Wear Analysis during End Milling AISI 1018 Steel Using Microlubrication

Vasim Shaikh and Nourredine Boubekri*

Department of Engineering Technology,
University of North Texas Discovery Park,
Denton, Texas, USA, 76207.

*Corresponding author. Tel.: +1 940 565 2022;
Fax: +1 940 565 2666
E-mail address: boubekri@unt.edu

Abstract
Microlubrication minimizes the exposure of metal working fluids (MWFs) leading to an economical, safer and healthy workplace environment. In this study vegetable based lubricant is used to conduct wear analysis during end milling AISI 1018 steel using microlubrication. Solid carbide cutting tool was used with varying cutting speed and feed rate having a constant depth of cut. A full factorial experiment was conducted and regression models were generated for the tool flank wear. Higher tool life was observed in the lowest cutting speed and feed rate combination. The study shows that with a proper selectionof the cutting parameters it is possible to obtain higher tool life.

Keywords: Microlubrication, Minimum Quantity Lubrication, Milling, Tool wear, Steel, Design of experiments.

1. Introduction

Metal working fluids (MWFs) are used to cool and lubricate the tool/workpiece interface during machining. The MWFs performs several important functions like reducing the friction-heat generation and dissipating generated heat at tool-workpiece interface which results in the reduction of tool wear. MWFs flush the chips away from the tool and clean the workpiece causing less built-up-edge (BUE).Therefore, we cannot completely avoid using MWFs. But the exposure of MWFs is also the cause of growing occupational health hazards. U.S. National Institute for Occupational Safety and Health(NIOSH) recommends that occupational permissible exposure limits to MWF aerosols be limited to 0.4 mg/m^3 of thoracic particulate mass which corresponds to approximately 0.5 mg/m^3 total particulate mass as a TWA concentration for up to 10-hrs per day during a 40-hrs work week [1].However, the oil mist level in the U.S. automotive parts manufacturing facilities has been estimated to be 20-90 mg/m^3 with the use of conventional lubrication by flood coolant [2]. The exposure to such amounts of metal working fluid may contribute to adverse health effects and safety issues, including toxicity, dermatitis, respiratory disorders and cancer [3].Also, the costs related to the use of MWFs range from 7-17% of the total costs of the manufactured work piece [4] as compared to the tool cost which is only about 2-4% [5].

Microlubrication is also known as 'Minimum quantity lubrication' (MQL) and 'Near-Dry Machining'. In microlubrication small amount of cutting fluid around 10 ml/hr in the form of aerosol is delivered to the cutting tool/workpiece interface. In microlubrication, the fluid does not recirculate through the lubrication system. It is almost allevaporated at the point of application. Hence no recirculation is required. It is important however to ensure an efficient extradition of aerosol from the machine. In a flood application, the same coolant is recirculated through the system, filtered and used again [6]. The lubrication is obtained via the lubricant, and the cooling is achieved by the pressurized air that reaches the cutting surface in microlubrication application. Further, microlubrication reduces induced thermal shock and helps to increase the workpiece surface integrity in situations of hightool pressure [7]. The efficiency of a machining process depends on the tribological conditions which lowers the tool wear rate obtained by the cooling and lubricating effectiveness of the cutting fluid.

The main objective of this work is to investigate the effectiveness of microlubrication during end milling AISI 1018 steel with solid carbide cutter under varying cutting speed and feed rate having a constant depth of cut. And to conduct full factorial experiment and generate regression models for the tool flank wear.

