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Influence of Tool Geometry on Surface Roughness and Tool Wear When Turning AISI 304L Using Taguchi Optimisation Methodology

Salah Gariani, Taher Dao, Ahmed Lajili

Abstract**—**This paper presents an experimental optimisation of surface roughness (Ra) and tool wear in the precision turning of AISI 304L alloy using a wiper and conventional cutting tools under wet cutting conditions. The machining trials were conducted based on Taguchi methodology employing an L9 orthogonal array design with four process parameters: feed rate, spindle speed, depth of cut, and cutting tool type. The experimental results were utilised to characterise the main factors affecting Ra and tool wear using the analyses of means (AOM) and variance (ANOVA). The results show that the wiper tools outperformed conventional tools in terms of surface quality and tool wear at optimal cutting conditions. The ANOVA results indicate that the main factors contributing to lower Ra are cutting tool type and feed rate, with percentage contribution ratios (PCRs) of 58.69% and 25.18% respectively. This confirms that tool type is the most significant factor affecting surface quality when turning AISI 304L. Additionally, a substantial reduction in tool wear was observed when a wiper insert was used, whereas noticeable increases in tool wear occurred when higher cutting speeds were employed for both tool types. These trends confirm the ANOVA outcomes that cutting speed has a significant effect on tool wear, with a PCR value of 39.22%, followed by tool type with a PCR of 27.40%. All machining trials generated similar continuous spiral or curl-shaped chips. A noticeable difference was found in the radius of the produced curl-shaped chips at different cutting speeds when turning AISI 304L under wet cutting conditions.

Keywords**—**AISI 304L alloy, conventional and wiper carbide tools, wet turning, average surface roughness, tool wear.

I. Introduction

IN today's, metal cutting industry, precision computer numerical control (CNC) machining is vital in increasing production rates and improving cutting efficiency. It is known that the choice of machining parameters has a significant impact on cutting energy consumption, metal removal rate, and product surface quality [1]. The optimisation of machining parameters is now seen by manufacturers and academics as essential; however, the values of these parameters have usually been determined according to the experience of machine operators or published handbooks [2]. AISI 304 and 304L stainless steel alloys are among the most important materials in manufacturing. They are used in many industrial applications, including food processing, construction, chemical containers, and the automotive and aerospace sectors. The unique properties of AISI 304L such as corrosion resistance make it an ideal metal for use in applications for severely corrosive environments [3], [4]. Generally, stainless steel alloys are considered to be among the most difficult-to-cut materials since they contain a high percentage of chromium (up to 21%, as well as 6-26% nickel and up to 7% molybdenum). These alloys have a low machinability index compared with carbon steel alloys and therefore machining results in high temperatures and rapid tool wear. This reduces tool life and affects the product's surface quality [5], and so the low machinability of stainless steel alloys combined with high demand means that the CNC turning of stainless steel alloys has received close attention [6]. Carbide tools with a wiper geometry have recently come to be considered a good alternative to conventional tools due to their unique optimised nose geometry. This includes a large radius of curvature that enables the application of high feed rates to improve productivity while at the same time leading to good surface quality [7], [8]. Fig. 1 shows schematic views of the geometry of wiper and conventional tools.

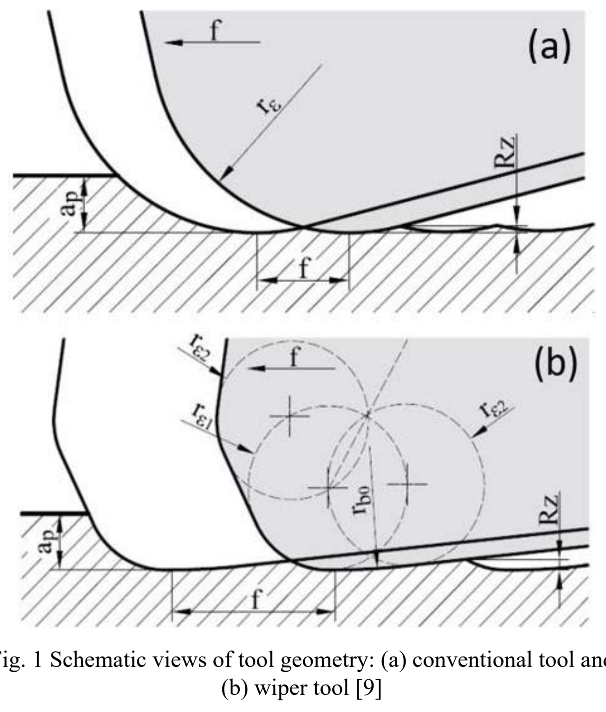

Fig. 1 Schematic views of tool geometry: (a) conventional tool and (b) wiper tool [9]

