Investigate the Machining Performance in High Speed Milling of AISI304 Stainless Steel using Thin Pulse Jet and Fluid Atomizer MQL Systems

A. Hamdan, M. Sayuti, Ahmed A. D. Sarhan, and M. Hamdi

Abstract**—** Austenitic stainless steel materials, i.e. AISI 304, have been widely used in many areas such as automotive and aerospace industries. AISI 304 austenitic stainless steel is categorized under a group of materials that are very hard to be machined. Machining operations of austenitic stainless steels are usually accompanied by a number of difficulties such as poor surface, irregular wear and premature tool failure. The poor machinability of this material is usually due to very low heat conductivity (50% of that of plain carbon steels), high ductility, high tensile strength, high fracture toughness and high work hardening rate. Metal working fluid is key solution to control the temperatures during machining. However, the use of cutting fluid has become more problematic in terms of employee health and environmental pollution. Thus, it is become important to minimize the use of cutting fluid in machining operations. Therefore, as an alternative, the strategy of minimum quantity lubrication (MQL) is recently introduced in machining operations. In this research, the optimization of two different MQL methods (thin pulsed jet and fluid atomizer) to reduce surface roughness and cutting force during high speed machining of AISI 304 stainless steel is investigated. The result and analysis from the Taguchi Method shows that depth of cut has been found as the most significant parameter affecting the cutting performance compared to the other machining parameters for both MQL methods. However, the strategy of cooling by the thin pulsed jet mode demonstrated a slightly better performance than that of the fluid atomizer mode.

Keywords**—** Machining performance; Stainless steel; MQL; Taguchi optimization; High speed milling

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I. Introduction

NOWADAYS, the trend of manufacturing industry particularly in advance machining operations is focusing on using different type cooling techniques for better machining performance as well as environmental friendly.

The conventional coolant method as based on a flooding system is not always effective as the coolant often fails to penetrate into the tool chip interface during the machining process [1]. Besides, due to the increment in environmental concerns caused by the damage brought from the coolant disposal and the cost involved because of cutting fluid recycling in bulk quantities [2], there is a strong tendency to eliminate or minimize the application of coolant in machining operation. Moreover, cutting fluid is hazardous and it would cause such as skin and breathing problems to the machine operators [3].

A survey which was carried out in the Germany automotive industry showed that the manufacturing costs incurred as a result of the consumption of cutting fluid is 7-17% of the total production cost which is relatively high compared with the 2-4% of total production cost associated with tooling [4, 5].

As a result of the advances in machine tool design and cutting tool technology, milling at high rotational speeds, known as High Speed Milling (HSM) has become a cost-effective manufacturing process. HSM designates an innovative and high-performance process in which the employed spindle speed is considerably high. Nonetheless, HSM faces the problem of rising temperatures during machining which would affect the tool life and machining quality. Hence, metal working fluid is very important to act as a coolant and lubricant [6].

A viable solution suggested by many researchers for the increasing demand to reduce the application of coolant in metal cutting by employing the minimal quantity lubrication techniques which provide the only sufficient amount of coolant to effectively cool down the cutting zone and supply necessary lubrication. Varadarajan, et al. [7], Thepsonthi, et al. [8] and Marzurkiewicz, et al. [9] indicated that the method of coolant application with high pressure jet could give better machining performance in terms of cutting force, tool life, surface finish, cutting temperature and tool-chip contact length. Machado and Wallbank [10] conducted machining experiments using a venturi to mix compressed air (the air pressure was 2.3 bar)

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with small quantities of liquid lubricant, water or soluble oil (the mean flow rate was between 3 to 5 ml/min). The literature also indicates that the MQL has many advantages in terms of environmental, economic and better machining quality. When dealing with steel materials, most of the research and applications of MQL are mainly focused on the milling and turning operations [4, 7, 9-16]. In addition, the investigations on high speed milling by using MQL technique are required further study especially on machining hardened steel and stainless steel [2, 17, 18]. Based on the literature above, the main objective of this research is to investigate the effect of MQL when milling a stainless steel material using the techniques of thin pulsed jet and fluid atomizer systems in HSM conditions.