2. Experimental Methods

End milling experiments were carried out on Mori Seiki computer numerical control (CNC) Dura vertical 5060 milling machine having a spindle power of 15HP and maximum spindle speed of 10,000RPM.AISI 1018 steel was used as workpiece material. The alloy can be easily formed, machined, welded and fabricated. The alloy is a free machining grade that is often employed in high volume screw machine parts applications and is commonly employed in shafts, spindles, pins, rods, sprocket assemblies and an incredibly wide variety of component parts. A Kuroda EcosaverKEP3 microlubrication unit was installed on the milling machine to provide a constant aerosol flow rate of 12ml/hr through external nozzle. Acculube LB-2000 was used as minimum quantity lubricant manufactured by ITW Rocol North America. An exhaust pump was used to pump out the mist generated during machining to replicate the exact factory production environment. End milling was carried out with a cutting speed of 24, 30 and 36 m/min and at a feed rate of 0.15 and 0.25 mm/rev.The cutting parameters were decided based on the recommendation in the ASM metal handbook for machining [8]. The axial depth of cut was 3.175mm and the radial depth of cut was 6.35mm. The cutting tool used in the experiment was 25.4 mm diameter solid carbide end mill having square ends and two flutes with bright oxide finish manufactured by Guhring Inc. The helix angle of the flute was 30º and the flute length was 38.1 mm. A particulate monitor DataRam4 manufactured by Thermo Scientific was used to collect the data for aerosol mean diameter particle size and the aerosol concentration. Flank wear on both the flanks was measured at regular interval by Mitutoyo Toolmakers microscope. The tool was declared failed if the flank wear of any one of the two flanks went above 0.5mm [8].

3. Design of Experiments

The study was conducted using a randomized factorial design. Table 1 shows the factorial experiment with six cutting speed and feed rate combinations. The experiment was fully randomized. An analysis of variance (ANOVA) was carried out for flank wear and F-ratios were calculated.

Table 1: Factorial experiment layout of cutting speed and feed rate combination.

Solid Carbide End Mill		**Cutting Speeds (m/min)**		
		24	**30**	**36**
Feed Rates (mm/rev)	**0.15**	24, 0.15	30, 0.15	36, 0.15
	0.25	24, 0.25	30, 0.25	36, 0.25

4. Analysis

All collected data was recorded using Microsoft Excel and transferred to Design Expert 8.0 analytical software for the ANOVA analyses.

4.1. ANOVA Assumptions

1. Individual differences and errors of measurement are normally distributed within each group.
2. Size of the variance and distribution of individual differences and random errors are identical in each group.
3. Individual differences and errors of measurement are independent from group to group.

4.2. Hypothesis

1. Null Hypothesis:

There is no significant difference between the responses obtained by varying theindividual input variables levels (i.e. cutting speed and feed rate).

2. Alternate Hypothesis:

There is a significant difference between the responses obtained by varying theindividual input variables levels (i.e. cutting speed and feed rate).

A normal probability plot was used to determine if the distribution of data approximates a normal distribution. In the ANOVA, the normal probability plot is usually more effective and straightforward when it is done with residuals. The normal probability plot of residuals for both the flank wear is shown in Figure 1and 2. The residual is the difference between the actual and predicted response values. The normal probability plot indicates that the residuals follow a normal distribution because the plot follows a straight line. There are some points which are slightly scattered but are acceptable as they do not follow any specific pattern. In general, these are moderate departures from normality which are of little concern in an analysis of variance. As the normal plot of residuals for both the sides of flank wear indicates the data is normalized, the analysis of variance can be said to be robust to the normality assumption.

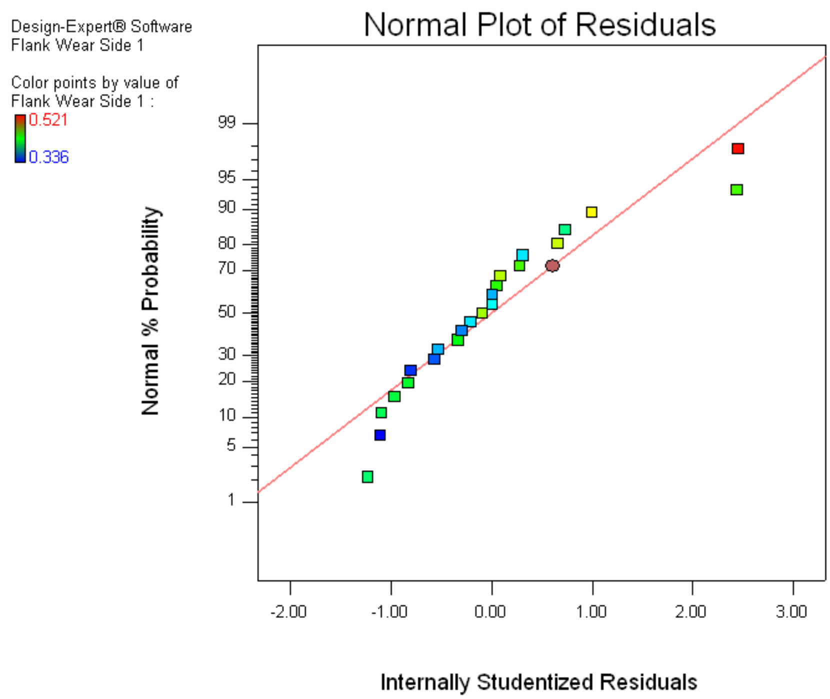

Fig 1: Normal plots of residual in data for flank wear side 1.