Close attention is usually paid to surface integrity and tool

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wear in traditional methods used for the optimisation of cutting parameters when machining stainless steel using wiper inserts. For example, an experimental study by Kiyak et al. [10] compared conventional cutting tools and those with a wiper geometry when turning AISI 420B stainless steel alloy, and found that the wiper inserts gave a better surface finish with slightly higher tool wear in comparison to conventional inserts. Noordin et al. [11] examined wiper inserts in the dry turning of AISI 420 martensitic stainless steel when cutting conditions were varied. They concluded that the wiper inserts produced better surface finish at lower speeds and rates but higher surface roughness was found at higher cutting speeds and feed rates alongside severe flank and crater wear. Mustafa and Basmaci [12] experimentally compared conventional tools with those using wiper-based geometry during the hard turning of 17-4 PH stainless steel. It was found that wiper tools provided better performance in terms of surface roughness and tool flank wear. The results also suggested that turning efficiency could be increased without affecting the machined surface roughness if wiper-based tools were used effectively [12]. Another experimental study conducted by Ay et al. [13] examined surface roughness and cutting force using a PVD-coated wiper and conventional inserts when dry turning AISI 304L. The grey-based Taguchi method was employed to identify the optimal cutting conditions, and values of surface roughness and cutting forces were lower with the wiper inserts. The optimal cutting conditions with the wiper tools were determined to be a feed rate of 0.1 mm/rev, 0.4 mm depth of cut, and 0.8 mm insert radius. Rosa et al. [14] also investigated the effect of using wiper and conventional tools on surface roughness during the dry turning of martensitic stainless steel AISI 420. The recorded values of surface roughness were between 0.74 µm and 1.44 µm for wiper tools and between 1.30 µm and 4.06 µm for conventional tools. It was concluded that wiper inserts significantly improved workpiece surface quality.

The Design of Experiments (DOE) is a set of statistical tools used to plan, perform, analyse, and interpret controlled tests in order to identify which parameters affect and drive the outcomes of a process [15]. To reduce the sensitivity of a process to variations in uncontrolled inputs, the Taguchi Orthogonal Array (OA) method is a potent balanced DOE technique used to determine the optimal levels of controllable input variables. Single and mixed-level matrix designs are most commonly employed with the Taguchi OA, where a distinction is made between control variables and discrete noise factors that cannot be controlled except during tests in the laboratory [16]. Additionally, this method can be applied using a small number of experiments, thereby minimising time and costs compared to other statistical experimental methods while still obtaining highly accurate results [16]. Meanwhile, the ANOVA is a powerful statistical significance test employed to examine whether the null hypothesis can be rejected during hypothesis testing [17], whereas the analysis of means (AOM) is a common methodology in quality management that compares the average of each group of data with the mean of the overall process in order to identify statistically significant differences [18]. Several studies [10]-[14] have demonstrated the cutting efficiency of inserts with a wiper-based geometry, which can be considered an alternative to conventional tools in the machining of different steel alloys. Nevertheless, limited research has been conducted on the performance of wiper-based tools, particularly in the wet precision turning of AISI 304L austenitic stainless steel. Thus, the knowledge gap addressed in this work relates to the study of the combined effect of tool geometry (either or conventional and wiper inserts) and input factors (feed rate, spindle speed, and depth of cut) on surface roughness and tool wear during the wet turning of AISI 304L austenitic stainless steel. Taguchi's DOE was utilised to investigate the effects of various factors or parameters and their levels on the performance of the process. The significance of the factors considered was identified using ANOVA, and the optimum level of each factor was determined using AOM.

