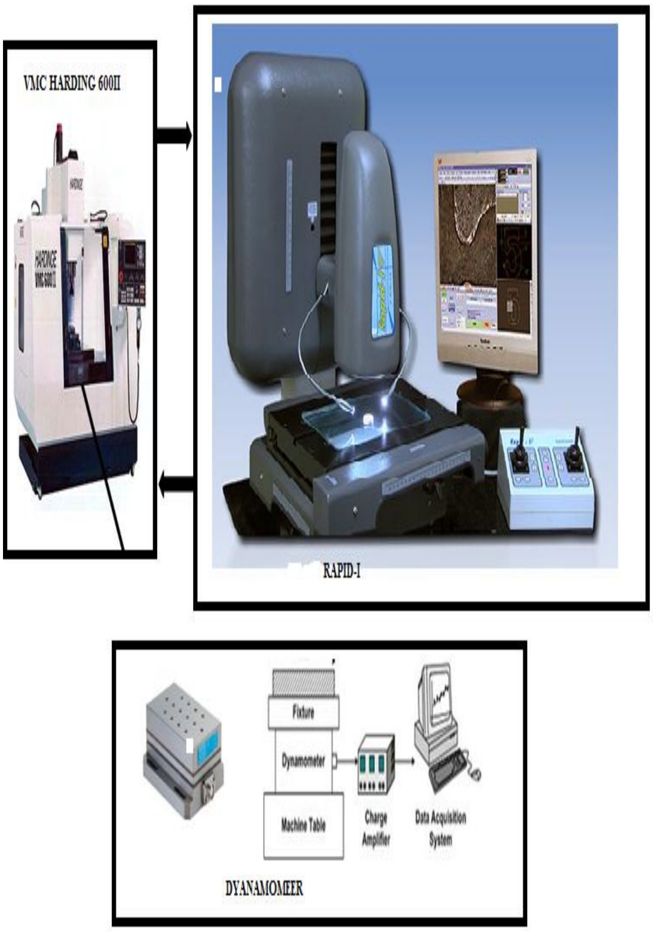


Fig -1: Experimental Setup

Fig -2: Roughness Measurement Instrument (Perthometer)

3. RESULT AND DISCUSSION

Analysis of experimental result involves two aspects. One is analyzing the milling cutter performance as the flank wear progresses and the effect of flank wear on the cutting forces in the milling operation. The second aspect involves surface quality analysis which refers to the effect of progression of tool wear on the quality of surface produced and chip morphology. In all the milling tests, solid carbide uncoated and coated milling cutters were used for milling experiments on Inconel 718 work specimen.

3.1 Effect of Process Parameters on Tool Life

Comparative study of tool life at different cutting speeds and at constant feed and depth of cut is shown in chart 1. Progression of flank wear at the cutting speed of 25 m/min is shown in chart 1 and progression of flank wear at the cutting speed of 75 m/min is shown in chart 2. The tool life of uncoated and coated milling cutters at different cutting speeds is carried out by keeping feed and depth of cut constant (Feed = 0.06 mm/tooth and Depth of Cut = 0.2 mm). From chart 1 and 2 it is cleared that the life of uncoated and coated milling cutters is comparatively less at 75 m/min of cutting speed as compared to at 25 m/min of cutting speed. We can say that the cutting speed affects the tool performance. As the cutting speed is increased from 25 m/min to 75 m/min the tool life of uncoated, TiAlN coated and TiAlSiN coated tool reduced. Percentage improvement in tool life at lower cutting speed for uncoated, TiAlN coated and TiAlSiN coated tool are 150%, 140% and 125% respectively than higher cutting speed at constant feed and depth of cut.

Comparison of Tool life at different cutting speed is also carried out at higher feed rate of 0.12 mm/ tooth and minimum depth of cut of 0.2 mm as shown in chart 3 and 4, it shows similar behavior as like in case of comparison of tool life shown in chart 1 and 2.