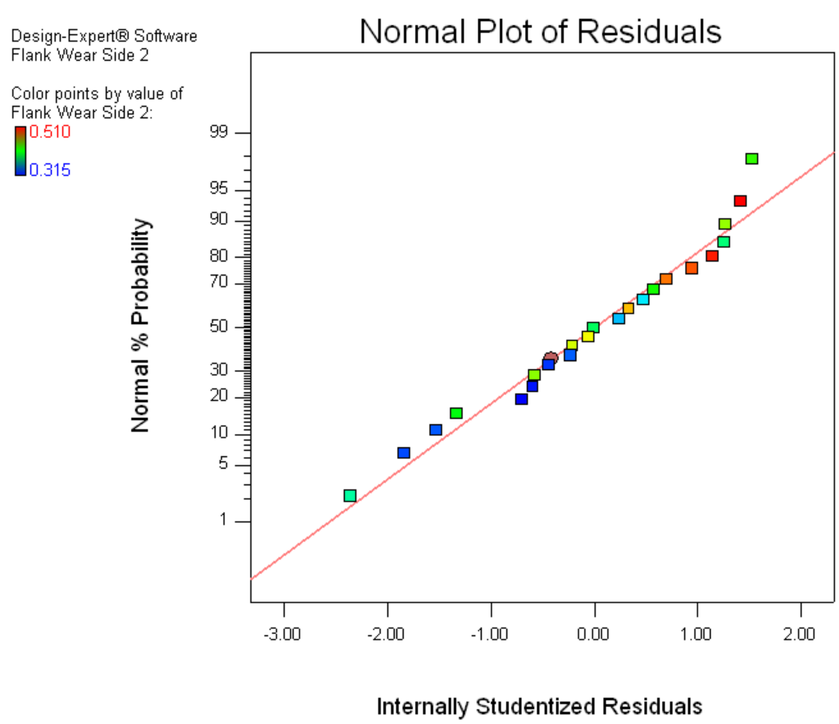

Fig 2: Normal plots of residual in data for flank wear side 2.

Figure 3 and 4 show plots of residuals versus predicted values which were used to test the assumption of constant variance for both sides of the flank wear. To fulfill the test, these plots should be a random scatter. The constant variance in the data demonstrates that the data does not follow a particular pattern, indicating constant variance.

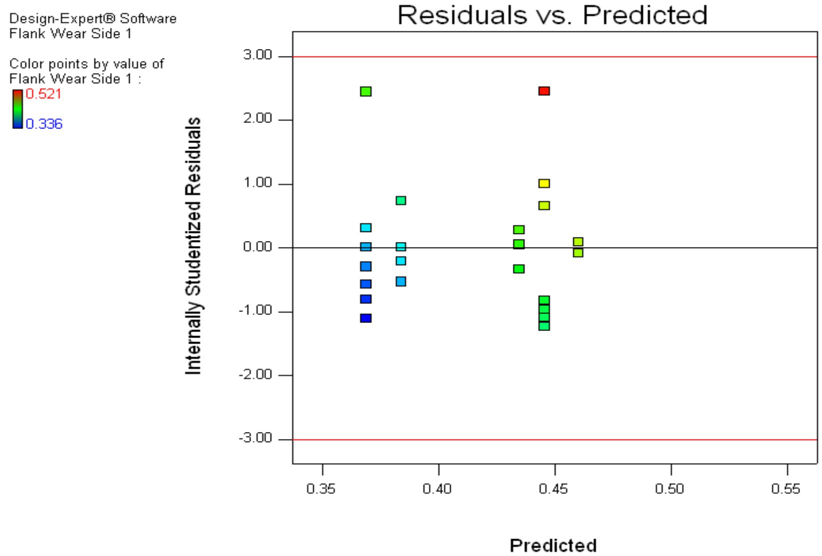

Fig 3: Constant variance in data for flank wear side 1.