II. Design of Experiment

The machining trials in this work were designed based on Taguchi's experimental design with an L9 array. Previous research shows that stainless steel alloys can be machined at low feed rates and cutting speeds to obtain better surface quality even when wiper inserts are used [13]. Thus, four levels of low feed rates and two levels of low cutting speeds were applied to determine the resulting variation in surface finish. Table I shows the control factors and corresponding levels. AOM and ANOVA using Minitab 21 software were employed to identify the optimal values of process factors in order to obtain a better surface finish and lower tool wear when wet turning AISI 304L.

TABLE I
Control Factors and Corresponding Levels

Factor	Level 1	Level 2	Level 3	Level 4
Feed rate (mm/rev)	0.1	0.15	0.2	0.25
Cutting speed (rpm)	950	1150		
Depth of cut (mm)	0.25	0.50		
Tool type	Wiper	Conventional		

III. Experimental Work

All turning tests were carried out utilising a Pinacho Mustang 200 CNC lathe machine. The CNC lathe machine was equipped with a GE Fanuc 21i-T series controller. It has a maximum spindle speed of 1250 rpm and a main drive power of 7.5 kW. Samples of AISI 304L austenitic stainless steel alloy 20 mm in diameter and 90 mm long were cut using a Q-80z type metallographic specimen cutting machine. The chemical composition of the AISI 304L austenitic stainless steel alloy is shown in Table II. Each machining test involved a cutting length of 50 mm and a fresh insert was employed in order to maintain identical machining conditions. The tests were performed using wiper and conventional chemical vapour deposition (CVD) TiCN+Al_2O_3+TiCN coated carbide tools supplied by Walter Tools Co. (Germany). All tools had the ISO designation CNMG120408. Table III details the geometry of the conventional and wiper tool tips used. All inserts were fixed in the same tool holder, which was the DCLNR 2020M12 model supplied by Sandvik Co. Fig. 2 shows images of the cutting tools, the dimensions of the AISI 304L samples, and the machine tool used in the machining experiments. All tests were conducted in wet conditions using a commercial water-soluble (Petrol ofisi BOR YAGI) cutting fluid. The cutting fluid was blended at a concentration ratio of 7%.

TABLE II
CHEMICAL COMPOSITION OF AISI 304L ALLOY

Weight (%)	C	Cr	Si	Ni	Mn	Mo	S	P
Min	0.018	17.6	0.343	7.71	1.42	0.264	0.02	0.03
Max	0.03	18.0	0.75	8.0	2.0	0.45	0.03	0.045

TABLE III
GEOMETRY OF THE TOOL INSERTS USED IN THE EXPERIMENTS

Cutting edge Angle (Kr)	Nose radius (r_ε)	Clearance angle (α)	Included angle (ε)	Rake angle (γ)
95˚	0.8 mm	0˚	80˚	−6°

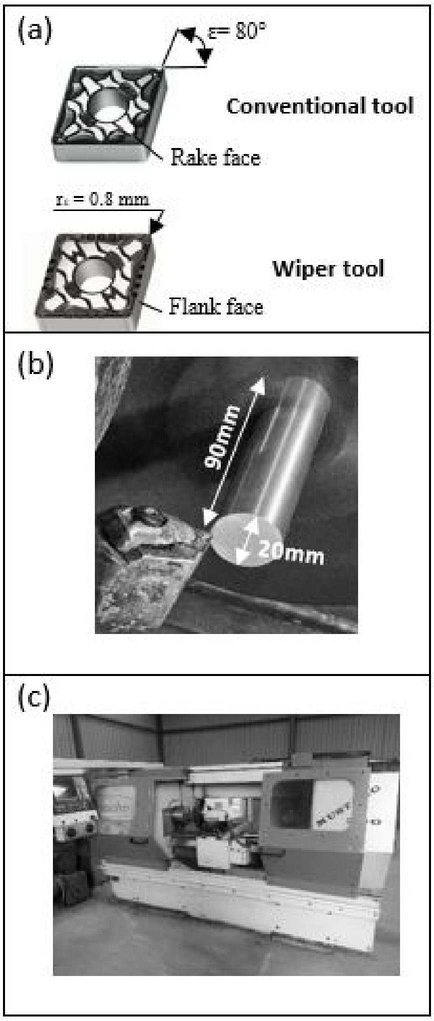


Fig. 2 Experimental set-up: (a) cutting tools; (b) sample dimensions; (c) CNC Pinacho Mustang 200 machine

