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Research Article

Milon Selvam Dennison*, Sivaram N M, Debabrata Barik, and Senthil Ponnusamy

Turning operation of AISI 4340 steel in flooded, near-dry and dry conditions: a comparative study on tool-work interface temperature

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Abstract: The objective of this study is to analyse the effect of tool-work interface temperature observed during the turning of AISI 4340 cylindrical steel components in three machining conditions, namely flooded, near-dry and dry conditions with three separate CNMG-PEF 80^0 diamond finish Titanium Nitride (TiN) coated carbide cutting tool. The machining parameters considered in this study are cutting velocity, feed rate and depth of cut. The experiments were planned based on full factorial design (3^3) and executed in an All Geared Conventional Lathe. The tool-work interface temperature was observed using a K-type tool-work thermocouple, while the machining of steel, and subsequently, a mathematical model was developed for the tool-work interface temperature values through regression analysis. The significance of the selected machining parameters and their levels on tool-work interface temperature was found using analysis of variance (ANOVA) and F-test. The results revealed that machining under near-dry condition exhibited lesser temperature at the tool-work interface, which is the sign of producing better quality products in equivalence with the machining under flooded condition.

Keywords: AISI 4340, tool-work interface temperature, flooded, near-dry, dry, ANOVA

***Corresponding Author: Milon Selvam Dennison:** Department of Mechanical Engineering, Karpagam Academy of Higher Education, Coimbatore, India; Email: milonds.mf@gmail.com
Sivaram N M: Department of Mechanical Engineering, Karpagam Academy of Higher Education, Coimbatore, India; Email: nmsivaram@gmail.com
Debabrata Barik: Department of Mechanical Engineering, Karpagam Academy of Higher Education, Coimbatore, India; Email: debabrata93@gmail.com
Senthil Ponnusamy: Mechanical and Industrial Section, Engineering Department, Higher College of Technology, Muscat, Sultanate of Oman; Email: senth.ksa@gmail.com

Nomenclature

AISI	American Iron and Steel Institute
C	Carbon
CNMG	ISO designation for tool
Cr	Chromium
Cu	Copper
d	Depth of cut in mm
f	Feed rate in mm/rev
Fe	Ferrous
Mn	Manganese
Mo	Molybdenum
NDM	Near-dry machining
Ni	Nickel
PCLNR	ISO designation for tool holder
PEF	ISO designation for insert chip breaker geometry
r	Correlation coefficient
Si	Silicon
T	Tool-work interface temperature in °C
v	Cutting velocity in m/min

1 Introduction

In the present day manufacturing environment, machining operations are inevitable in producing finished products. In any machining operation involving metal cutting, the usage of lubricants plays a vital role in maintaining favourable manufacturing conditions [1]. The favourable manufacturing conditions are a combination of certain process parameters and conditions, due to which best quality machine components are produced [2, 3]. Above 95% of gross energy sustained to the machine tool is changed over into heat, because of the relative movement between the cutting tool and workpiece [4, 5]. This form of heat energy is considered to be a waste and such a form of generated heat causes poor product surface quality and wear and tear of the tools [6].

In spite of the fact that rapid machining is most desirable for superior productivity, the quicker tool wear due to the relative motion between the cutting tool and workpiece confines the cutting speed. So, the extreme heat created due to the friction could be controlled for predominant product quality and better tool life. The heat generated at the tool-work interface also leads to microstructural distortion of the machined components [7]. The amount of friction generated between tool and workpiece has an influence on the quality of machined components [8]. The aforementioned issue could be overcome by applying cutting fluids on tool-work interface [5, 9]. The usage of cutting fluids are primarily: (i) to reduce the heat generated in the tool-work interface [6, 10], (ii) to reduce the friction between the tool and work due to machining operation [11] and (iii) to wash away the metal chips removed during the machining operation [12]. The metal chips washed away by the lubricants and coolants keep the tool-work interface free from any chips, leading to smooth material removal from the workpiece [13]. These qualities of lubricants and coolants enable the wide usage of lubricants and coolants in various metal cutting operations including turning, milling, grinding and drilling operations [14]. In metal cutting, the choice of cooling method influences the deformation mechanism [15].

In spite of the numerous advantages mentioned, the use of lubricants and coolants has numerous disadvantages also [13]. The lubricants and coolants used in a manufacturing environment facilitate colonization of bacteria and fungi in workplace [16], or the lubricants and coolants are made of carcinogenic materials [17], and may lead to diseases like cancer, dermatitis and allergy in humans when coming into contact with the human skin [18]. Also, the cost of lubricants and coolants adds up to 8% to total machining cost, which can be a considerable overhead on everyday operation [19].

In order to overcome these disadvantages of lubricants and coolants, many researchers and practitioners are working towards developing alternate methods that would involve less usage of lubricants and still not compromise on the benefits obtained by lubricants and coolants.