II. Experimentation

A. Design of experiment

Robust design is an engineering method to obtain information about the process and product conditions. With very minimal sensitivity to the deviation of various causes, this approach can establish experimental procedures of relatively low cost. Taguchi designed an efficient tool for robust design, which offers a simple and systematic approach that optimize the design for performance, quality and cost [19]. The factors and levels used in this experiment and the standard $L_9\ (3)^3$ orthogonal array are specified in Table I and Table II, respectively. The values of depth of cut and feed rate were selected based on the tool manufacturer's recommendation. Meanwhile, the cutting velocity was chosen after being increased three times from the conventional machining parameter in order to run the experiment in the HSM condition. Further analysis was conducted using analysis of variance (ANOVA) for each cutting mode. Based on the results from the analysis, a confirmation experiments were conducted to validate the indicated findings.

B. Experimental details

The experiments were conducted on a vertical high-speed machining centre (MITSUI SEIKI VT3A) of 15 kW spindle power with a maximum spindle speed of 20,000 min^{-1} and 10 m/min of maximum cutting feed. The workpiece used was stainless steel AISI 304 (85.1HRB) and it was prepared as a 50 × 50 × 220 mm^3 rectangular block. Slot milling process using thin pulsed jet and fluid atomizer systems were separately conducted. The characteristics of the two coolant systems are shown in Table III. The coolant ECOCUT SSN 322 neat oil (FUCHS), with 40.2 cSi at 40ºC is used as the MQL oil for both thin pulsed jet and fluid atomizer system. KORLOY carbide insert with an ISO designation of APXT 11T3PDSR-MM coated with TiAlN, shown in Fig. 1, was mounted on a 12 mm diameter KORLOY Alpha mill tool holder.

TABLE I
THE CONTROL FACTORS AND EXPERIMENTAL CONDITION LEVELS

Factor	**Level (*i*)**		
	1	2	3
A- Cutting speed (m/min)	300	350	400
B- Feed rate (mm/tooth)	0.05	0.1	0.15
C- Depth of cut (mm)	0.5	0.75	1

TABLE II
STANDARD $L_9\ (3)^3$ ORTHOGONAL ARRAY

Tests	Level of input process parameter (i)		
	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

TABLE III
CHARACTERISTICS OF TWO MQL SYSTEMS

Minimal Quantity Lubricant	
Thin pulsed jet system	Pressure: 200 MPa, pulse rate: 400 pulse/min, delivery rate: 2 ml/min
Fluid atomizer system	Air pressure : 7 Bar, Lubricant Pressure: 200 Bar, pulse rate: 400 pulse/min, delivery rate: 2 ml/min

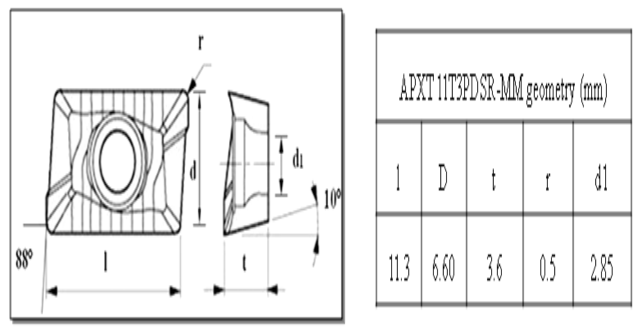


Fig. 1 Geometry of KORLOYS carbide insert

Fig. 2 shows a schematic diagram of the thin pulsed jet system. A minimal fluid delivery system was developed from a conventional diesel injection pump (Bosch pump) which was coupled to a 2.2-kW electric motor. The fluid pulsing frequency was determined by a variable speed motor, which controlling the motor speed. These systems were run using a pintle nozzle (DN0SD21) which has 1 mm of orifice diameter. For the fluid atomizer system, the nozzle was replaced by a mist coolant mechanism nozzle with diameter of 1 mm. High air stream is needed to atomize cutting fluid into small droplets. Fig. 3 shows a schematic diagram of the fluid atomizer system.