IV. MEASUREMENT EQUIPMENT

The average surface roughness (Ra) of the machined samples was measured using a handheld roughness tester (SRT- 6120 model). All Ra tests were conducted according to ISO 4287 and ISO 4288 specifications and using a 0.8 mm cut-off and an evaluation length of 4 mm. Six surface roughness readings were recorded for every sample at three different points and positions (180 degrees between each point at the top and bottom of the cut). The Ra values presented in Table IV are the means of these 6 measurements. Images of the machined surfaces and tool wear were captured using an FL8000 Upright metallurgical optical microscope. Fig. 3 shows the measurement equipment used in the study.

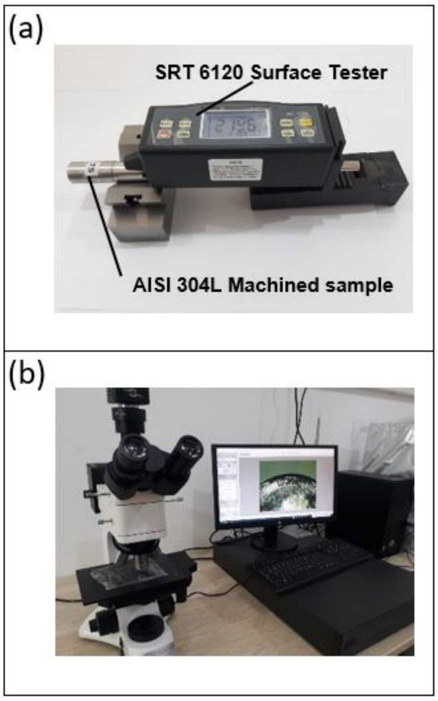


Fig. 3 Measurement equipment used: (a) surface roughness tester; (b) FL8000 optical microscope

V. RESULTS AND DISCUSSION

The values of control factors and measurements of surface roughness and tool wear are shown in Table IV. Fig. 4 shows the effect of feed rate, cutting speed, and depth of cut on the Ra of the machined AISI 304L bars for different tool types using an AOM as suggested by the Taguchi methodology. According to the AOM, the combinations of control factors associated with the lowest values of surface roughness (Ra) when turning AISI 304L were determined to be a cutting speed of 1150 rpm, a feed rate of 0.1 mm/rev, and a depth of cut of 0.25 mm with a wiper cutting tool. Cutting speed and depth of cut were found to have only a marginal impact on surface roughness irrespective of the type of tool employed. However, the effects of tool type and feed rate were shown to be more significant, confirming the ANOVA results shown in Table V with PCRs of 58.69% and 25.18% respectively. The relatively small error level of 2% associated with the average surface roughness evaluation was within acceptable levels (of up to 16%), suggesting that all important variables had been considered and the measurements accurately performed. Regardless of the tool type used, surface roughness was shown to increase consistently with increasing feed rate. This is likely to be due to the theoretical Ra being directly proportional to the square of feed per revolution. On the other hand, the use of wiper inserts resulted in a dramatic drop in mean values of Ra. This could be attributed to the unique multi-radius geometry of the wiper tools, which helps to improve the surface quality of machined parts. These findings are in accordance with those of Kiyak et al. [10] and Noordin et al. [11] for the cutting of AISI 420 stainless steel alloy, where lower surface roughness was attained when wiper inserts were used. Fig. 5 shows optical images of the surface topography of the machined parts obtained for conventional and wiper inserts at a cutting speed of 1150 rpm, 0.1 mm/rev feed rate, and 0.5 mm depth of cut.