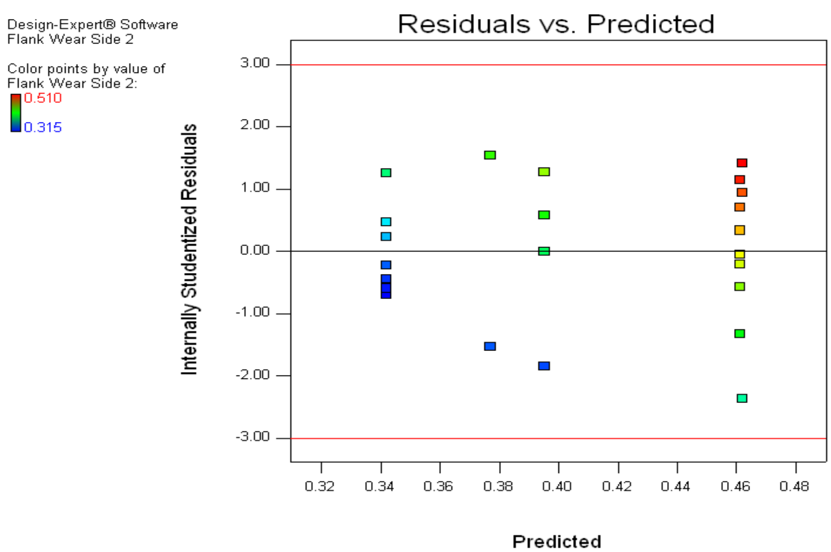

Fig 4: Constant variance in data for flank wear side 2.

The ANOVA for flank wear side 1 is shown in Table 2. The model gave an F-value of 8.18 which indicates that the model is statistically significant based on 95% confidence level. The resulting R-Squared value indicates that the model is able to predict 69.44 percent of the variation in the data. The remaining percent is considered noise and may not be predicted by this model. The sources of which may be manual variations while taking flank wear readings, machine vibrations, variations within the tools. The 'Adeq Precision' measures the signal to noise ratio. The ratio of 9.524 indicates an adequate signal. Hence, the model can be used as a good predictor of the flank wear side 1 as a result of changing the cutting speed and feed rate levels. The resulting regression model is shown below:

$$\text{Flank wear side 1} = + 0.44 + 0.012 \times \text{Speed} + 0.017 \times \text{Speed}^2 + 0.040 \times \text{Feed} - 0.027 \times \text{Speed} \times \text{Feed} + 0.029 \times \text{Speed}^2 \times \text{Feed}$$

Similarly, the ANOVA for flank wear side 2 is shown in Table 3. The model gave an F-value of 7.67 which indicates that the model is statistically significant based on 95% confidence level. The resulting R-Squared value indicates that the model is able to predict 68.06 percent of the variation in the data. The remaining percent is considered noise and may not be predicted by this model. The sources of which may be same as given for flank wear side 1. The 'Adeq Precision' measures the signal to noise ratio. The ratio of 5.975 indicates an adequate signal. Hence, the model can be used as a good predictor of the flank wear side 2 as a result of changing the cutting speed and feed rate levels. The resulting regression model is shown below:

$$\text{Flank Wear Side 2} = +0.40 + 0.024 \times \text{Speed} - 0.029 \times \text{Speed}^2 - 0.044 \times \text{Feed} + 1.089E\text{-}3 \times \text{Speed} \times \text{Feed} + 0.015 \times \text{Speed}^2 \times \text{Feed}$$