The slot milling tests were conducted through the whole length of the workpiece (220 mm). The experiments were run following the orthogonal array that design shown in Table II with three repetitions. During the experiments, the resultant cutting force was recorded via a Kistler three components dynamometer (type 9255B), Kistler charge amplifier and oscilloscope. The workpiece surface roughness, Ra, was measured using a M1 perthometer from Mahr, Germany, with a cut off distance of 0.8mm.

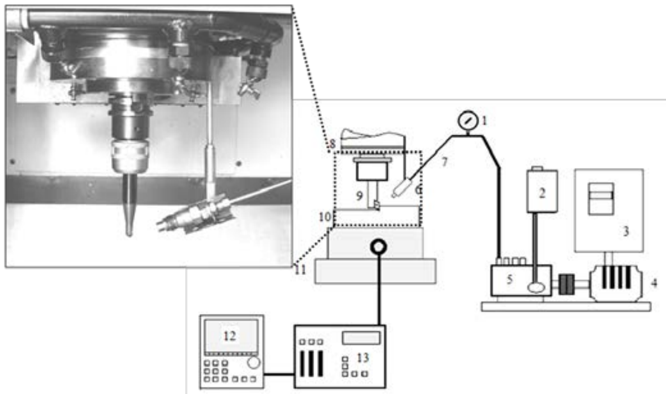


Fig. 2 Thin pulsed jet system experiment set up: 1- pressure gauge; 2- fluid tank; 3- variable speed control drive; 4- electric motor; 5- injection pump; 6- nozzle; 7- steel pipe; 8- spindle; 9- insert tool holder; 10- workpiece; 11- Dynamometer 12-charge amplifier;13- oscilloscope)

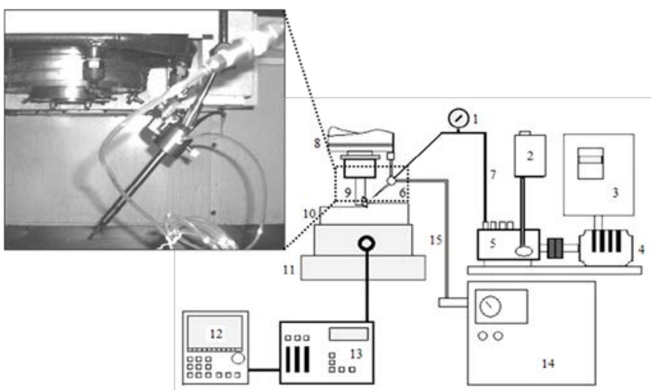


Fig.3. Fluid atomizer system experiment setup: 1- pressure gauge; 2- fluid tank; 3- variable speed control drive; 4-, electric motor; 5- injection pump; 6, mist coolant; 7, steel pipe; 8- spindle; 9, insert tool holder; 10,- workpiece; 11- Dynamometer; 12- charge amplifier; 13- oscilloscope; 14-air compressor; 15-air stream supply

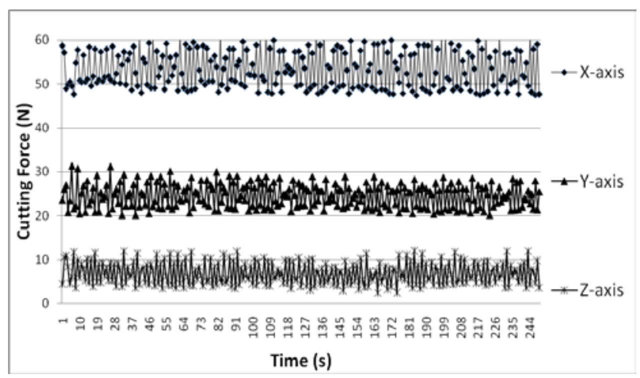
III. RESULTS, ANALYSIS AND DISCUSSION

The experimental tests are carried out using the proposed experimental set-up. The measured values of cutting forces and surface roughness at the different lubrication modes (fluid atomizer system and thin pulse jet system) are summarized in Table IV. As the average of three experimental runs for each test level, Figure 4 (a) and (b) shows an example of measured cutting forces and surface roughness at 300m/min cutting speed, 0.05 mm/tooth feed rate and 0.5 mm depth of cut using fluid atomizer mode.