TABLE IV
CONTROL FACTORS WITH MEASURED VALUES OF THE Ra & V_B

Run	Feed rate rev/min	Cutting Speed (rpm)	Tool type	DoC (mm)	Ra (µm)	V_B (µm)
1	0.10	950	Conventional	0.25	1.322	190.26
2	0.10	1150	Wiper	0.50	0.657	230.87
3	0.15	950	Wiper	0.25	0.787	150.14
4	0.15	1150	Conventional	0.50	1.651	240.44
5	0.20	950	Conventional	0.50	2.207	185.64
6	0.20	1150	Wiper	0.25	0.757	152.98
7	0.25	950	Wiper	0.50	1.261	112.08
8	0.25	1150	Conventional	0.25	2.636	185.23
9	0.10	1150	Wiper	0.25	0.527	200.82

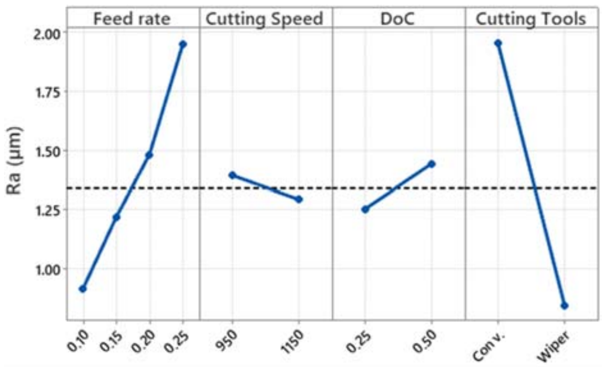


Fig. 4 AOM for average surface roughness (Ra)

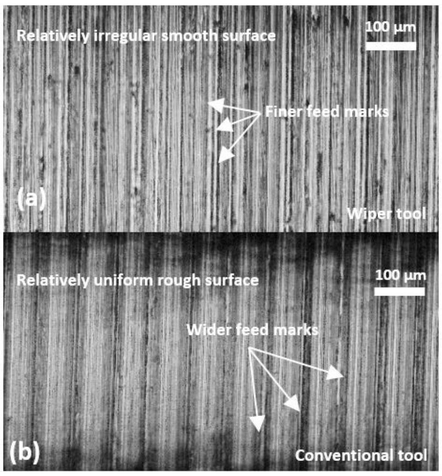


Fig. 5 Optical images of machined surface obtained at 1150 rpm cutting speed, 0.1 feed rate, and 0.25 mm depth of cut for: (a) wiper tool (b) conventional tool

Fig. 6 shows the interaction effects on average surface roughness (Ra) of all cutting parameters tested. In general, there are noticeable mutual interactions among all of the parameters investigated, the most significant being those between feed rate and cutting speed and feed rate and depth of cut. However, those parameters have a low degree of interaction with tool type. Additionally, the parallel trends of the lines also suggest that there is no interaction between insert type and feed rate. This is in line with the AOM results, indicating that insert type and feed rate have more significant effects on Ra than other cutting parameters.

TABLE V
ANOVA RESULTS FOR AVERAGE SURFACE ROUGHNESS (Ra)

Source	DF	SS	MSS	F	P	PCR
Feed rate (mm/rev)	3	1.62650	0.31978	2.35	0.048*	25.18 %
Cutting speed (rpm)	1	0.01251	0.01251	0.09	0.790	0.314 %
Depth of cut (mm)	1	0.00114	0.00114	0.01	0.935	0.02%
Tool type	1	2.33155	2.33155	17.16	0.023*	58.69%
Error	2	0.27179	0.13589			
Total	8	3.97508				
S = 0.368637; R-Sq = 93.16%; R-Sq (adj) = 72.65%						

DF = Degrees of freedom; SS = Sum of squares; F = F-test value; * Significant at the 5% level with a confidence level of 95%; P = Probability.