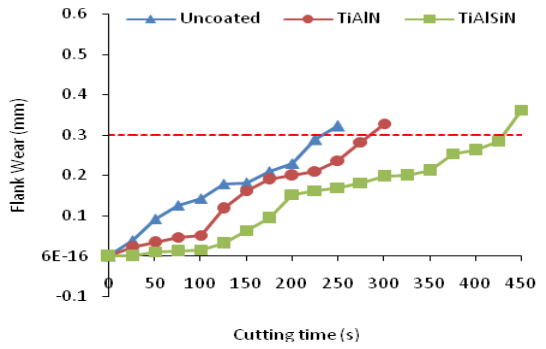


Chart -1: Comparative Study of Tool Life at Cutting Speed = 25 m/min, Feed = 0.06 mm/tooth, Depth of Cut = 0.2 mm.

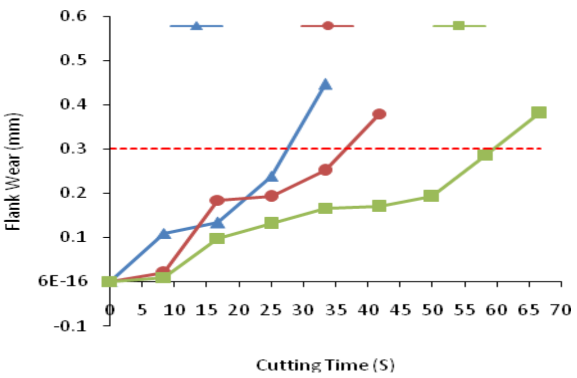


Chart -2: Comparative Study of Tool Life at Cutting Speed = 75 m/min, Feed = 0.06 mm/tooth, Depth of Cut = 0.2 mm.

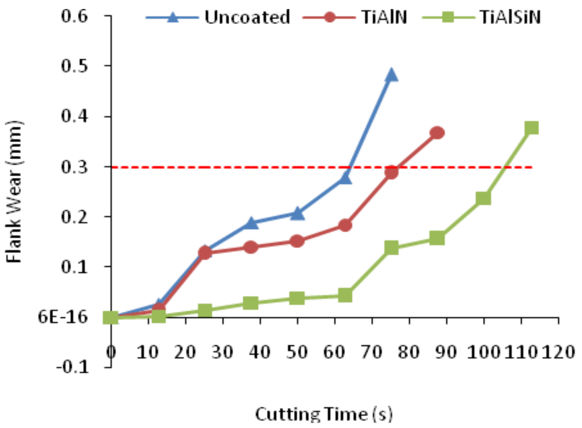


Chart -3: Comparative Study of Tool Life at Cutting Speed = 25 m/min, Feed = 0.12 mm/tooth, Depth of Cut = 0.2 mm.

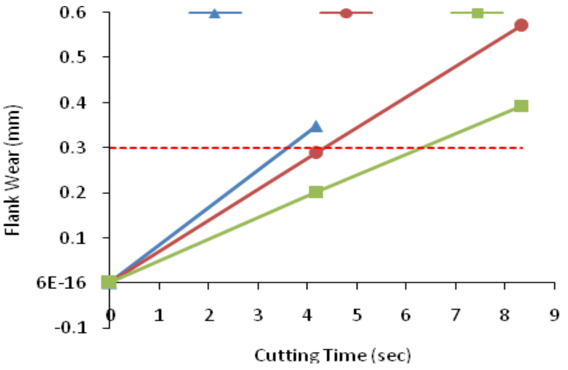


Chart -4: Comparative Study of Tool Life at Cutting Speed = 75 m/min, Feed = 0.12 mm/tooth, Depth of Cut = 0.2 mm.

Furthermore, Chart 1 and Chart 3 shows the effect of feed (0.06 mm/tooth and 0.12 mm/tooth) on life of tools at constant cutting speed of 25 m/min and at constant depth of cut of 0.2 mm. As the feed rate increased from 0.06 mm/tooth to 0.12 mm/tooth, the tool life of uncoated tool reduced from 235s to 65s, approximately 72% reduction in tool life at constant cutting speed and depth of cut. Similar behavior is obtained for TiAlN coated tool and TiAlSiN coated tool. The life of TiAlN coated tool reduced from 285s to 77s and the life of TiAlSiN coated tool reduced from 435s to 110s, approximately 72% and 74% tool life is reduced for TiAlN and TiAlSiN coated tool respectively.

