Metalworking Fluids Selection and Application Effect on Tool Wear

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Abstract
The research concentrates on finding out the influence of Metalworking fluids (MWFs) on the extent of the wearing of the tools, so the researcher focused on the selection and application of these fluids during the experimentation to find out the influence on the tool life and wearing level. For the experimentation, a machine having a 3-axis CNC machining center Mynx II, equipped with a motor-spindle prime drive of twenty hp (30 kW) vector drive, 12000 rpm, is utilized. After selecting metalworking fluid, delivery method, and cutting conditions, conventional milling was performed on the workpiece with fourteen passes starting each run with a new insert. At the end of each run, the width of the major flank wear land, VB, was measured using an optical microscope. The tool wear land widths are measured through section profile of the cutting edge using Zygo's image processing software. The results are presented that for achieving longer tool life, fluid with higher viscosity should be selected to efficiently reduce the friction between the cutting edge of the tool and the workpiece surface. In addition, the research significantly suggests that when using the flooding and through-spindle cooling (TSC) methods, semisynthetic fluid contributes to the better usage and enhancement of the life of the tools. In contrast, during minimum quantity lubrication (MQL), Emulsion fluid should be selected to achieve a better tool life.
Keywords:
Metalworking Fluids, Tool wear, flooding, minimum quantity lubrication, through-spindle cooling, emulsion fluid, semisynthetic fluid, synthetic fluid.

1. Introduction

The heat generated during the cutting processes of the metals, such as milling, turning, and drilling processes of the metal, can result in the temperature increasing up to seven hundred centigrade. Significantly high temperatures in the cutting process negatively influence the cutting tool and the workpiece [1]. The negative impacts on the workpiece can involve surface burning, the inaccuracy of the dimensions, rapid corrosion, microcracks because of the thermal damage, and significantly damaged surface [2]. Moreover, the impacts of the high heat in the zone of cutting on the surface of the cutting tool also involved the thermal fracture of the tool, deformation of the tool, formation of the building up edge, and the significant wear of the tool, which negatively influences the life of the tool and shortens it as well [2].

Specifically, in the case of tool damage, there are three mechanisms and procedures: thermal, adhesive, and mechanical. There is a significant role of the cutting temperature in promoting the wearing of the tool and reducing the life of the tool [3]. So, lowering the level of temperature during the cutting process is a significant objective, as a very small minimization of the temperature can also result in a significant decrease in the wearing and will increase the life of the tool. So, it has also been found by various researchers that the reduction of the temperature of cutting can enhance the life of the tool by a significant amount. There is a power-dependent relationship between the tool's life, T, and the temperature of the cutting area, t, which is represented by T = C/tn [3].

In this equation, C and n represent the empirically determined constants. Furthermore, by minimizing the temperature of cutting, the total machining cost also decreases significantly. So, the primary focus of the research is on the metalworking fluids and the impacts of the application of these fluids on the wearing of the tools. The metalworking fluids are significantly being utilized to achieve the prolonged life of the tools and maintain the significant dimensional accuracy of these tools with the help of the enhanced lubrication that comes with the metalworking fluids and the cooling capacity of these fluids [5, 6]. However, in some cases, it has also been found that the metalworking fluids can negatively influence the process of machining, like, enhancing the force of cutting with that enhancement in the durability of the workpiece, resulting from minimizing the temperature.

However, in other cases, in the process of operations having interrupted cutting, like the operations of milling, the application of metalworking fluids can significantly enhance the thermal cracking, resulting from the fluctuations in the temperature of the tool, specifically during the process of cutting with high speed [6]. The

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metalworking fluids are significantly directed towards the zone of cutting while trying an effort to increase the cutting performance and by significantly cooling down the heat generated in the secondary and primary share zones. It has been found out by most of the studies that applying metalworking fluids can decrease machining costs in various ways; these fluids significantly minimize the tool cost, with the help of the tool wearing reduction [7].