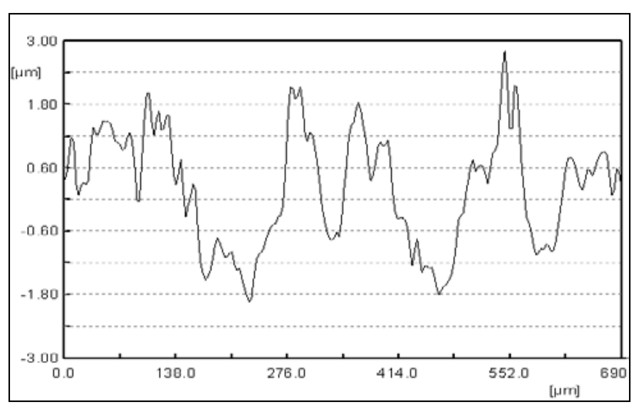
In order to analyze the data, the average of surface roughness and cutting forces are considered as the target performance measure (TPM). These values are used to identify control factors that largely affect the mean. These factors are called target control factors. Target control factors are used to adjust the mean response to the desired target. The type of quadratic loss function applied for this purpose is the smaller the better, where the target value is zero. The percentage contribution, ρ (rho), determines the contribution of a factor to an effect. Experimental error refers to unknown and uncontrolled factors. If the percentage contribution due to error is low (25% or less), then it can be assumed that no important factors have been omitted from the experiment. From point of view of the industry, the maximum allowable percentage of error contribution is not more than 50% [20]. The optimum parameters for each performance analysis are determined from the response table and graph. The minimum value of TPM is chosen as the optimum level for each factor. Then, the suggested optimum parameters were validated through confirmation test to double check the findings.

TABLE IV
THE MEASURED CUTTING FORCES AND SURFACE ROUGHNESS AT DIFFERENT LUBRICATION MODES

Exp. run	Fluid atomizer system mode		Thin pulsed jet system	
	Resultant cutting force, N	Ra, µm	Resultant cutting force, N	Ra, µm
1	38.490	0.924	34.641	0.599
2	55.976	1.577	54.547	1.532
3	86.585	1.144	86.341	1.627
4	31.61	0.739	30.443	0.440
5	48.129	1.487	46.032	0.880
6	70.132	1.508	72.737	0.895
7	28.354	0.848	25.981	0.449
8	40.368	1.508	38.816	1.572
9	67.398	2.192	67.826	3.006



a) An example of measured cutting forces in X, Y and Z-axis directions



b) An example of measured surface roughness

Fig.4. An example of measured cutting forces in and surface roughness at 300m/min cutting speed, 0.05 mm/tooth feed rate and 0.5 mm depth of cut using Fluid atomizer system mode

A. Surface roughness analysis

The degree of predictable performance of a process in the presence of TPM (Target Performance Measurement) is equal to the average of the surface roughness and cutting force. In this case, the smaller the TPM would be the better the result. The calculated TPM values for both lubrication modes are summarized in Table V of measured surface roughness.

As an example of TPM response calculation, A_i is the average of all TPM values corresponding to the same control factor level (i) under A in Tables II and IV. In this case, (i) is equal to 1, 2, or 3. The difference under Ai column is equal to the maximum minus the minimum of the TPM response values. Similarly, TPM response values and the differences are calculated for B_i, and C_i. The rank is given in order from the highest to the lowest difference values. The significance of each factor is determined based on the value of the difference of TPM. The desired "smaller the better" criteria implies that the lowest TPM response would be the ideal result. This is the criteria employed in this study to determine the optimal machining parameters.