3.2 Tool Wear Mechanisms

Figure 3 shows the tool wear comparison of uncoated, TiAlN coated and TiAlSiN coated milling cutters at cutting speed = 75 m/min, feed = 0.12 mm/tooth and depth of cut = 0.6 mm. Uncoated tool fails catastrophically at the engagement itself. TiAlN coated and TiAlSiN coated Tool breaks at the point where cutting distance reaches 28 mm and 42 mm respectively. Each of the coated tools fails catastrophically before reaching the cutting distance of 50 mm.

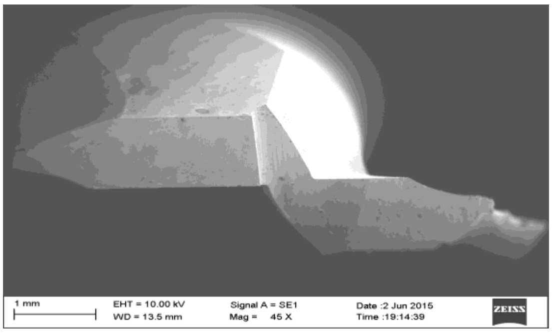


Fig -3: Catastrophic Failure

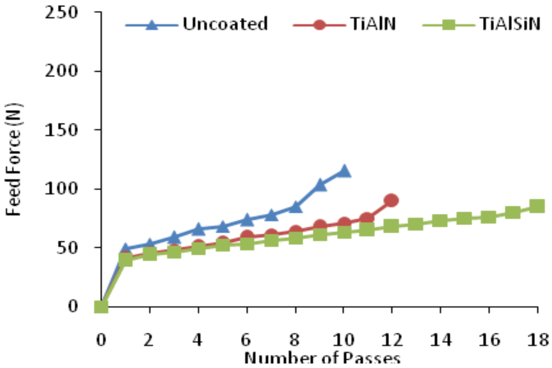
3.3 Analysis of Cutting Force in Milling

During the machining of each slot cutting forces were recorded by using Kistler dynamometer. The table system of cutting forces (i.e. F_x, F_y and F_z) measured for eight different settings. Waveform of cutting forces for cutting speed= 25 m/min, feed = 0.06 mm/tooth and depth of cut =0.2 mm. The cutting force data is analyzed when cutting tool exceeds tool rejection criteria. After analyzing the result, observations were made that cutting forces get increased after each run due to development of tool wear during machining of Inconel 718. Along with the progression of tool wear during machining, the work hardens of work material, temperature change in the tool-workpiece interface and the thermal expansion of the cutting tool and workpiece. The thermal effect could be a significant cause for the peak force variation within a single cutting pass, and that the tool wears progression was the major reason for the gradual increase of peak force in successive cutting passes.

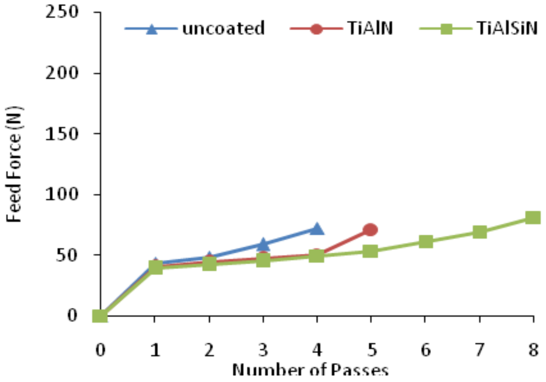
3.4 Effect Process Parameters on Cutting Forces

Chart 5 (a-b) shows the effect of cutting speed on feed force at constant feed and depth of cut. Chart 5 (a) shows the variation of peak force after each run on feed force at cutting speed of 25 m/min and Chart 5 (b) shows the variation of peak force after each run on feed force at cutting speed of 75 m/min.