Furthermore, these fluids also enhance the production rate, and because of this, the machining speed enhances. Thirdly, the labor cost also decreases with the help of the application of these fluids, as the downtime decreases and the labor's engagement time decreases. Furthermore, the application of the fluids also significantly minimizes the extent of energy consumption, which results in the minimization of the frictional forces and the adverse influence of the rough surfaces as well [8, 9]. Recently, green machining has significantly attained much attention, as it is significantly safe for the environment and the operators. Moreover, this process can significantly cut the effort and cost of many machining operations, and an estimation of 20% of the cost of the total machining has been obtained because of the application of metalworking fluids [9, 20].

Some researchers have argued the fact that dry machining is the future of the process of machining; nonetheless, there are various challenges related to this process, like the challenge of overheating, the challenge of lower resultant production, lower extent of operation speed, lower level of rust protection and the lower level of to life as well [10]. The process of heat transfer during the operations of cutting metal can significantly involve the usage of metalworking fluids; however, it depends on the selection of the fluid and the criteria and method of the application. Moreover, some other factors and operations can impact this process, like the factor cutting conditions, workpiece, tool geometry, and the tool's material. In the process of cutting the metal, it has been found that around 98% of the mechanical energy that is being produced is directly converted into another form of energy which is the heat in energy, whereas the rest of the two percent of the energy remains in the form of plastic energy, within the chips that are being produced [11, 17].

The researchers have divided the metal cutting heat into three different types of territories. The first one is known as the primary shear zone. The second one is known as the deformation zone, whereas the third is called the tertiary deformation zone. The first zone is the zone where the heat is generated resulting from the elastoplastic form of deformation, and it is the one representing around 80% of the accumulative heat generated in the process of cutting [11]. The second zone is the one in which the heat is being produced because of the deformity in the chipped plastic, and it consists of around 18% of the accumulative heat produced during the process of cutting. Furthermore, the third zone is the one that represents the smallest amount of the generated heat, and it is also considered the least significant amount and zone for heat generation, as it is around 2% of heat only [12].

Wickramasinghe, Sasahara, Abd Rahim, and Perera (2020) have significantly estimated that there is a significant role of the removed chips in the dissemination of most of the heat in the zone of cutting. This accounts for around 80% of the produced heat, whereas 20% of the rest of the heat is significantly divided between the cutting tool and the workpiece, which stores and absorbs that generated heat and later is released after a specific time [13].

2. Applications of the metalworking fluids and properties

Various researchers have found the benefits of applying the fluids during metalworking, as these result in a significant reduction in the temperature of cutting, During the different procedures and operations of machining. Indeed, the fluid for metalworking significantly dissipates around 96% of the heat generated during the operations of the cutting tool and the piece of work because of the conviction of the forces. Following the research work of Sun et al. (2013), it has been found that the coolant application can enhance the extent of heat minimization or generation during machining, up to a 90% level. While utilizing the heavier and significantly aggressive methods of cutting, in the case of a low level of application of speed, fluids having a significantly high level of viscosity are considered the best material of application [10].

On the other hand, in the case of significantly high-speed cutting operations, there is a requirement for metalworking fluid that has a significantly great extent of specific heat, and it is preferred over the other properties [11]. The properties associated with these fluids, including the specific heat of the fluids, the extent of viscosity of the fluids, and the consistency of the fluids, have a significant impact on the processes of cutting compared to all the other properties. As experts have found out, the specific heat and the viscosity of the metalworking fluids can promote the lubrication capability of the fluids, and these can also significantly increase the cooling ability of these fluids. Hence, it results in a better extent of control and the machining operations in the process [12].

3. Method and Materials

3.1. Apparatuses used

Machine: A machine having 3-axis CNC machining center Mynx II, equipped with a motor-spindle prime drive of twenty hp (30 kw) vector drive, 12000 rpm.
Cooling Capability of the machine: The machine has a built-in 60-gallon (272 liters) flood coolant system. Through-spindle coolant system was installed, which enables the machine to provide close to 350 psi, equal to around twenty-four bars of the coolant, into the cutting tool, resulting in a significantly heavier level of cuts and maximized high feed rates and better surface finishes. An external Accu-Lube precision pump applicator is used to perform a minimum level or quantity of the lubrication, also called the MQL or "near-dry machining," also known as the NDM. The chosen flow rates were for flood, MQL, and cool 8 liter/min, 60 ml/h, and twenty-five liter/min, respectively [13].