Near-dry machining (NDM) is a step in the direction of using lesser lubricants and coolants [13]. NDM aims at providing sustainable and green manufacturing in a modern machine shop [20, 21]. NDM is one such development that has proven to be highly useful in leading to a greener manufacturing process [22–25].

From the literature stated above, it becomes clear that machining studies have been carried out by various researchers in the field of near-dry machining. Still, there remains some difficulty in the application of the near-dry machining concept in the field of machining, which reveals that still more research has to be carried out to find a reasonable solution. In this direction, the work being reported in this paper was carried out to develop a 'near-dry machining' unit to overcome the disadvantages of the conventionally flooded lubrication. The details of the fabricating unit are presented in the next section. The experimental details are presented in the third section. An experiment was carried out using an NDM unit in 'near-dry' condition and the results of this experiment are compared with the experiments carried out in flooded and dry conditions in the fourth section. The details of the comparative study and analysis that was carried out are discussed in the fifth section. The conclusions of this paper are discussed in the sixth section.

2 Near-dry Machining Unit

This section presents the construction details of the NDM unit. The schema of NDM unit is depicted in Figure 1. This NDM unit consists of a piston pump with a cyclic timer that dispenses very little quantity of coolant to mix with the stream of air from the air compressor, along with all other supporting accessories, which include a solenoid valve, pressure regulators, non-return valve, coolant reservoir and nozzle (Figure 2) [23].

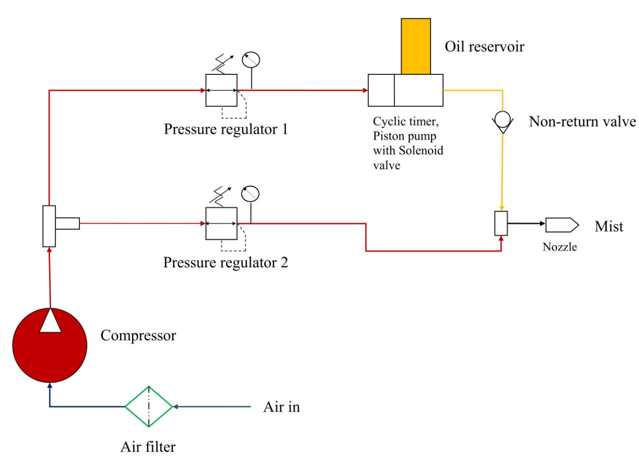


Figure 1: Schema of NDM unit

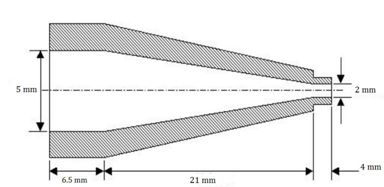


Figure 2: Nozzle

The NDM unit used in this work was capable of dispensing the cutting fluid ranging from 22.4 ml/hr to 224 ml/hr.

3 Experiment Details

3.1 Work Piece

A cylindrical workpiece made of AISI 4340 steel with dimensions (⌀50 mm × 120 mm) was selected for this study. AISI 4340 steel is a high tensile alloy steel with wear resistance properties and is extensively used in the automotive and general engineering applications, which include aircraft, propeller or gear shafts, connecting rods and aircraft landing gear components. The chemical composition and the mechanical properties of AISI 4340 steel are shown in Table 1 and Table 2, respectively.

Table 1: Chemical composition of AISI 4340

Element	% Composition	
	Standard	Tested
Fe	95.195–96.33	95.74
Ni	1.65–2.00	1.41
Cr	0.900–1.400	1.27
Mn	0.600–0.800	0.456
C	0.370–0.430	0.412
Mo	0.200–0.300	0.203
Si	0.150–0.300	0.211
Cu	0.180–0.310	0.294

Table 2: Mechanical properties

Property	Value
Tensile strength	951 MPa
Yield strength	651 MPa
Impact strength	44 J
Hardness	282 BHN
Elongation	13%

3.2 Cutting Tool

PCLNR tool holder and three separate CNMG-PEF 80° diamond finishing TiN coated carbide insert with 0.4 mm nose radius were used in the turning of AISI 4340 steel under flood, near-dry and dry conditions.

3.3 Cutting Fluid

Servocut 'S' grade oil emulsified with water was used as cutting fluid in both flooded and near-dry machining conditions. Properties of cutting fluid Servocut 'S' grade oil is given in Table 3.

Table 3: Fluid properties of Servocut 'S' grade oil

Property	Value
Specific gravity	0.877
Kinematic viscosity at 40°C	20 cSt
Flash point	150°C

4 Experimental Conditions

- **Workpiece used** – AISI 4340 (⌀50 mm × 120 mm)
- **Cutting tool used** – TiN coated carbide insert
- **Machine tool** – Turning centre (All Geared Conventional Lathe)
- **Cutting fluid** – Mineral based (Servocut 'S') emulsion
- **Coolant application technique** – flooded and near-dry
- **Coolant flow rate** – 44.8 ml/hr (near-dry)
- **Mist pressure** – 5 bar
- **Planning of experiment** – ($3^3 = 27$) full factorial design
- **Output response** – Tool-work interface temperature

The experiments were planned based on a full factorial design (3^3). From the set of experiments, the effect of machining parameters, namely cutting velocity, feed rate and depth of cut on the response output were studied. The experimental setup comprising the lathe, NDM unit, compressor and the tool-work thermocouple arrangement is shown in Figure 3.