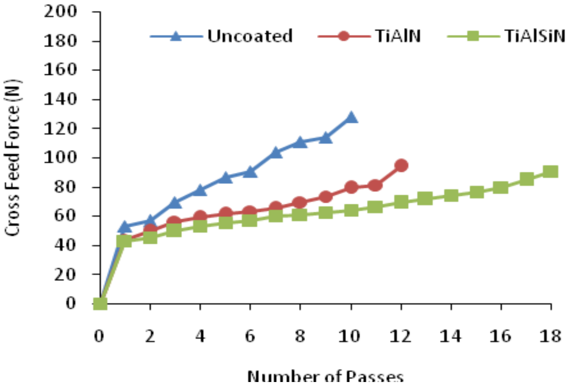
The cutting forces for uncoated and coated tool were also compared at different cutting speeds. It was observed that cutting forces at the lower cutting speed (25 m/min) are higher than that of the higher cutting speed (75 m/min). At lower speeds the forces were influenced by the presence of a built up edge. This is because, as the cutting speed decreases the shear angle decreases and friction coefficient increases. Both of these effects increase the cutting force. At higher cutting speed of 75 m/min, formation built up edge was not observed and also at higher speed friction coefficient reduces thereby decrease in cutting force was observed. Feed force is also compared with the cross feed force. From Chart 5 (a) and Chart 5 (c) it was observed that cross feed force is greater than that of the feed force for same process parameter.


Uncoated
TiAlN
TiAlSiN
Feed Force (N)
Number of Passes
0
50
100
150
200
250
0
2
4
6
8
10
12
14
16
18

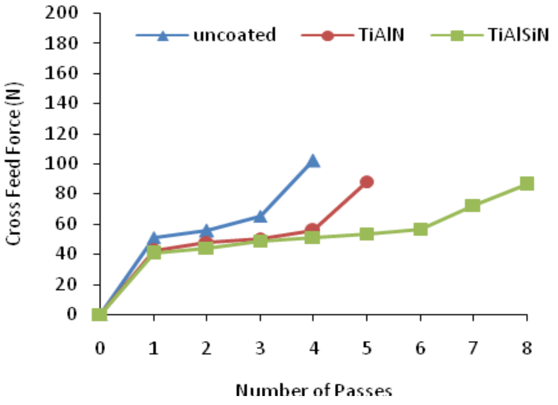
(a)


uncoated
TiAlN
TiAlSiN
Feed Force (N)
Number of Passes
0
50
100
150
200
250
0
1
2
3
4
5
6
7
8

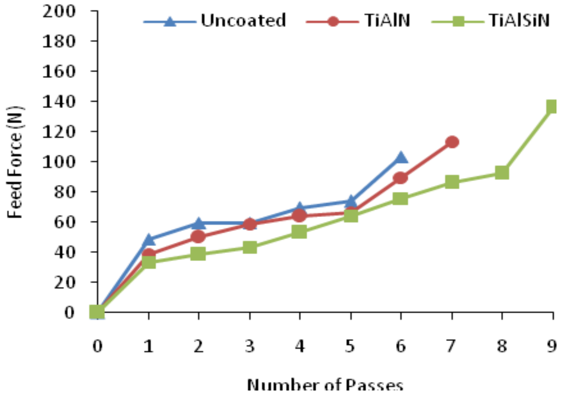
(b)


Uncoated
TiAlN
TiAlSiN
Cross Feed Force (N)
Number of Passes
0
20
40
60
80
100
120
140
160
180
200
0
2
4
6
8
10
12
14
16
18

(c)


uncoated
TiAlN
TiAlSiN
Cross Feed Force (N)
Number of Passes
0
20
40
60
80
100
120
140
160
180
200
0
1
2
3
4
5
6
7
8

(d)


Uncoated
TiAlN
TiAlSiN
Feed Force (N)
Number of Passes
0
20
40
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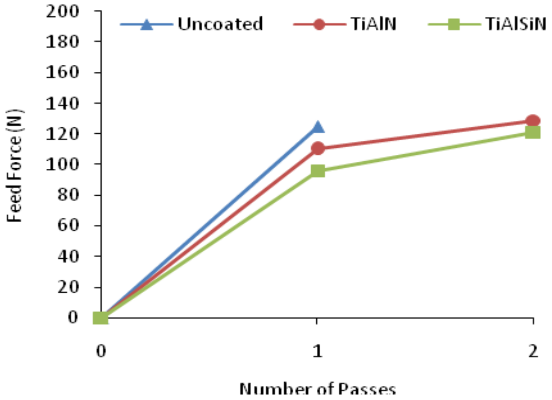
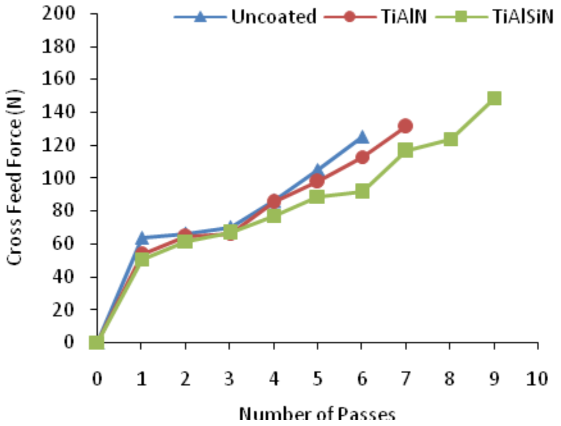
6
7
8
9