Figure 5 is presenting the response graph for selecting best combination levels for lowest surface roughness. Based upon the criteria of smaller TPM response, the axial feed rate (factor B) shown in Fig. 5(a), is found to be of most significant factor affecting surface roughness for thin pulse jet MQL mode. The spindle speed (factor A) is found to be the second most significant factor followed by the depth of cut (factor C). The smallest feed rate (B1, 0.05 mm/tooth) with the medium spindle speed (A2, 350mm/min) and the highest axial depth of cut (C3, 1.0mm) are determined to be the best choices for obtaining the best surface roughness. Therefore, the optimal parameters for the best surface roughness for thin pulse jet MQL mode are set as A2 B1 C3. The confirmation tests have been conducted and the result of surface roughness for the thin pulsed jet system is 0.42 µm.

On the other hand, the feed rate (factor B) shown in Fig. 5(b) is found as most significant factor affecting surface roughness for fluid atomizer MQL mode. The depth of cut (factor C) is found to be the second most significant factor followed by the cutting speed (factor A). The smallest feed rate (B1, 0.05 mm/tooth) with the highest axial depth of cut (C3, 1.0mm) and smallest cutting speed (A1, 300m/min) are determined to be the best choices for obtaining the best surface roughness. Therefore, the optimal parameters for fluid atomizer MQL mode are set as A1B1C3. The confirmation tests have been conducted and the result of surface roughness is 0.71 µm.

Comparison analysis of the results after confirmation experiment indicates that the thin pulsed jet application gives 41% better results than the fluid atomizer system. This would be attributed to the fact that the cutting oil injected by the thin pulsed jet is applied directly to the tool-chip interface. On the other hand, the misting system would penetrate the cutting oil into the cutting zone through a specialized fluid-atomization (FA) nozzle to produce a cloud of mist at a predetermined misting location.

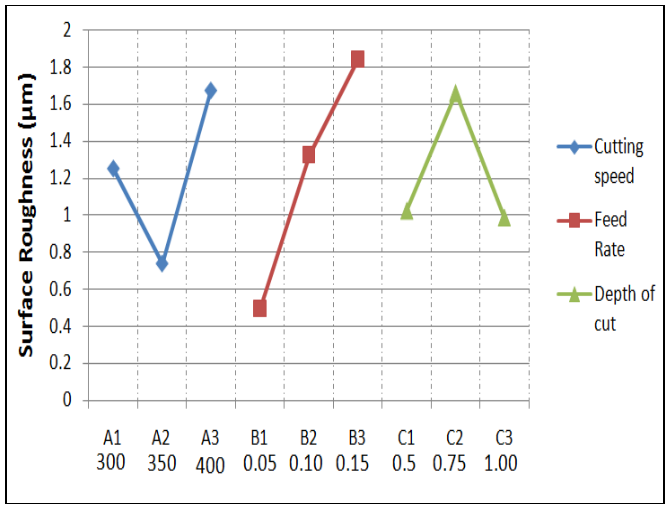
TABLE V
TPM RESPONSE OF SURFACE ROUGHNESS FOR BOTH LUBRICATION MODES

(A) THIN PULSED JET MQL MODE

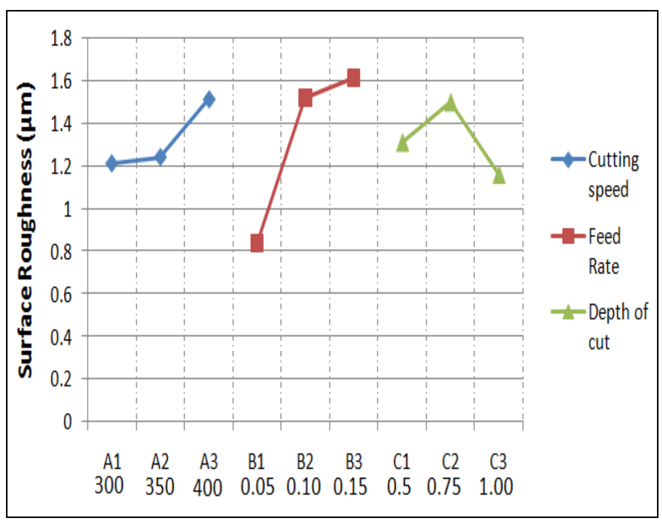
	A_i	B_i	C_i
Level 1	1.253	0.496	1.022
Level 2	0.738	1.328	1.659
Level 3	1.676	1.843	0.985
Different	0.937	1.347	0.674
Rank	2	1	3
Optimum	2	1	3