NDM nozzle shown in Figure 4 was attached parallel to the flood coolant nozzle available in the lathe. The NDM unit was placed as a peripheral device, which generates coolant mist. The flexible hose enables the nozzle to move in any direction. For achieving a near-dry machining condition, a constant pressure of 5 bar was applied throughout

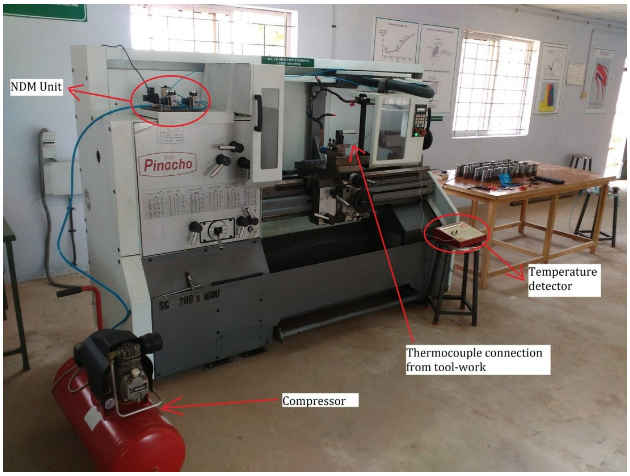


Figure 3: Experimental setup

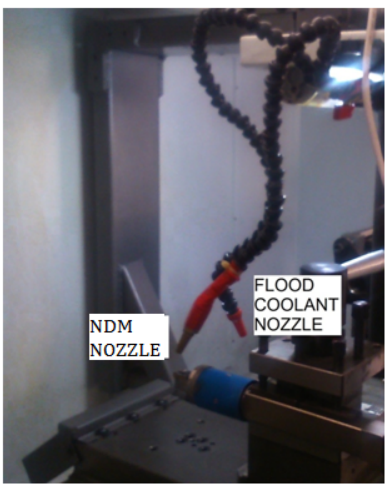


Figure 4: NDM and flood coolant nozzles

the experimentation and coolant oil was dispensed at the rate of 44.8 ml/hr.

The machining parameters, namely cutting velocity, feed rate and depth of cut, were considered in the turning of cylindrical AISI 4340 steel under flood, near-dry and dry machining conditions. The various levels of the machining parameters are given in Table 4.

The turning operation was carried out under flooded, near-dry and dry conditions, which are shown in Figure 5, Figure 6 and Figure 7, respectively.

Subsequently, the tool-workpiece interface temperature under flooded, NDM and dry machining conditions was measured using a tool-work thermocouple technique (K-type thermocouple having a temperature range from 0°C to 1200°C with a digital temperature indicator) with proper calibration during turning of AISI 4340 steel at different cutting velocities, feeds and depth of cuts in the present investigation, which is shown in Figure 8.

Table 4: Machining parameters and their levels

Parameters	Unit	Notation	Levels		
			1	2	3
Cutting velocity	m/min	v	325	350	375
Feed rate	mm/rev	f	0.1	0.15	0.2
Depth of cut	Mm	d	0.3	0.6	0.9