(e)


Uncoated
TiAlN
TiAlSiN
Feed Force (N)
Number of Passes
0
20
40
60
80
100
120
140
160
180
200
0
1
2

(f)


Uncoated
TiAlN
TiAlSiN
Cross Feed Force (N)
Number of Passes
0
20
40
60
80
100
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160
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1
2
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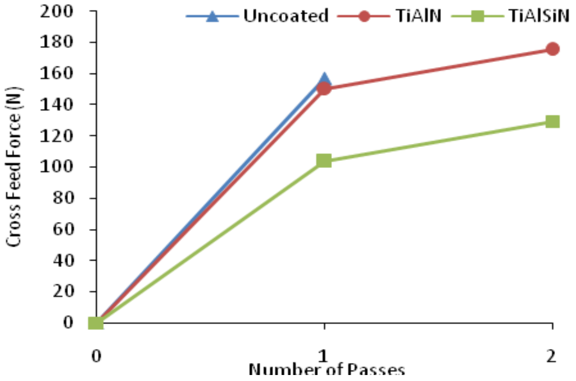
8
9
10

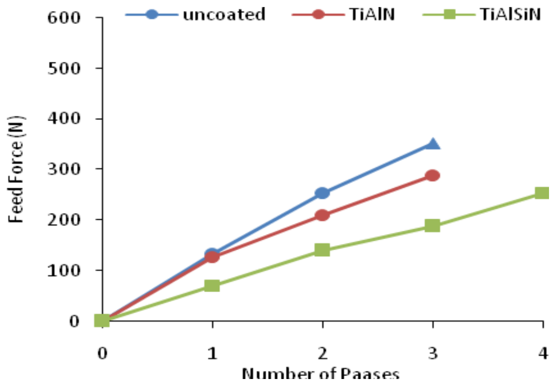
(g)


Uncoated
TiAlN
TiAlSiN
Cross Feed Force (N)
Number of Passes
0
20
40
60
80
100
120
140
160
180
200
0
1
2

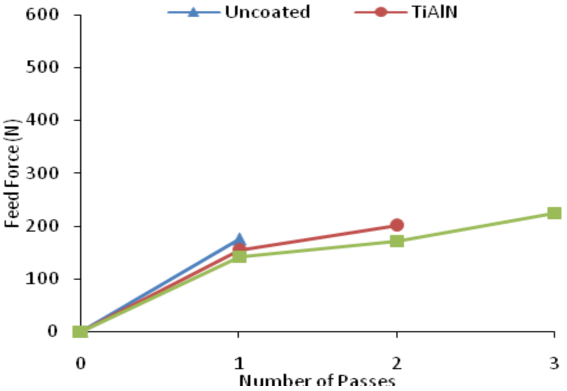
(h)

Chart -5: Effect of Process Parameters on Cutting Forces at (a-c) Cutting Speed = 25 m/min, Feed = 0.06 mm/tooth, Depth of Cut = 0.2 mm. (b-d) Cutting Speed = 75 m/min, Feed = 0.06 mm/tooth, Depth of Cut = 0.2 mm. (e-g) Cutting Speed = 25 m/min, Feed = 0.12 mm/tooth, Depth of Cut = 0.2 mm. (f-h) Cutting Speed = 75 m/min, Feed = 0.12 mm/tooth, Depth of Cut = 0.2 mm.