(B) FLUID ATOMISER MQL MODE

	A_i	B_i	C_i
Level 1	1.215	0.837	1.313
Level 2	1.245	1.524	1.503
Level 3	1.516	1.615	1.16
Different	0.301	0.778	0.343
Rank	3	1	2
Optimum	1	1	3



a) Thin pulse jet MQL mode



b) Fluid atomizer MQL mode

Fig. 5 Response graph for selecting best combination levels for lowest surface roughness value

This caused the cutting oil in the fluid atomizer system mode to perform poorly as the penetration into the tool tip area becomes more difficult, thus resulting in less lubrication at the tool-chip contact area. Besides, the application of medium cutting speed (350 mm/min) seems to gives better results compared to the lower (300 mm/min) in thin pulse jet. This phenomenon possibly because of chips velocity in high cutting speed is faster than in low cutting speed. In high cutting speed, the tendency for chips to wrap back to the newly formed surface is low and therefore the contact time between the chip and new surface is shorter compared to low cutting speeds. Consequently, the chip will evacuate with less material deformation hence preserves the workpiece surface roughness and prevent built-up edge (BUE) formation [19].

B. Cutting Force Analysis

The calculated TPM values of measured cutting force for both lubrication modes are summarized in Table VI while Fig. 6 is presenting the response graph for selecting best combination levels for lowest cutting force. Based upon the criteria of smaller TPM response, the axial feed rate (factor B) shown in Fig. 6(a), is found to be of most significant factor affecting cutting force for thin pulse jet MQL mode. The spindle speed (factor A) is found to be the second most significant factor followed by the depth of cut (factor C). The smallest feed rate (B1, 0.05 mm/tooth), with the highest spindle speed (A3, 400mm/min) and smallest axial depth of cut (C1, 0.5 mm), are determined to be the best choices for obtaining the smallest cutting force. Therefore, the optimal parameters for the best cutting force for thin pulse jet MQL mode are set as A3 B1 C1. The resultant cutting force of thin pulsed jet from the confirmation experiment is 22.78 N.

On the other hand, the feed rate (factor B) shown in Fig. 6(b) is found to be the most significant factor affecting the cutting forces for fluid atomizer MQL mode. The cutting speed (factor A) is found to be the second most significant factor followed by the depth of cut (factor C). The smallest feed rate (B1, 0.05 mm/tooth), with the highest spindle speed (A3, 400mm/min) and smallest axial depth of cut (C1, 0.5 mm), are determined to be the best choices for obtaining the smallest cutting force. Therefore, the optimal parameters for fluid atomizer MQL mode are set as A3B1C1. The confirmation experiments were conducted and the result produces 23.35 N cutting force for fluid atomizer MQL.

From cutting force analysis, the results obtained from the thin pulsed jet mode and fluid atomizer system shows small differences. It is worthy to note that, when using both coolant systems, depth of cut is the most dominant factor. Both systems showed that the optimum level of depth of cut to get the lower cutting force is at level 1. According to this theory, Ghani et al. [19] stated that the force is fully dependent on the shear yield strength of the workpiece at the tool-chip interface and shearing zone. This explained why the depth of cut plays a significant role in determining the cutting force.