Tool: The tool involves "PVD multilayer-coated" (TiAlN) or the "TN 6010 carbide" inserts for cutting that are placed into the indexable Ingersoll, having a single flute and mill holder for the tool (PCLNR2525M12) with a nominal diameter of 13 mm.

Workpiece: The workpiece is a block of AISI 4340 is a low alloy steel "**0.4% C, 0.8% Cr, 0.25% Mo and 1.8% Ni**." With HRC 24/53 hardness. The dimensions of the block are L=1800, W=90, H=100 mm.

Metal Working Fluids: Three at 15% concentration metalworking fluids were used in the experiment, (Emulsion, semisynthetic and full Synthetic) [14]. Table 1 shows their properties at 15% concentration. The table provides the details of the kinematic viscosity of the emulsion, semi-synthetic and synthetic metalworking fluids, from 1.4945E-06, 1.2923E-06 to 1.1160E-06, respectively. Moreover, the specific heat is 3307, 3986, and 3831, respectively. Furthermore, the table represents the density of the metalworking fluids, ranging from 979, 988 to 990, respectively [14, 25].

Table 1. Metalworking fluids properties at 21 °C

Fluid	**Kinematic Viscosity**	**Specific Heat**	**Density**
	(M^2/S)	$(J/Kg \cdot K)$	(Kg/M^3)
Emulsion	1.4945E-06	3307	979
Semisynthetic	1.2923E-06	3986	988
Synthetic	1.1160E-06	3831	990

3.2. Procedures

After selecting metalworking fluid, delivery method, and cutting conditions, conventional milling was performed on the workpiece with fourteen passes starting each run with a new insert. At the end of each run, the width of the major flank wear land, VB, was measured using an optical microscope (smart scope FOV, 128X), and the surface metrology of the insert was analyzed using a 3D Optical Surface Profilers (ZYGO, two hundred). The tool inspections are made at regular intervals with an optical microscope, Zygo New View 5000 microscope, which uses white light interferometry to produce images of surface topography. The tool wear-land widths are measured through section profile of the cutting edge with Zygo's powerful image processing software, MetroPro [15].

3.3. Design of the experiment

Experimental investigations were conducted to evaluate metalworking fluids selection and application effect on the tool wear. Three metalworking fluids under three delivery methods were used to study the effect of fluid properties, application, and cutting conditions on cutting performance. Two hundred forty-three runs were undertaken, consisting of nine separate experiments with varied cutting conditions, and conducted depending on the fluid type and delivery method [16, 17]. Each experiment contains a thirty-three full-factorial design to effectively capture the relationship between the controllable variables, which are speed of cutting (Vc), feed of cutting (f), and cutting axial depth (ap), and dependent variables (flank wear land, VB). The factor levels were selected based on the recommendations of the Ingersoll technical guide, as represented in table 2.

Table 오류! 지정한 스타일은 사용되지 않습니다.. Added parameters and the recorded levels

Parameters	Notation	Units	Levels		
			-1	0	1
Cutting speed	V_C	M/min	120	140	160
Cutting feed	F	Mm/rev	0.075	0.085	0.095
Axial depth of cut	A_p	Mm	1.25	1.5	1.75
Fluid Type			Emulsion	Semisynthetic	Synthetic
Application			Flood	MQL	TSC

Table two represents the included parameters for the study, along with the recorded levels, the cutting speed, cutting feed, axial depth of the cut, fluid type, and application is represented in the table, along with the notations, units, and levels.
Furthermore, after the experimentation and collecting the desired data, the researcher has utilized the software Microsoft Excel and SPSS for data analysis. The data has been presented in the section on results and discussion, along with the figurative and tabular forms of the results that the researcher has obtained as the outcomes of the current research [17].

4. Results and discussion

This section presents the results of the experimentation and research, along with the discussion regarding the results, in association with the other research and studies. This section significantly adds to the significance of relevant studies, the work of the relevant researchers, and the previous data that also supports the research results.