Table 2: Analysis of variance for flank wear side 1

ANOVA for selected factorial model Analysis of variance table [Classical sum of squares - Type II]						
Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**	
Model	0.042	5	8.363E-3	8.18	0.0004	significant
A-Speed	8.170E-3	2	4.085E-3	3.99	0.0367	
B-Feed	0.030	1	0.030	29.70	< 0.0001	
AB	6.068E-3	2	3.034E-3	2.97	0.0770	
Pure Error	0.018	18	1.023E-3			
Cor Total	0.060	23				
Std. Dev.			0.032	R-Squared		0.6944
Mean			0.42	Adj R-Squared		0.6095
C.V. %			7.69	Pred R-Squared		N/A
PRESS			N/A	Adeq Precision		9.524
Term	**Coefficient Estimate**	**df**	**Standard Error**	**95% CI Low**	**95% CI High**	**VIF**
Intercept	0.44	1	8.203E-3	0.42	0.45	
A	0.012	1	0.012	-0.013	0.036	
A^2	0.017	1	0.013	-0.011	0.044	
B	0.040	1	8.203E-3	0.023	0.057	1.54
AB	-0.027	1	0.012	-0.052	-2.509E-3	
A^2B	0.029	1	0.013	1.044E-3	0.056	
Final Equation in Terms of Coded Factors: Flank Wear Side 1 = $+0.44+0.012\times A+0.017\times A^2+0.040\times B-0.027\times AB + 0.029\times A^2B$						

Table 3: Analysis of variance for flank wear side 2

ANOVA for selected factorial model Analysis of variance table [Classical sum of squares - Type II]						
Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**	
Model	0.066	5	0.013	7.67	0.0005	significant
A-Speed	0.012	2	5.778E-3	3.35	0.0578	
B-Feed	0.058	1	0.058	33.72	< 0.0001	
AB	2.991E-3	2	1.496E-3	0.87	0.4366	
Pure Error	0.031	18	1.723E-3			
Cor Total	0.097	23				
Std. Dev.			0.042	R-Squared		0.6806
Mean			0.40	Adj R-Squared		0.5919
C.V. %			10.29	Pred R-Squared		N/A
PRESS			N/A	Adeq Precision		5.975
Term	**Coefficient Estimate**	**df**	**Standard Error**	**95% CI Low**	**95% CI High**	**VIF**
Intercept	0.40	1	0.011	0.37	0.42	
A	0.024	1	0.015	-8.447E-3	0.056	
A^2	-0.029	1	0.017	-0.065	6.704E-3	
B	-0.044	1	0.011	-0.066	-0.021	1.54
AB	1.089E-3	1	0.015	-0.031	0.033	
A^2B	0.015	1	0.017	-0.021	0.051	

Final Equation in Terms of Coded Factors:

Flank Wear Side 2 = $+ 0.40 + 0.024\times A - 0.029\times A^2 - 0.044\times B + 1.089E\text{-}3 \times AB + 0.015\times A^2B$

5. Results and Discussions

Figure 5, shows the tool life in minutes for different cutting speed and feed rate combinations. Cutting with lower feed rate resulted in prolonged tool life whereas cutting with higher feed rate decreased the tool life tremendously.The highest tool life was realized using treatment 24 m/min and 0.15 mm/rev. The tool failed after 861 minutes of machining at this treatment. Due to the lower cutting speed and feed rate the aerosol particle produced by microlubrication can easily penetrate through to the tool/workpiece interface. This leads to the cooling of the cutting tool and simultaneously the lubrication of the tool/workpiece interface. At low cutting speed, the cutting temperature is also low as compared to the other cutting speed and feed rate combinations. This also leads to the increase in tool life.