Figure 5: Machining under flooded condition

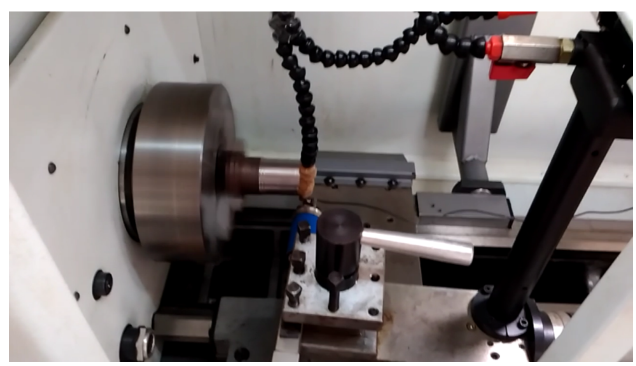


Figure 6: Machining under near-dry condition

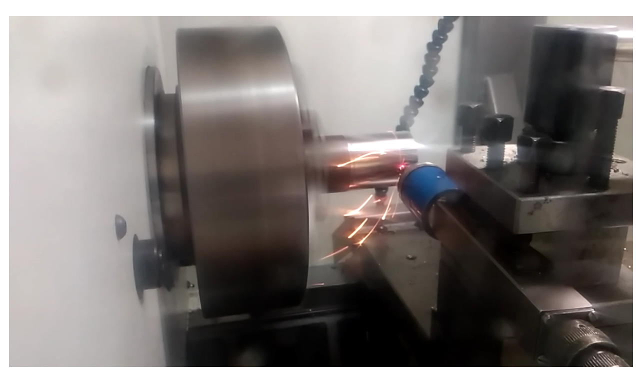


Figure 7: Machining under dry condition

Table 5: Experimental conditions and results

Run	Machining parameters			Tool-work interface temperature (°C)		
	v	f	d	Flooded	NDM	Dry
1	1	1	1	51.0	61.4	241.6
2	1	1	2	65.5	76.9	262.2
3	1	1	3	80.0	90.3	282.8
4	1	2	1	66.9	78.0	264.3
5	1	2	2	81.4	93.6	284.9
6	1	2	3	95.9	109.5	305.5
7	1	3	1	81.4	98.0	284.9
8	1	3	2	95.9	109.5	305.5
9	1	3	3	110.4	121.0	326.2
10	2	1	1	85.8	97.0	291.1
11	2	1	2	100.3	112.9	311.7
12	2	1	3	114.8	124.4	332.3
13	2	2	1	87.2	98.2	293.1
14	2	2	2	101.7	114.1	313.8
15	2	2	3	116.2	125.6	334.4
16	2	3	1	100.3	112.9	311.7
17	2	3	2	114.8	124.4	332.3
18	2	3	3	129.3	135.9	353.0
19	3	1	1	109.0	119.8	324.1
20	3	1	2	123.5	131.3	344.7
21	3	1	3	138.0	142.8	365.4
22	3	2	1	127.8	134.8	350.9
23	3	2	2	142.3	146.3	371.5
24	3	2	3	156.8	162.6	392.2
25	3	3	1	139.4	144.0	367.4
26	3	3	2	153.9	165.1	388.0
27	3	3	3	168.4	176.8	408.7
			Average	**108.7**	**118.8**	**323.9**

Figure 8: Tool-work interface thermocouple insulated and coupled with the tool holder

5 Results and Discussion

5.1 Experimental Conditions and Results

5.1.1 Effect of machining parameters on tool-work interface temperature

The effect of cutting velocity was studied with a constant feed rate of 0.15 mm/rev and with a constant depth of cut of 0.6 mm, while machining steel AISI 4340 under flood, NDM and dry conditions. It was observed from Figure 9 that the tool-work interface temperature while machining AISI 4340 under flooded, near-dry and dry conditions increased rapidly with an increase in cutting velocity.

The effect of feed rate was studied with a constant cutting velocity of 350 m/min and with a constant depth

Table 6: ANOVA for tool-work interface temperature under flooded machining condition

Parameters	Sum of Squares	Degrees of freedom	Mean sum of squares	F ratio	Rank	Prob. > F
Cutting velocity	15786.0	2	7893.00	455.51	1	0.0001 Significant
Feed rate	2836.6	2	1418.32	81.85	3	0.0001 Significant
Depth of cut	3784.5	2	1892.25	109.20	2	0.0001 Significant
Error	346.6	20	17.33			
Total	22753.7	26				

Table 7: ANOVA for tool-work interface temperature under near-dry machining condition

Parameters	Sum of Squares	Degrees of freedom	Mean sum of squares	F ratio	Rank	Prob. > F
Cutting velocity	13177.3	2	6588.66	266.12	1	0.0001 Significant
Feed rate	2966.1	2	1483.03	59.90	3	0.0001 Significant
Depth of cut	3333.6	2	1666.78	67.32	2	0.0001 Significant
Error	495.2	20	24.76			
Total	19972.1	26				

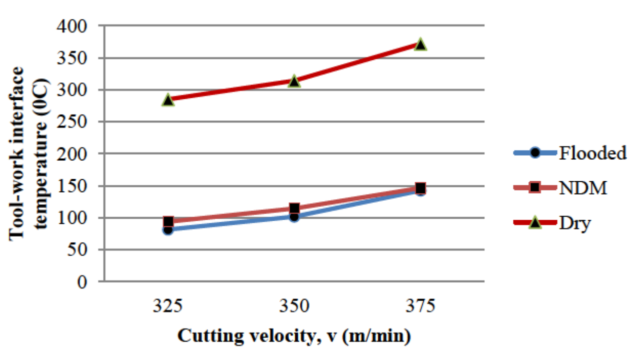


Figure 9: Effect of cutting velocity on tool-work interface temperature

of cut of 0.6 mm, while machining steel AISI 4340 under flooded, near-dry and dry conditions. It was observed from Figure 10 that the tool-work interface temperature value increased gradually with an increase in the feed rate for all the machining conditions.

The effect of depth of cut was studied with a constant cutting velocity of 350 m/min and with a constant feed rate of 0.15 mm/rev when machining steel AISI 4340 under flooded, near-dry and dry conditions. It was observed from Figure 11 that the tool-work interface temperature value increased with an increase in the depth of cut for all the three machining conditions.