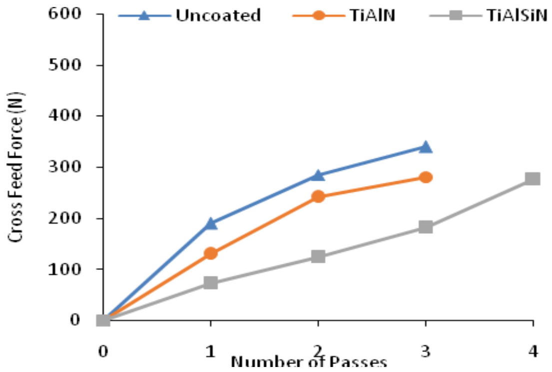
From Chart 5 (a) and Chart 5 (e) it was observed that cutting forces were increased as feed increased from 0.06 mm/tooth to 0.12 mm/tooth. This increasing behavior of the feed as well as cross feed force is due to the formation of thicker chips at higher feed rate. At the lower feed rate cutting tool scraped the material rather than cutting, therefore very less forces were observed in case of lower feed rate.



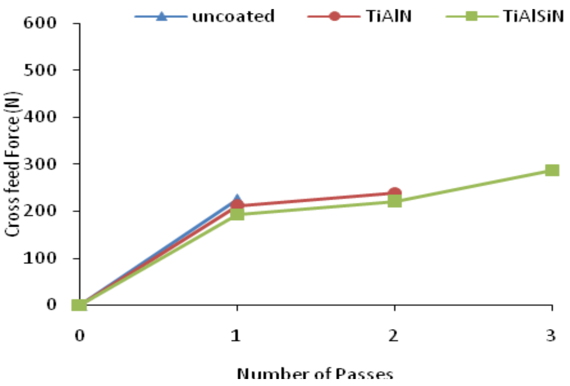
(a)



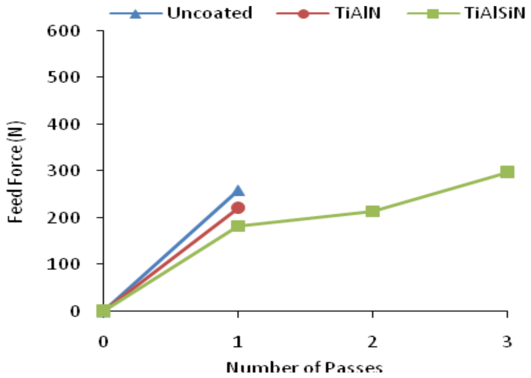
(b)



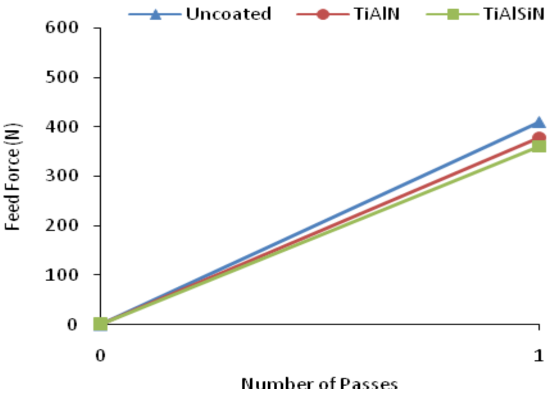
(c)



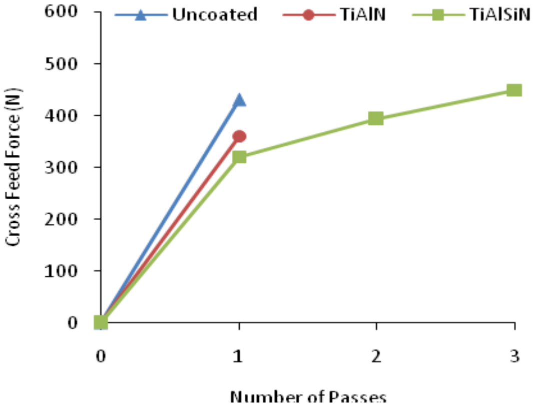
(d)