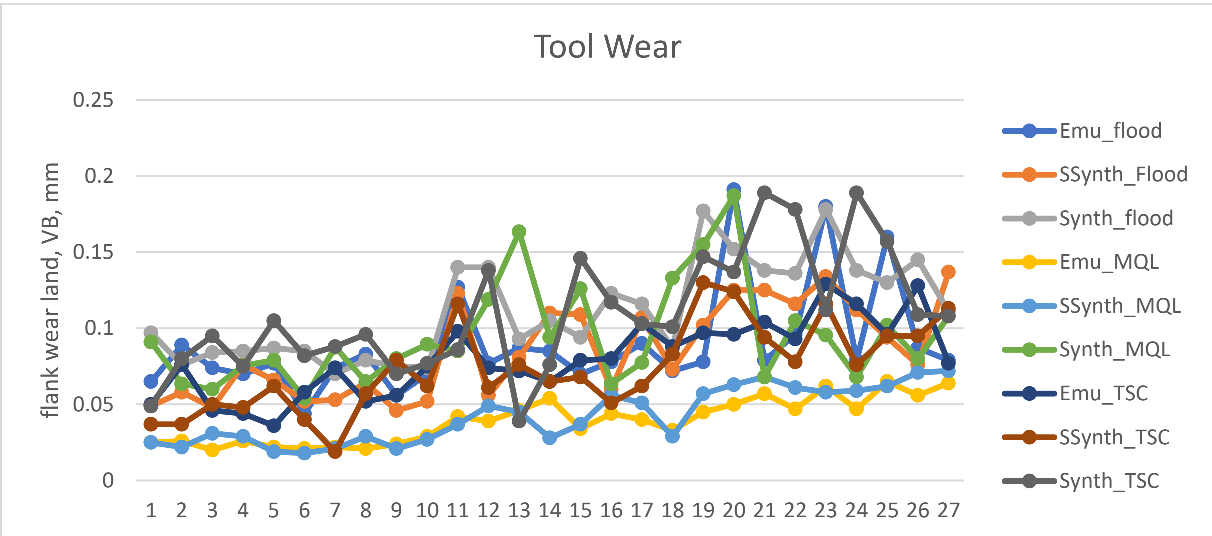

Figure 1. Comparison of the tool wear

In the first run, the tool wear is highest for the Synth_MQL, equal to 0.054, whereas the lowest tool wear is for the ssynth_MQL and is equal to 0.018. In the case of the second run, Synth_flood has the highest tool wear, whereas, in the case of ssynth_MQL, there is the lowest extent of tool wear; both values are equal to 0.074 and

0.019, respectively. In the case of the third run, the highest level of tool wear is for Synth_flood, equal to 0.075, whereas the lowest level of tool wear is for, Emu_MQL, and the value for this is equal to the value of 0.021. In the fourth run, the highest level of wearing of the tool is for Synth_flood 0.076, and the lowest level of tool wear is for Emu_MQL 0.021.

In the fifth run, the significantly high level of tool wear is associated with Synth_flood 0.079, and the lowest level of wearing of tools is associated with the fluid Emu_MQL 0.022 and ssynth_MQL 0.022 both. In the sixth run, the significantly high level of tool wear is associated with Synth_flood 0.084, and the lowest level of wearing of tools is associated with the fluid Emu_MQL 0.024. In the seventh run, the significantly high level of tool wear is associated with Synth_flood 0.085, and the lowest level of wearing of tools is associated with the fluid Emu_MQL 0.025. In the eighth run, the significantly high level of tool wear is associated with Synth_flood 0.085, and the lowest level of wearing of tools is associated with the fluid Emu_MQL 0.026. In the ninth run, the significantly high level of tool wear is associated with Synth_flood with a value equal to 0.087, and the lowest level of wearing of tools is associated with the fluid Emu_MQL, with a value equal to 0.026. In the case of the tenth run, the significantly high level of tool wear is associated with Synth_TSC 0.088, whereas the lowest level of wearing of tools is associated with both fluids Emu_MQL ssynth_MQL equal to a value of 0.029.

Furthermore, for the eleventh run, the significantly low level of tool wear is associated with ssynth_MQL 0.029, and the high level of wearing of tools is associated with the fluid Synth_TSC 0.095. For the thirteenth run, the lowest level of wearing of tools is associated with the fluid ssynth_MQL 0.031; the significantly high level of tool wear is associated with Synth_TSC 0.096. Whereas, for the twenty-seventh run greatest extent of tool wear is associated with the fluid Emu_flood with a value equal to 0.191, whereas the lowest value of tool wear is associated with the fluid Emu_MQL, with a value that is equal to 0.065.