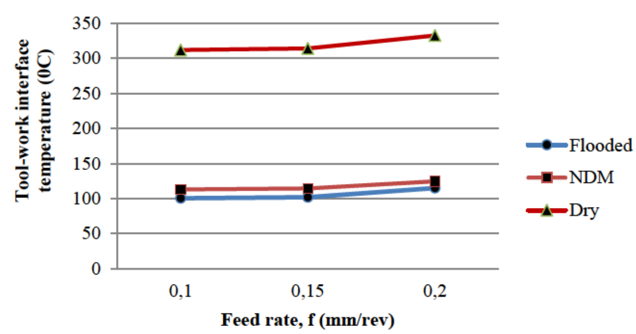


Figure 10: Effect of cutting feed on tool-work interface temperature

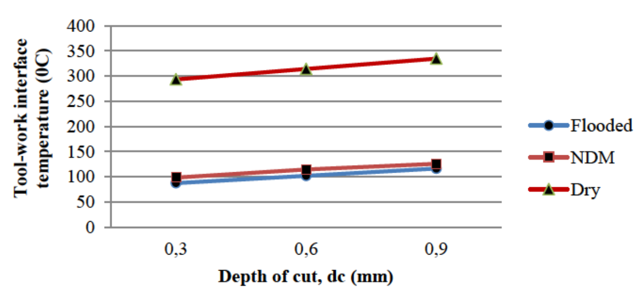


Figure 11: Effect of depth of cut on tool-work interface temperature

5.2 Analysis of Variance (ANOVA)

The most significant factor on the response output was analysed using the analysis of variance (ANOVA) and F-test with a probability of $p = 0.05$ for flooded, near-dry, and dry machining conditions.

Table 8: ANOVA for tool-work interface temperature under dry machining condition

Parameters	Sum of Squares	Degrees of freedom	Mean sum of squares	F ratio	Rank	Prob. > F
Cutting velocity	31952.8	2	15976.4	454.51	1	0.0001 Significant
Feed rate	5755.9	2	2878.0	81.88	3	0.0001 Significant
Depth of cut	7663.2	2	3831.6	109.01	2	0.0001 Significant
Error	703.0	20	35.2			
Total	46074.9	26				