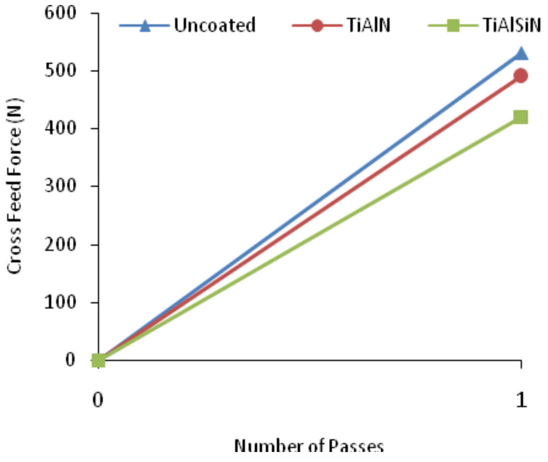
(e)



(f)



(g)



(h)

Chart -6: Effect of Process Parameters on Cutting Forces at (a-c) Cutting Speed = 25 m/min, Feed = 0.06 mm/tooth, Depth of Cut = 0.6 mm. (b-d) Cutting Speed = 75 m/min, Feed = 0.06 mm/tooth, Depth of Cut = 0.6 mm. (e-g) Cutting Speed = 25 m/min, Feed = 0.12 mm/tooth, Depth of Cut = 0.6 mm. (f-h) Cutting Speed = 75 m/min, Feed = 0.12 mm/tooth, Depth of Cut = 0.6 mm.

Comparisons of cutting forces were also carried out from Chart 5 and Chart 6 it was observed that feed and cross feed forces was increased as depth of cut increased from 0.2 mm to 0.6 mm. This increasing behavior of the feed as well as cross feed force is due to the formation of wider chips at higher depth of cut. Higher chip width increases the tool-work contact area which result in the increase in shear force as well as friction force which increases the feed and cross feed force.

It was also observed that feed and cross feed forces in the TiAlN and TiAlSiN coated tools are less as compared to uncoated tools for all the settings. Comparison of cutting forces amongst coatings was also carried out, which showed that the cutting forces in TiAlN coated tool were higher than that of the TiAlSiN coated tool.

3.5 Effect of Process Parameters on Surface Roughness

Chart 7 and 8 shows the effect of cutting speed on the surface roughness at constant feed and constant depth of cut. Figure 8 shows the plot of surface roughness at cutting speed of 25 m/min and Chart 8 shows the plot of surface roughness at cutting speed of 75 m/min. It is observed that at low cutting speeds, the shear angle is low and thus cutting forces are high. Furthermore, each section of the workpiece was in contact with the cutting tool for relatively long period of time than high cutting speed. This fact led to wear of cutting tool due to which surface finish reduced. At low cutting speed built up edges were formed which increases surface roughness thereby affects surface finish.

Chart 7, 8 and 9 shows the effect of feed on the surface roughness at constant cutting speed and constant depth of cut. Chart 7 shows the plot of surface roughness at feed rate of 0.06 mm/tooth and chart 7 and 9 shows the plot of surface roughness at feed rate of 0.06 mm/tooth and 0.12 mm/tooth. It was observed that at low feed surface finish was relatively less than that of at high feed. At low feed rate chip thickness was less which have relatively less effect on lay produced than high feed rate. However, surface finish at higher feed rate was very high due to tool wear.

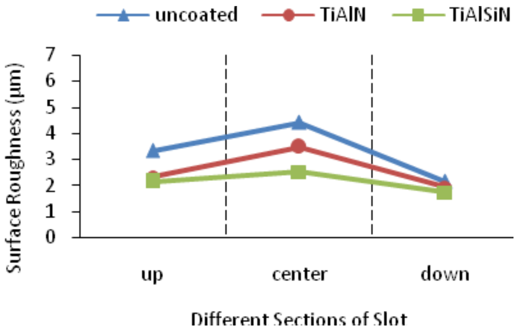


Chart -7: Comparative Study of Surface Roughness at Cutting Speed = 25 m/min, Feed = 0.06 mm/tooth, Depth of Cut = 0.2 mm.

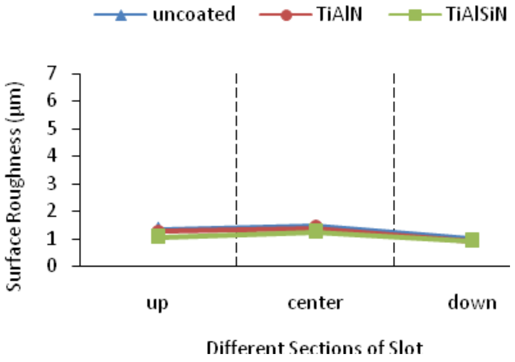


Chart -8: Comparative Study of Surface Roughness at Cutting Speed = 75 m/min, Feed = 0.06 mm/tooth, Depth of Cut = 0.2 mm.