The influence of the four process parameters of feed rate, cutting speed, depth of cut, and tool type on tool wear using the AOM is shown in Fig. 7. The optimal cutting conditions that resulted in lower tool wear were a cutting speed of 950 rpm, feed rate of 0.25 rev/mm, and depth of cut of 0.25 mm with the wiper cutting tool. However, manufacturers sometimes decide to achieve a trade-off between surface quality and the cost of cutting tools, particularly when machining critical parts that are used in vital industries such as the automotive, food and aerospace industries. It was found that the variables with the most statistically significant effect on tool wear were cutting speed and tool type, with PCRs of 39.22% and 27.40% respectively as shown in Table VI. Although tools with both wiper and conventional inserts are made of similar material, they have different geometries, and the wiper insert outperformed the conventional tool in terms of tool wear owing to its unique tool tip geometry, as mentioned earlier. Additionally, the ANOVA results show that feed rate and depth of cut had no significant impact on tool wear. However, it seems that an increase in feed rate directly causes increases in the areas of the primary and secondary shear zones as well as the contact length between the chip and tool. This consequently leads to an increase in heat generation. Although cutting temperature and flow heat generation measurements were not considered in this study, it is recognised from metal cutting theory that an increase in heat generation leads to lower shear strength for most materials which consequently facilitates the cutting process. Also, when the length of contact between the chip and the tool increases, more heat is dissipated from the cutting zone and, in some cases, the rate of heat transfer to the cutting tool is decreased [19]. This may help to explain the lower tool wear values recorded at the higher feed rate in this study. Fig. 8 presents images of tool wear after the turning of AISI 304L using wiper and conventional tools at a cutting speed of 1150 rpm, 0.25 mm/rev feed rate, and 0.5 mm depth of cut.

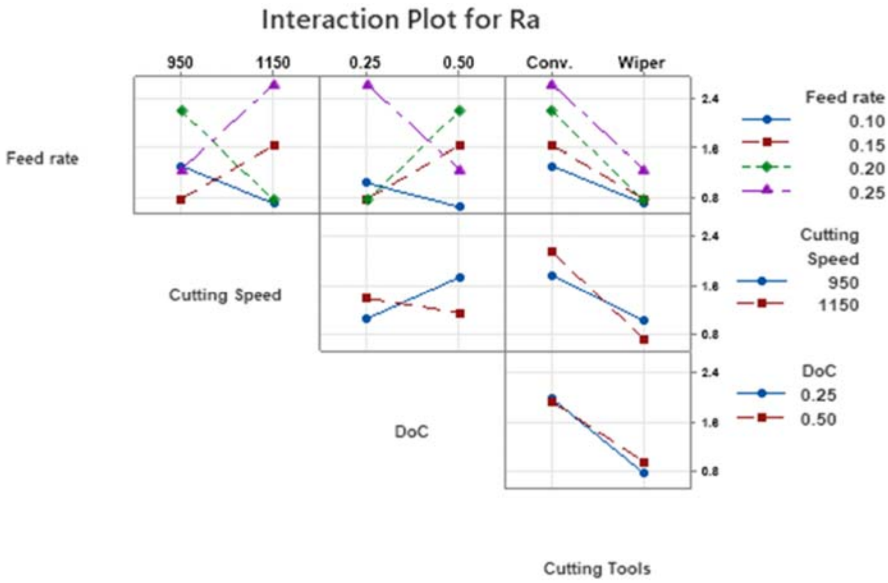


Fig. 6 Interaction effects of process factors on average surface roughness (Ra)

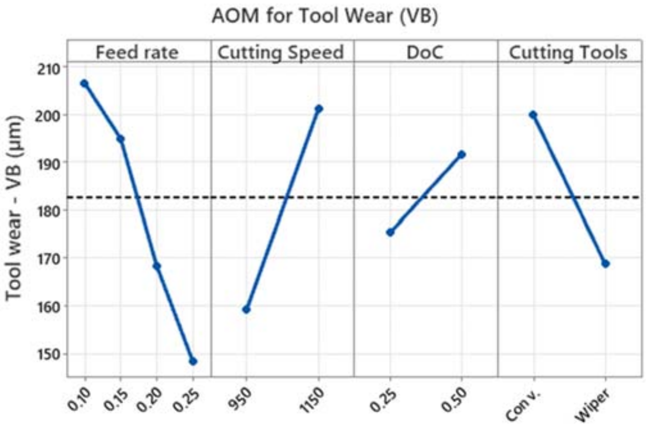


Fig. 7 AOM for tool flank wear (V_B)

TABLE VI
ANOVA RESULTS FOR TOOL WEAR (VB)