Figure 2 below represents the accumulative frequency of tool wearing, liquid wise, to assess the lowest and highest extent of a cumulative frequency of the wearing of the tools after the application of metalworking fluids.

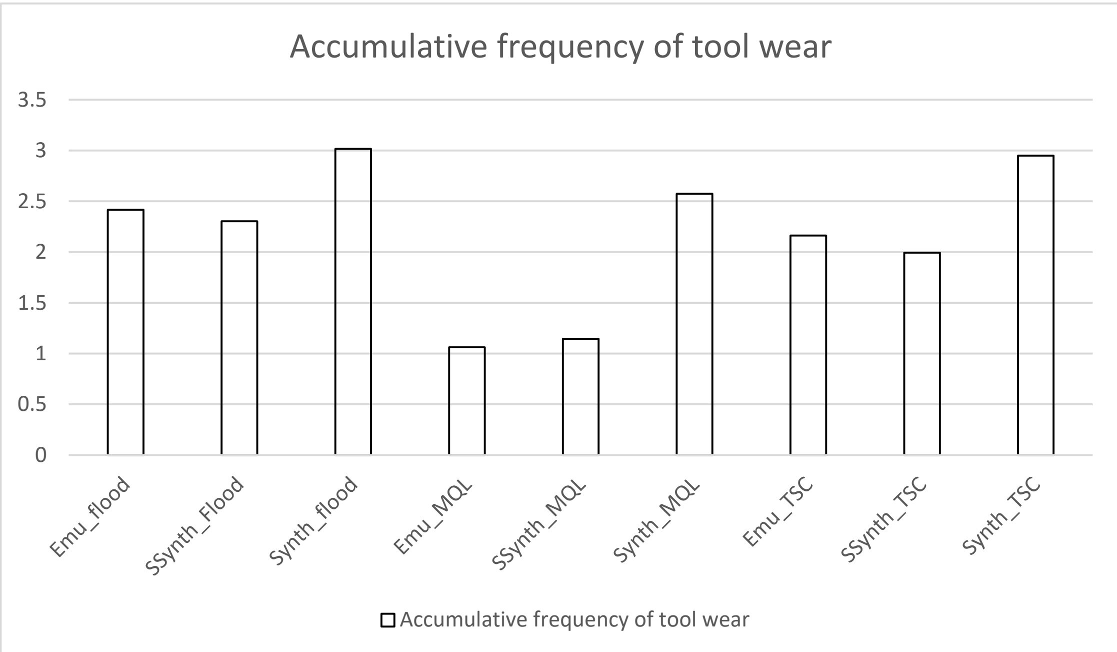

Figure 2. Accumulative frequency of tool wear

In the case of the total or accumulative tool wear, the lowest level can be observed in the case of the fluid Emu_MQL with a value equal to 1.061, then comes the fluid ssynth_MQL for the value 1.145, then comes the tool wear for the fluid ssynth_TSC, having a value of 1.994, furthermore, at the fourth position, the fluid is Emu_TSC, with a value 2.162. Moreover, the fluid ssynth_Flood has a level of tool wear having a value equal to 2.304, whereas, after this, there is the fluid Emu_Flood, with the value of tool wear equal to 2.417; after this, there is the fluid Synth_MQL, with the value 2.574, and after this comes the fluid Synth_Flood, with the value 2.949. Whereas the fluid with the highest value of tool wear is Synth_flood, having the value of 3.015.

Table three compares the tool wear, representing the maximum amount of the wearing of the tool, the average amount of the tool wear, and the sum of the wearing of the tool during the processes of experimentation.