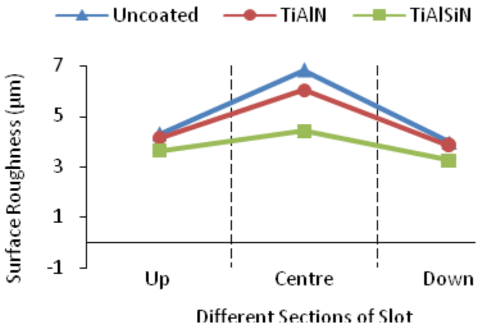


Chart -9: Comparative Study of Surface Roughness at Cutting Speed = 25 m/min, Feed = 0.12 mm/tooth, Depth of Cut = 0.2 mm.

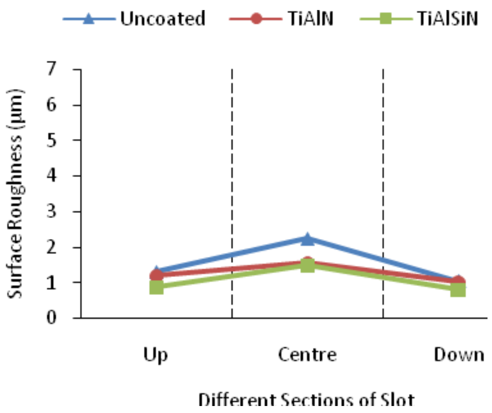


Chart -10: Comparative Study of Surface Roughness at Cutting Speed = 75 m/min, Feed = 0.12 mm/tooth, Depth of Cut = 0.2 mm.

4. CONCLUSIONS

Advanced materials are being used over a wide area of the manufacturing industry. Present research work on the machinability assessment of Inconel 718 using tungsten carbide uncoated and coated milling cutters under dry condition by experimentation a leads to the following conclusions:

Cutting condition

- Though the machinability of Inconel 718 is poor, it could be machined satisfactorily at cutting speed of 25 m/min, feed of 0.06 mm/tooth and depth of cut up to 0.2mm.
- Worst cutting condition is observed at cutting speed of 75 m/min, feed of 0.12 mm/tooth and depth of cut of 0.6 mm.

Tool life

- Comparison of life of uncoated and coated tool is carried out, from which it is cleared that TiAlSiN coated tool performed better for every cutting condition followed by TiAlN coated tool and uncoated tool.
- TiAlN coated tool performed significantly better than uncoated tool.
- Less tool life is observed at higher feed, higher cutting speed and higher depth of cut.

Tool wear

- Deterioration of uncoated tool occurred at premature stage due to chipping of cutting edge and flank face. TiAlN coated tools failed due to abrasion of flank face, chipping of cutting edge and flank face, formation of BUE is also one of the mechanism for deterioration of TiAlN coated milling cutter but its influence is not that much high like abrasion and chipping.
- TiAlSiN coated milling cutters failed due to abrasion of flank, chipping of cutting edge and flank, edge rounding and formation of BUE.
- At higher feed, higher cutting speed and higher depth of cut, even coated tools failed catastrophically along with the uncoated tools.

Cutting forces

- Cutting forces in slot milling decrease as the cutting speed increases while cutting forces increase with either an increase in feed or axial depth of cut.
- Cross feed force (F_x) was observed to have higher force magnitude than feed force (F_y).
- Forces in slot milling of inconel 718 were seen to be reduced in case of both the coated tools in comparison with the uncoated tools, however TiAlSiN coated tool was observed to have more force reduction than TiAlN coated tool.

Surface roughness

- Surface roughness in slot milling decreases as the cutting speed increases and/or feed rate decreases and/or depth of cut decreases.
- There is no significant difference in the surface finish produced by coated tools and uncoated tool but better surface finish was observed by machining using coated tool. TiAlSiN coated tool gives better surface finish than TiAlN coated tool.
- As compared to coated tool, cutting conditions has a major influence on surface roughness.

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