Source	DF	SS	MSS	F	P	PCR
Feed rate (mm/rev)	3	3858.4	1685.8	8.60	0.106	24.92 %
Cutting speed (rpm)	1	5057.5	3858.4	19.68	0.039*	39.22 %
Depth of cut (mm)	1	1091.3	1091.3	5.57	0.142	8.46%
Tool type	1	3270.4	3270.4	16.68	0.049*	27.40%
Error	4	392.1	196.1			
Total	10	12894.0				
S = 14.002; R-Sq = 96.96%; R-Sq (adj) = 87.84%						

DF = Degrees of freedom; SS = Sum of squares; F = F-test value; * Significant at the 5% level with a confidence level of 95%; P = Probability

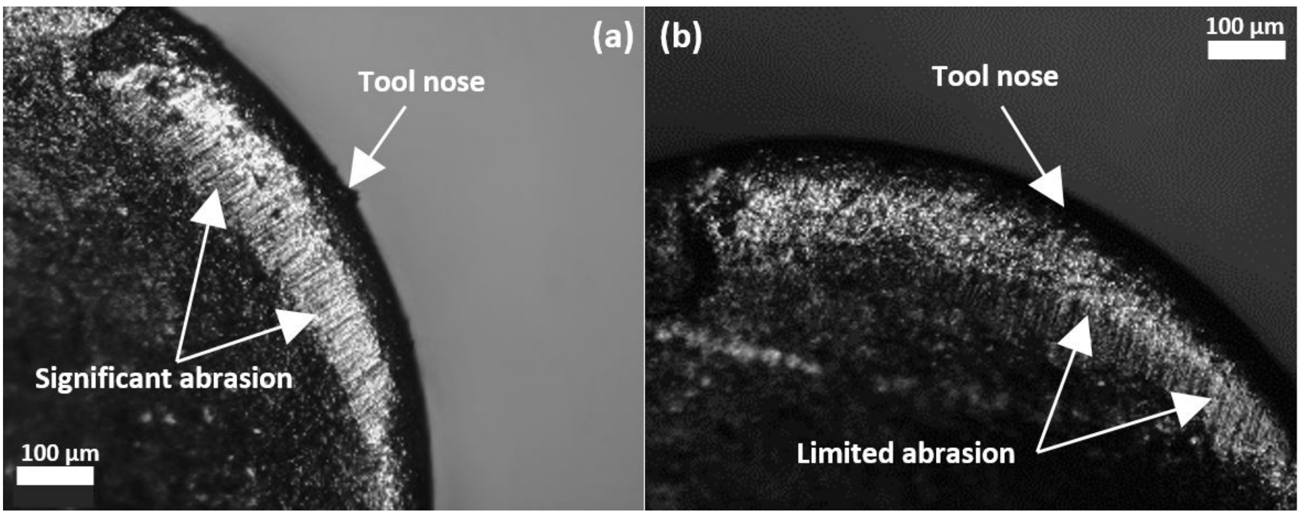


Fig.8 Images of abrasion marks on the rake faces of the tested tools obtained at 1150 rpm cutting speed, 0.1 feed rate, and 0.25 mm depth of cut for: (a) conventional tool; (b) wiper tool

Fig. 9 shows the interaction effects on tool wear (V_B) of all cutting parameters evaluated. It can be seen that there are noticeable mutual interactions among all of the parameters investigated, particularly between feed rate and cutting speed, depth of cut, and tool type. However, those parameters have only a slight degree of interaction, especially between cutting speed and depth of cut and depth of cut and cutting tools. Additionally, the parallel trends of the lines also suggest that there is no interaction between cutting tool type and cutting speed. This is in agreement with the AOM results, suggesting that cutting speed and cutting tool type have a more substantial impact on tool wear than other cutting parameters.

Fig. 10 shows the shapes of all collected chips when wet turning AISI 304L under all cutting conditions. In general, a continuous spiral or curled shape was observed for all chips produced during the machining tests. These continuous shapes are probably due to the high ductility of AISI 304L which prevents the chips from breaking during the cutting process. Nevertheless, the radius of the curl for curled chips varied to some extent. It can be inferred from Fig. 10 that there is a noticeable relationship between the curl radius and cutting speed since increasing the cutting speed from 950 rpm to 1150 rpm is associated with an increase in the curl radius as seen in the chips produced in runs 7 and 9. Regardless of the cutting tool used, the chip curl radius increases at higher speeds. According to Nakayama's chip-breaking criterion, when the actual chip fracture strain is smaller than the tensile strain of the chip, then the chip will break. It is considered that the actual chip fracture strain is proportional to the ratio of the chip's curl radius to its thickness [20].