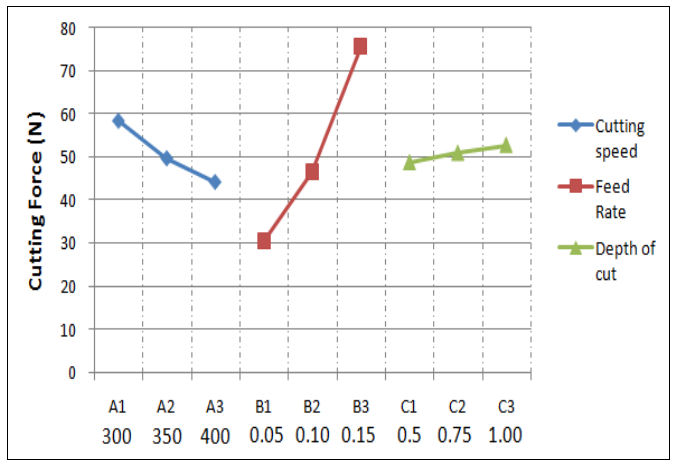
TABLE VI
TPM RESPONSE TABLE OF RESULTANT CUTTING FORCE FOR BOTH LUBRICATION MODES

(A) THIN PULSED JET MQL MODE

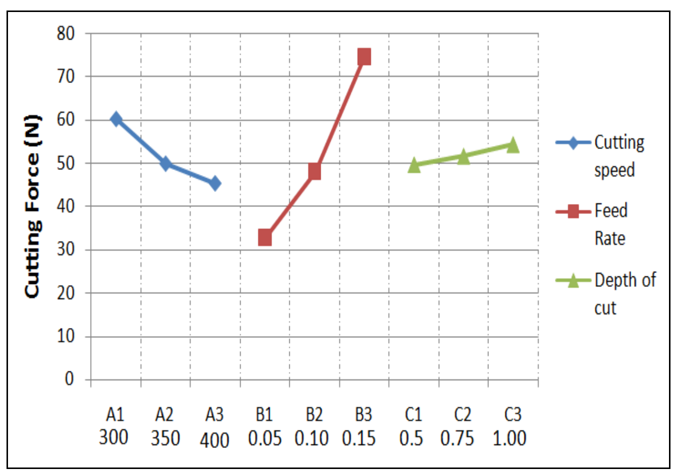
	A_i	B_i	C_i
Level 1	58.51	30.355	48.731
Level 2	49.737	46.465	50.939
Level 3	44.208	75.635	52.785
Different	14.302	45.28	4.053
Rank	2	1	3
Optimum	3	1	1

(B) FLUID ATOMISER MQL MODE

	A_i	B_i	C_i
Level 1	60.35	32.818	49.663
Level 2	49.957	48.158	51.661
Level 3	45.373	74.705	54.356
Different	14.977	41.887	4.693
Rank	2	1	3
Optimum	3	1	1



a) Thin pulse jet MQL mode



b) Fluid atomizer MQL mode

Fig. 6 TPM response graph for selecting best combination levels for lowest cutting force value

The findings also imply that the thin pulsed jet system demonstrate 3.2 % better performance in terms of cutting force compared to the fluid atomizer system. The ability of thin pulsed jet system to deliver the cutting oil to penetrate into the cutting zone helps to reduce of the cutting force. The jet

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action may also prevents the adhesion of the virgin chip surface to the tool surface and shifts the condition from seizure zone to sliding zone and consequently resulting in reduction of tool-chip contact length. As a result, the friction at tool-chip interface as well as shear force is reduced.

IV. Conclusions

In this research, the machining performance of the AISI304 stainless steel using thin pulse jet and fluid atomizer minimal quantity lubrication system is investigated by using Taguchi experimental design. The response analysis was conducted to analyze the surface roughness and cutting force of both lubrication modes. The following conclusions can be drawn from this study were:

(1) The surface finish of slot milling during thin pulsed jet MQL application is found to be better than that obtained from the application of fluid atomizer MQL system.

(2) Feed rate shows the highest contribution among other machining parameters in affecting the surface roughness and cutting force for both cooling methods.

(3) The thin pulsed jet demonstrates a 41 % and 3.2% better performance compared to fluid atomizer system in term of surface roughness and cutting force, respectively, due to its better penetration ability.

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