Table 3. Comparison of the tool wear

	Emu flood	**SSynth Flood**	**Synth flood**	**Emu MQL**	**Ssynth MQL**	**Synth MQL**	**Emu TSC**	**SSynth TSC**	**Synth TSC**
Maximum wear	0.191	0.137	0.178	0.065	0.072	0.187	0.129	0.13	0.189
Average wear	0.0895	0.0853	0.1117	0.0393	0.0424	0.0954	0.0801	0.0739	0.1092
Sum of wear	2.417	2.304	3.015	1.061	1.145	2.5749	2.162	1.994	2.949

For Emu_flood, the maximum amount is 0.191, the average amount is 0.0895, and the maximum amount or some of the wearing equals 2.417. For ssynth_Flood, the maximum amount is equal to 0.137, the average amount equals 0.0853, and the sum of all the amounts equals 2.304. For Synth_flood, the maximum total amount is equal to 0.178, the average amount is equal to the value 0.1117, whereas the sum of the amounts is equal to 3.015. For Emu_MQL, the maximum value is equal to the value of 0.065, the average value is equal to the number 0.0393, whereas some of the included values are equal to 1.061.

For ssynth_MQL, the maximum value is equal to 0.072, the average value equals 0.0424, and the sum of all the values equals 1.145. For Synth_MQL, the maximum amount is 0.187, the average amount is equal to 0.0954, and the total of all the values equals 2.5749. For Emu_TSC, the maximum value is equal to the amount 0.129, the average value equals the amount 0.0801, and the sum of the included values equals 2.162. For ssynth_TSC, the maximum value is equal to 0.13, the average value equals 0.0739, and the sum of the amounts of tool wearing is equal to 1.994. However, for Synth_TSC, the maximum amount is equal to 0.189, the average of tool wearing is 0.1092, and the sum of tool wearing equals 2.949.

Table four presents the validity analysis, and the results are presented for the WOC (1.3, 1.6 mm), the feed (0.08, 0.09 mm/rev), the speed (130, 150 m/min), and the included metalworking fluids.

Table 4. Test of validity

Validation	**Emu flood**	**SSynth Flood**	**Synth flood**	**Emu MQL**	**Ssynth MQL**	**Synth MQL**	**Emu TSC**	**SSynth TSC**	**Synth TSC**
V1	0.053	0.048	0.07	0.035	0.034	0.039	0.063	0.052	0.078
V2	0.062	0.055	0.082	0.038	0.036	0.0415	0.072	0.059	0.105