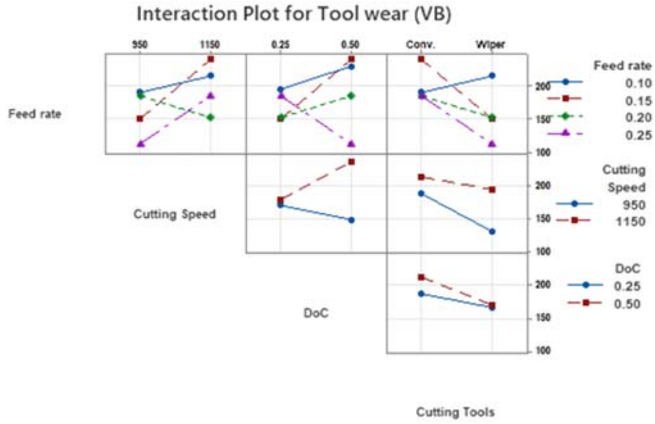


Fig. 9 Interaction effects of process factors on tool flank wear (V_B)

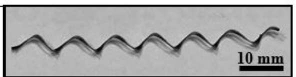
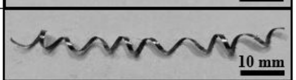
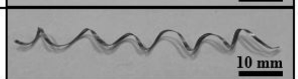
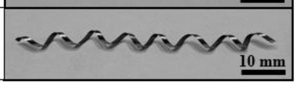
Run No. 1: 950 rpm, 0.1 mm/rev, 0.25 mm and conventional tool		**Run No. 6:** 1150 rpm, 0.2 mm/rev, 0.25 mm and wiper tool	
Run No. 2: 1150 rpm, 0.1 mm/rev, 0.5 mm and wiper tool		**Run No. 7:** 950 rpm, 0.25 mm/rev, 0.5 mm and wiper tool	
Run No. 3: 950 rpm, 0.15 mm/rev, 0.25 mm and wiper tool		**Run No. 8:** 1150 rpm, 0.25 mm/rev, 0.25 mm and conventional tool	
Run No. 4: 1150 rpm, 0.15 mm/rev, 0.5 mm and conventional tool		**Run No. 9:** 1150 rpm, 0.1 mm/rev, 0.25 mm and wiper tool	
Run No. 5: 950 rpm, 0.2 mm/rev, 0.5 mm and conventional tool			

Fig. 10 Chip shape when turning AISI 304L in all cutting conditions

VI. Conclusion

This study has compared the machinability of AISI 304L stainless steel alloy material when using conventional and wiper-coated CVD TiCN+Al_2O_3 + TiCN carbide tools. The use of the wiper insert has shown useful results, for the criteria for machinability which are surface roughness and tool wear. Four different control factors were considered to be effective in creating the most suitable conditions for lower surface roughness and tool wear: feed rate, cutting speed, depth of cut, and tool type. The following conclusions were drawn:

1) A combination of a cutting speed of 1150 rpm, feed rate at 0.1 mm/rev, and depth of cut of 0.25 mm achieves the minimal surface roughness when turning AISI 304L when using wiper tools under wet cutting conditions.
2) Tool type and feed rate are the most statistically significant factors in minimizing Ra, with PCRs of 58.69% and 25.18% respectively when turning AISI 304L.
3) The study's results prove the effectiveness of the wiper insert, which leads to lower tool wear. This is due to its unique tool tip geometry that may help to minimise tool wear.
4) The ANOVA results show that cutting speed and tool type have a substantial impact on tool wear with PCRs of 39.22% and 27.40% respectively, whereas feed rate and depth of cut have only a marginal impact on tool wear when turning AISI 304L.
5) Significant abrasion was observed on the rake face of the conventional tool, whereas only limited abrasion marks were observed on the wiper tool. However, there was hardly any sign of crater wear on either type of cutting tool.
6) All machining trials produced similar continuous spiral or curl-shaped chips. However, the curl radius of the chips generated increased with cutting speed.

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