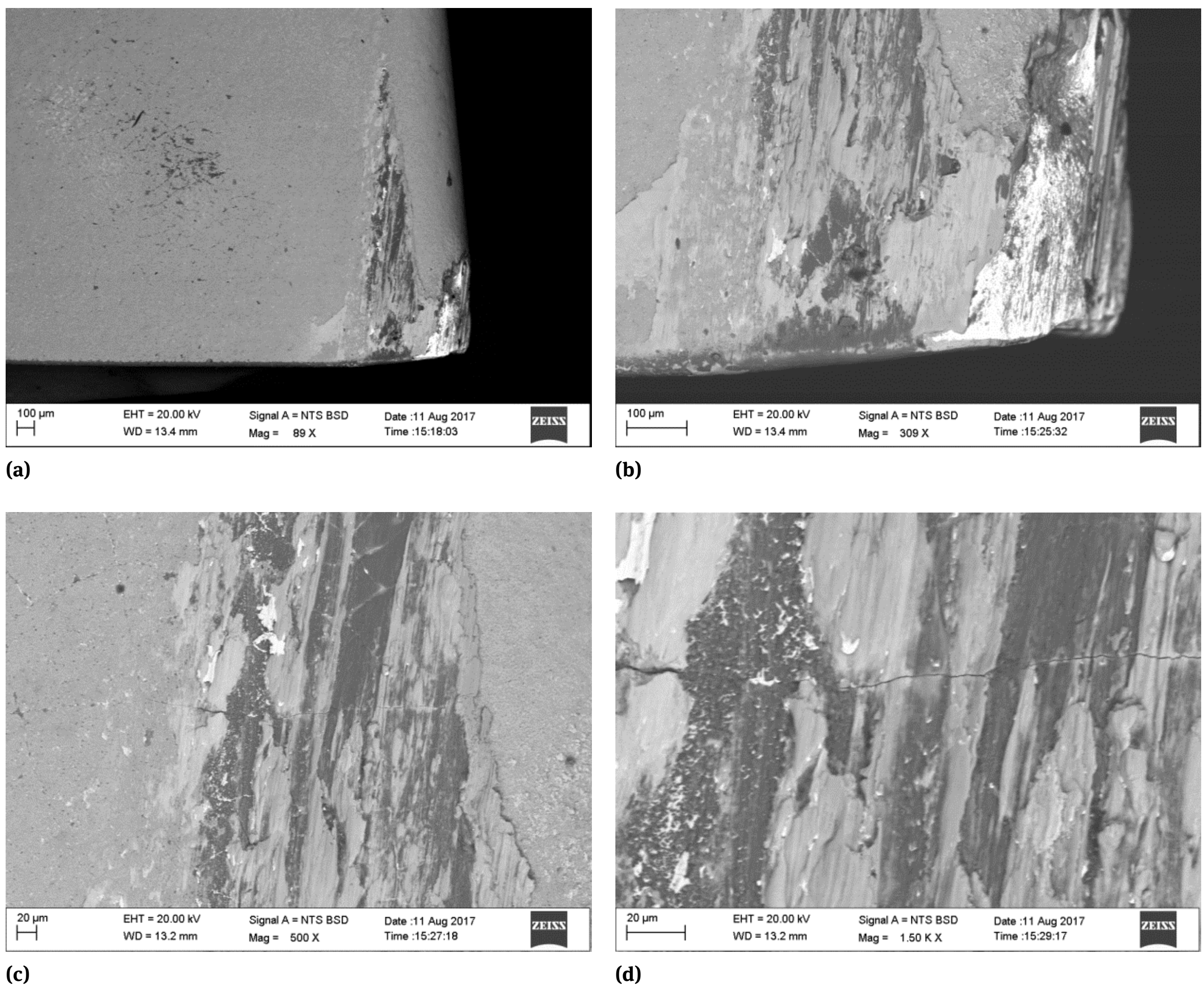


Figure 12: SEM images of the worn nose and flank face of the cutting tool for machining under flooded machining condition

5.2.1 Analysis of variance (ANOVA) for tool-work interface temperature

The value of 'Prob. > F' in Tables 6, 7 and 8 for the model is less than 0.05, which indicates that the model is significant; this is enviable, as it indicates that the terms in the model have a significant effect on the tool-work interface temperature. From ANOVA results, it was evident that cutting velocity has a higher influence on the tool-work interface temperature, followed by the depth of cut and feed rate for the three machining conditions. This coincided with the existing theories of machining.

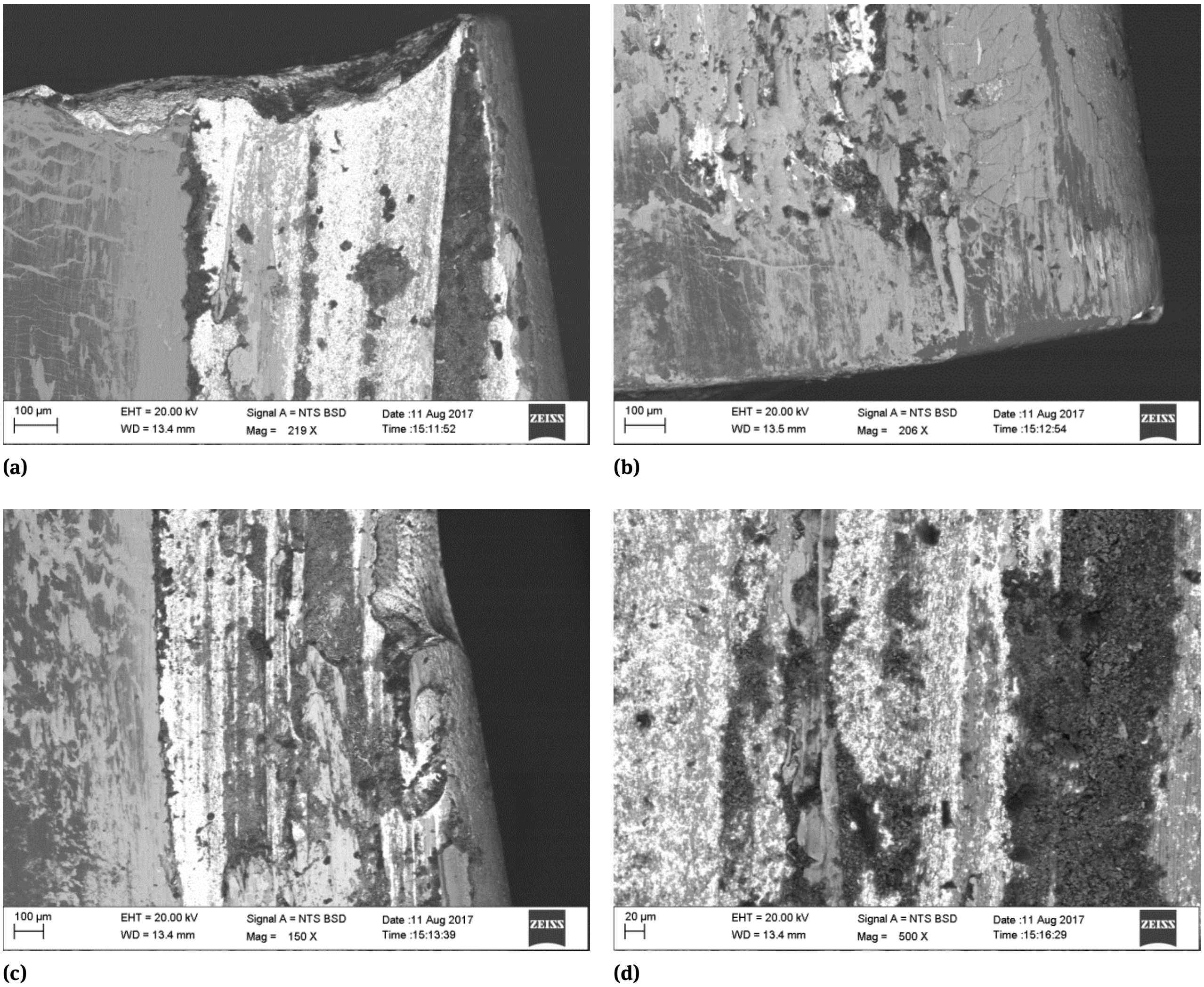


Figure 13: SEM images of the worn nose and flank face of the cutting tool for machining under near-dry machining condition (Servocut 'S' emulsion)