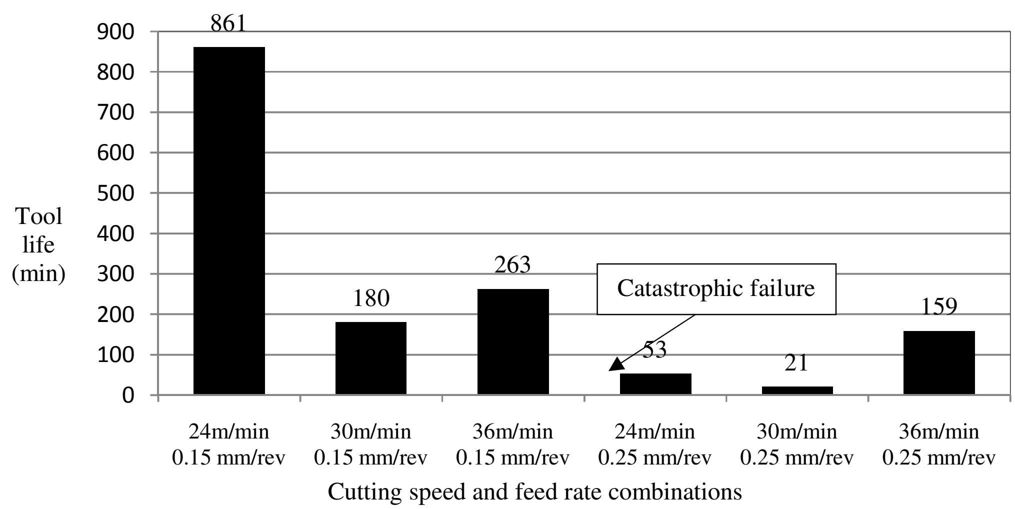

Fig 5: Tool life for different cutting speed and feed rate combinations

The lowest tool life was realized using treatment 30 m/min and 0.25 mm/rev . The tool failed only after 21 minutes of machining. Several reasons can be attributed to the lower tool life. Due to high feed rate the cutting fluid cannot effectively cool and lubricate the cutting zone leading to high temperature. The tip of the tool is highly sensitive at high temperature [9]. Due to high feed rate the subsurface of the workpiece experiences work hardening due to increase in dislocation densities. The tip of the tool has to experience a harder surface than the bulk resulting into earlier tool failure.

All the cutting tool under consideration failed with gradual abrasive wear except for treatment 24m/min and 0.25 mm/rev, which underwent a catastrophic failure. Figure 6, 7, 8, 9 and 10 shows the cutting tool at failure for treatment 24 m/min and 0.15 mm/rev, treatment 36 m/min and 0.15 mm/rev, treatment 30 m/min and 0.25 mm/rev, treatment 36 m/min and 0.25 mm/rev, and treatment 30 m/min and 0.15 mm/rev, respectively. Two-body abrasion may have been dominant. Chips form a foreign body and slide between the tool flank wear and the workpiece causing the tool tip to gradually wear out at the contact zone. Figure 11, shows that for treatment 30m/min and 0.15 mm/rev, the tool had gone through chipping before it underwent failure.