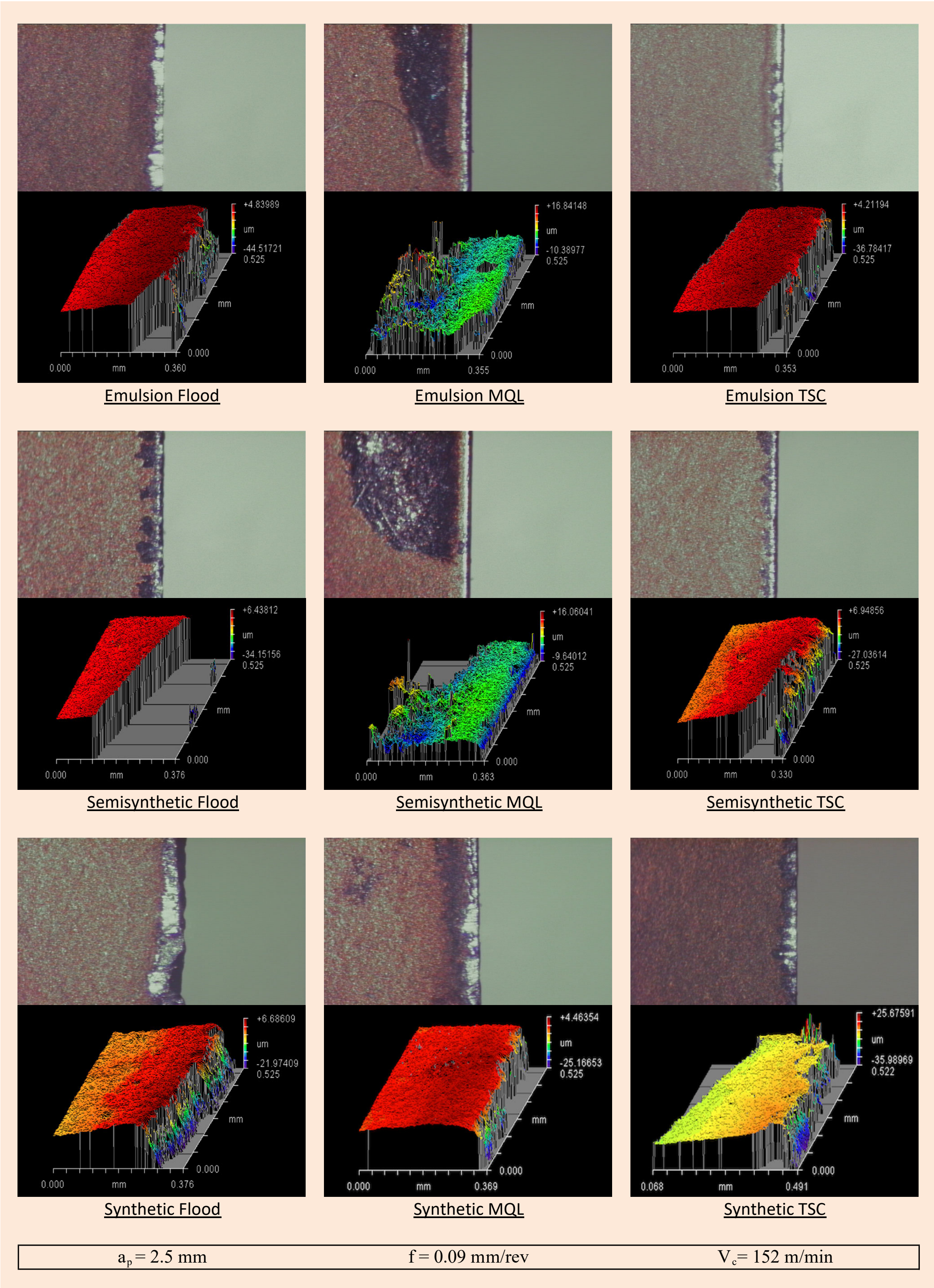

Figure 3. The effect of MWFs and applications on tool flank wear

Figure 3 represents the influences of the metalworking fluids on the tool flank wear. In this way, it is being observed that what is the influence of the applications of different fluids. The figure represents the insert photograph after 50 minutes of the operation in conjunction with high-pressure waterjet cooling in Fig. ll(a), and the corresponding insert used in the case of flood cooling is shown in Fig. ll(b). It can be observed that the width of flank wear is much higher in the case of flood cooling as compared to that in the case of high-pressure waterjet cooling, indicating a longer tool life in the case of high-pressure waterjet cooling. Moreover, the figure reveals the nature and extent of tool wear in the three environments.

The photographs were taken at the end of the tool life for all three environments. At the center points, the high-pressure water-soluble oil is much more effective in enhancing tool life than neat high-pressure oil. Close examination of the crater surface reveals a significant amount of crater wear at the end of tool life under all the environments. By the research and experimentation results, it is proposed by the researchers that there is a significant influence of the different metalworking fluids on the operations, working, and life of the tools being utilized [17, 24].

The results are in accordance with the previous research work and studies as well, as in accordance with the research works [18], [19], and [20] as well, there is a significant influence of the metalworking fluids on the extent of the quality of work, operations, and extent of life of the tool being utilized for the operations. Furthermore, in accordance with the study of Outeiro, Lenoir, and Bosselut (2015) as well, the total usable life of the tool can be positively enhanced and improved with the help of the application of proper and suitable metalworking fluid. So, the results also show a significant improvement in tool life after applying the suitable and proper metalworking fluid to the tool [22, 23].

As a result of the outcomes of this research, it has been found that with the application of the MQL on the tool, it has been observed there was a 38% decrease in the wear of flank in comparison with the fluid flood. However, a 33% lesser level of wearing was observed in the case of the application of TSC as well. So, MQL developed 38% less flank wear than flood and 33% less than TSC application. Furthermore, the application of TSC resulted in the tool flank wear, which was significantly around 8% less, so it represents significant results as well [21]. Furthermore, according to Schwarz et al. (2015), TSC application produced around 10% less tool flank wear. So, the results are significantly close and similar, which enhances the validity and authenticity of the results. Semi-synthetic fluid developed 37% less flank wear than Synthetic fluid and 4% less than emulsion fluid. These results are also in line with the study results of Oh (2012), which proposes that semi-synthetic fluids significantly minimize the extent of the wearing of the tools while positively and significantly influencing the usable life of the tools.