5.3 Mathematical Modelling

In this study, generalized non-linear mathematical models were developed and the effect of machining parameters on tool-work interface temperature (T) under flooded, near-dry and dry machining conditions were modelled by using regression analysis tool available in MINITAB 17 statistical software package. The mathematical equations are given below:

$$T_{-flooded} = 13.5 + 10.22v + 10.48f + 14.5d + 4.82v^2 + 0.52f^2 \quad (1)$$

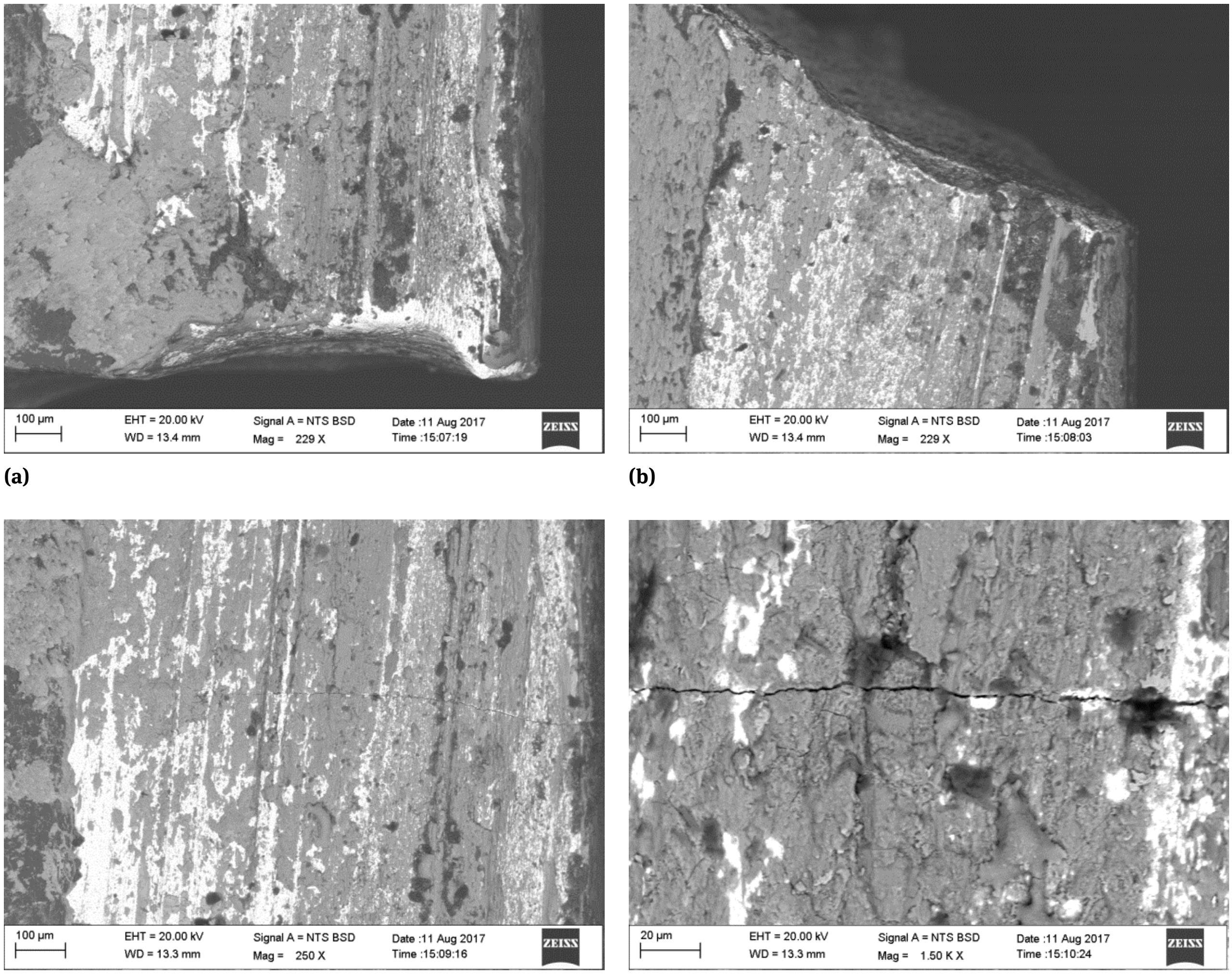
$$T_{-near-dry} = 25.8 + 11.21v + 8.60f + 16.98d + 3.94v^2 + 1.06f^2 - 0.84d^2 \quad (2)$$

$$T_{-dry} = 188.3 + 14.39v + 15.12f + 20.54d + 6.89v^2 + 0.69f^2 + 0.02d^2 \quad (3)$$

For the above mathematical equations, it was found that the values of r^2 were 0.98, 0.97 and 0.98 for flooded, near-dry and dry machining conditions respectively, where 'r' is the correlation coefficient and the value range of 'r^2' should be between 0.8 and 1 [26]. The value of 'r^2' indicates the closeness of the mathematical equations representing the output response.