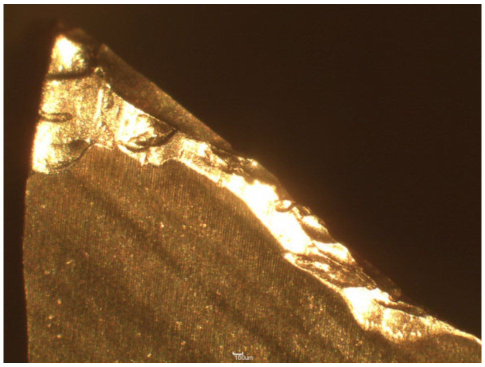

Fig 6: Tool flank wear for treatment 24 m/min and 0.15 mm/rev

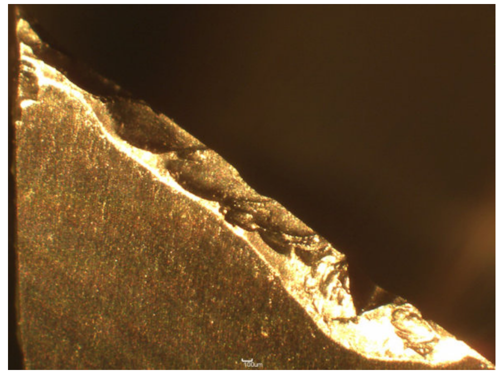

Fig 7: Tool flank wear for treatment 36 m/min and 0.15 mm/rev

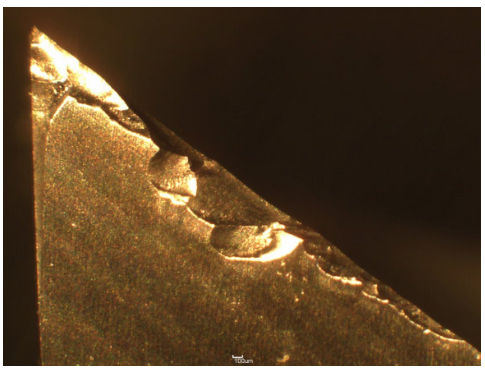

Fig 8: Tool flank wear for treatment 30 m/min and 0.25 mm/rev

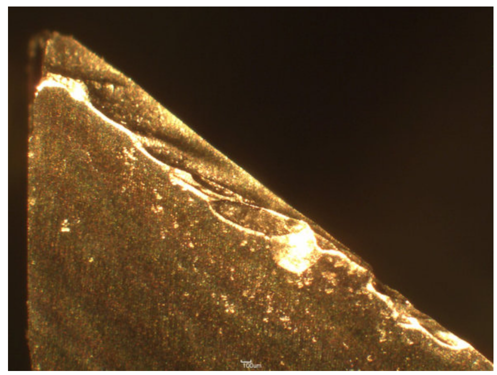

Fig 9: Tool flank wear for treatment 36 m/min and 0.25 mm/rev

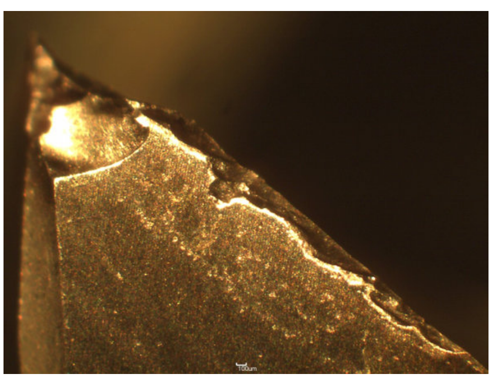

Fig 10: Tool flank wear for treatment 30 m/min and 0.15 mm/rev

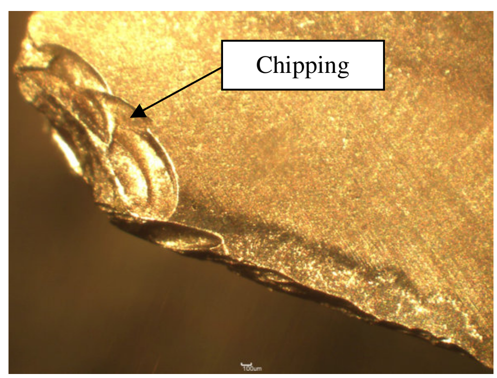

Fig 11: Tool rake for treatment 30 m/min and 0.15 mm/rev

Figure 12, shows the cutting tool for treatment 24m/min and 0.25 mm/rev, which underwent a catastrophic failure. The massive chipping seen in the figure is the reason for the failure of the tool. Chipping is generally caused by high temperatures at higher speed or higher feed rate conditions. Improper selection of cutting fluid may be another reason for chipping. Failure is linked to the fatigue crack promoted by cyclic variation of the tooltemperature during machining [10]. Cutting tool embrittlement takes place causing fracture under mechanical and thermal impacts.

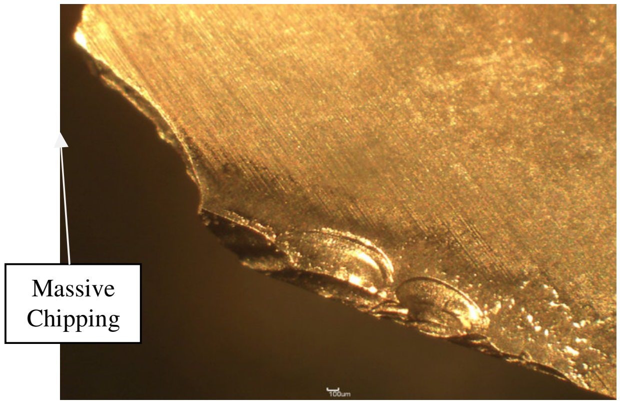

Fig 12: Tool rake for treatment 24 m/min and 0.25 mm/rev

6. Conclusion

The cutting performance under microlubrication is 5 times better under low cutting speed and feed rate combination (i.e. 24 m/min and 0.15 mm/rev) as compared to high cutting speed and feed rate combination (i.e. 36m/min and 0.25 mm/rev) for AISI 1018 steel using a vegetable based cutting fluid. Gradual abrasion was the dominant wear mechanism except for treatment 24m/min and 0.25 mm/rev where the tool underwent catastrophic failure due to massive chipping.

The ANOVA clearly indicated that both the cutting speed and feed rate are statistically significant factors based on a 95% confidence level for both the flank wear sides. It can be concluded that the flank wear can be predicted using the obtained regression models, under the conditions investigated in this study.

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