Furthermore, the emulsion fluid developed 34% less flank wear than synthetic fluid. Semisynthetic fluid produced the lowest flank wear (24% less than synthetic and 5% less than emulsion). During MQL application, emulsion developed the least tool flank wear (59% less than synthetic fluid and 7% less than semisynthetic fluid) [18]. During TSC application, semisynthetic fluid developed the lowest tool flank tool wear (32% less than synthetic and 8% less than emulsion fluid). These results are presented because for achieving longer tool life, fluid with higher viscosity should be selected to efficiently reduce the friction between the cutting edge of the tool and the workpiece surface [19]. These results are also supported by the analysis conducted in the study, and it can be observed that the fluids that have a higher level of viscosity represent a higher level of efficiency and the achievement of longer life for the tools [20].

5. Summary and conclusion

The research was focused on finding out the influence of metalworking fluids on the extent of the wearing of the tools, so the researcher focused on the selection and application of these fluids during the experimentation to find out the influence on the tool life and wearing level. For the experimentation, a machine having a 3-axis CNC machining center Mynx II, equipped with a motor-spindle prime drive of twenty hp (30 kW) vector drive, 12000 rpm, is utilized. After selecting metalworking fluid, delivery method, and cutting conditions, conventional milling was performed on the workpiece with fourteen passes starting each run with a new insert. At the end of each run, the width of the major flank wear land, VB, was measured using an optical microscope. The tool wear land widths are measured through section profile of the cutting edge using Zygo's powerful image processing software. The results present that for achieving longer tool life, fluid with higher viscosity should be selected to efficiently reduce the friction between the cutting edge of the tool and the workpiece surface. The research significantly contributes toward the better usage and enhancement of the life of the tools with the application of metalworking fluids.

There is a significant role of the cutting temperature in promoting the wearing of the tool and reducing the life of the tool. So, lowering the temperature level during the cutting process is a significant objective, as an exceedingly small minimization of the temperature can also result in a significant decrease in the wearing and will increase the life of the tool as well. So, it has also been found by various researchers that the reduction of the temperature of cutting can enhance the life of the tool by a significant amount. The metalworking fluids are significantly being utilized to achieve the prolonged life of the tools and maintain the significant dimensional accuracy of these tools with the help of the enhanced lubrication that comes with the metalworking fluids and the cooling capacity of these fluids. The process of heat transfer during the operations of cutting metal can significantly involve the usage of metalworking fluids; however, it depends on the selection of the fluid and the criteria and method of the application.

The properties associated with these fluids, including the specific heat of the fluids, the extent of viscosity of the fluids, and the consistency of the fluids, have a significant impact on the processes of cutting compared to all the other properties. After selecting metalworking fluid, delivery method, and cutting conditions, conventional milling was performed on the workpiece with fourteen passes starting each run with a new insert. At the end of each run, the width of the major flank wear land, VB, was measured using an optical microscope, and the surface metrology of the insert was analyzed using a 3D Optical Surface Profilers. The tool inspections are made at regular intervals with an optical microscope, Zygo New View 5000 microscope, which uses white light interferometry to produce images of surface topography. The tool wear land widths are measured using the section profile of the cutting edge using Zygo's image processing software.

In accordance with the results, MQL developed 38% less flank wear than flood and 33% less than TSC application. TSC application produced around 8% less tool flank wear. Semisynthetic fluid developed 37% less flank wear than Synthetic fluid and 4% less than emulsion fluid. Emulsion fluid developed 34% less flank wear than synthetic fluid. Semisynthetic fluid produced the lowest flank wear (24% less than synthetic and 5% less than emulsion). During MQL application, emulsion developed the least tool flank wear (59% less than synthetic fluid and 7% less than semisynthetic fluid). During TSC application, semisynthetic fluid developed the lowest tool flank tool wear (32% less than synthetic and 8% less than emulsion fluid). These results reveal that fluid with higher viscosity should be selected to efficiently reduce the friction between the edge of cutting of the tool and the workpiece zone to achieve longer tool life.

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