5.4 Scanning Electron Microscopy analysis

Figure 12 illustrates the scanning electron microscopy results of the worn nose and flank face of the cutting tool for



(a) **(b)** **(c)** **(d)**

Figure 14: SEM images of the worn nose and flank face of the cutting tool for machining under dry machining condition

machining under flooded condition. The cutting tool insert was found fractured (nose wear) at the tool nose (Figure 12(a)); flaking associated with flank wear was observed at the flank face (Figure 12(b)); attrition of adhering chips was also observed at the cutting tool (Figure 12(c) and Figure 12(d)).

Figure 13 illustrates the scanning electron microscopy results of the worn nose and flank face of the cutting tool for machining under near-dry condition. The cutting tool insert was found fractured (nose wear) at the tool nose (Figure 13(a)); flaking associated with flank wear was observed at the flank face (Figure 13(b)); attrition was also observed at the cutting tool (Figure 13(c) and Figure 13(d)).

Figure 14 illustrates the scanning electron microscopy results of the worn nose and flank face of the cutting tool for machining under dry condition. The cutting tool insert was found fractured heavily (nose wear) at the tool nose (Figure 14(a)); flaking associated with flank wear was observed at the flank face (Figure 14(b)); attrition was also observed at the cutting tool (Figure 14(c) and Figure 14(d)).

6 Conclusion

Any machining process is required to produce products with a good surface finish so as to improve the quality of the product. Inherently, machining processes utilize lubricants to improve the tool and work properties along with the quality of the finished product. However, certain drawbacks of using flooded lubricants are reported in the literature, namely unclean work environment, increased lubricant cost and health hazard to the operator. In order to overcome these drawbacks of flooded lubrication, the use of NDM is finding more applications in the recent scenario.

Based on the tool-work interface temperature test conducted on AISI 4340 steel during turning operation with titanium nitride coated carbide insert under flooded, NDM and dry machining conditions, this research work is concluded with the following key points:

(i) From the average tool-work interface temperature chart plotted for the three machining conditions, it was evident that the tool-work interface temperature under NDM condition deviates 9.16% from the tool-work interface temperature observed under flooded condition. But in the case of dry condition, it was poorer than the flooded and near-dry condition. So, NDM aids the performance of machining. The comparison chart of tool-work interface temperature for the three machining conditions is depicted in Figure 15.

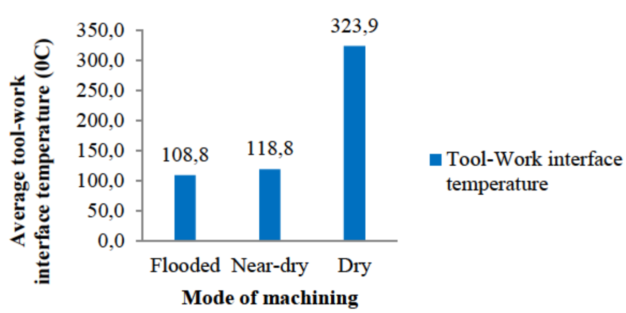


Figure 15: Comparison chart of tool-work interface temperature

(ii) From the experimentation for flooded, NDM and dry machining conditions, it could be concluded that cutting velocity has a greater effect on the tool-work interface temperature followed by the depth of cut and feed rate for the three machining condition, which was proven by ANOVA and F-test results.

(iii) Non-linear regression models were developed for tool-work interface temperature. From those equations, the tool-work interface temperature value could be computed if the parameters, namely cutting velocity, feed rate and depth of cut are known for the three machining conditions, that is, flooded, NDM and dry.

(iv) The scanning electron microscopy results revealed that the cutting tool insert used for machining under dry condition was entirely worn out; however, the wear observed in the cutting tool insert used for machining under the near-dry condition was almost at par with the wear observed in the cutting tool insert used for machining under flooded condition.

(v) During machining under near-dry condition, no coolant spillage or wastage was observed during the entire process, which resulted in no residual coolant to be discarded. Hence, near-dry machining would eliminate any pollution that coolants might generate. Additionally, this led to a clean work environment.

(vi) A measured quantity of 10.5 ml cutting fluid was consumed for the entire machining under the near-dry condition, which was much lesser than the quantity spilled away in flooded machining.

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