The Effectiveness of Ceramic Wiper Tool in Turning of Monel K500

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Abstract
In this study, turning operation of Monel K500 copper-nickel super-alloy was evaluated. Ceramic cutting tools with two different cutting noses (conventional and wiper) were utilized. At first, the experimental tests were designed by using central composite design method. After implementation of the tests, the statistical models for output data (surface roughness, cutting force, and flank wear) have been developed. Furthermore, the effect of cutting parameters on output data was taken into account with help of analysis of variance. In third step, the optimal cutting condition was introduced for both cutting tools by using response surface method. In total, it was revealed that low depth of cut and feed rate coupled with high cutting speed is an optimal condition for turning of Monel super-alloy when ceramic tools are selected. In particular, the positive effect of wiper tool on output data was more when depth of cut has been lower than the length of wiper edge.

Keywords
Turning, Surface Roughness, Monel K500, Tool Wear, RSM, Wiper

1. Introduction

Feed rate and nose radius are the most effective factors on surface roughness in turning operation. By considering the fact that increase of tool nose radius increases cutting forces, increment of this geometry has some limitations [1, 2]. Therefore, wiper tools are introduced by researchers to solve this problem. A wiper edge is located in nose radius where the straight edge meets the corner radius. The remarkable properties of ceramic tools are exceptionally good hardness (very resistant against wear) and toughness, also excellent thermal conductivity [3]. These properties of ceramic tools let the users to utilize higher range of cutting speeds during turning operation [4]. Some works carried out by wiper ceramic tools in turning of different materials are reviewed in order to find the advantage of wiper ceramic tools. Aouici et al. evaluated the performance of wiper ceramic tools by considering cutting forces and flank wear in hard turning of AISI 4140 steel [5]. They used RSM method to find the effective factors. They stated that the uncoated ceramic tools performed better than coated ones regarding force analysis. In addition, wiper ceramic tools performed better than conventional one regarding flank wear analysis. Ozel et al. investigated surface roughness and flank wear in finish turning of AISI D2 steel by using wiper ceramic tools [6]. They showed that surface roughness with the value of lower than 0.2 μm is obtainable when wiper tools are used. Besides, they developed a neural networks model to predict output values. Grzesik and Wanat studied generated surface finish of quenched alloy steel during hard turning by using conventional and wiper tools [7]. The topography analysis showed that sharp peaks were generated when conventional tools were used. But blunt peaks were seen when wiper tools were used. Davim and

Figueira proposed a comparative study between conventional and wiper ceramic tools where surface roughness, cutting forces, and tool wear have been measured in hard turning of AISI D2 steel [8]. It was revealed that tool wear propagation was directly effective on surface roughness. In total, wiper tools outperformed the conventional ones.
Monel K500 is a copper-nickel alloy with ability of hardening. In fact, this grade of Monel super-alloy is produced by combination of existed the excellent properties of Monel K400 (corrosion resistance) with greater hardness and strength which are achieved by adding some elements (aluminum and titanium)to the copper-nickel base. In particular, tool wear is quickly propagated after a short period of time during turning of these super-alloys due to its poor thermal conductivity [9, 10]. This event affects the surface quality and cutting forces. Therefore, finding the optimum conditions in turning of Monel K500 super-alloy is so required. As rare study, Amini et al. compared two kinds of coated carbide tools with non-coated one in turning of Monel K500 [11]. The coatings were TiN/Al2O3/TiCN and TiN/TiAlN. In their research tool flank wear has been analyzed. At the end, it was revealed that TiN/Al2O3/TiCN coated tool had lowest flank wear among others. Furthermore, severe plastic deformations of cutting tools have been seen in high cutting speeds due to increase of temperature. In another work, Amini and Paktinat investigated the performance of wiper ceramic tool on surface roughness and cutting force without considering tool wear conditions in near dry turning of Monel K500 [12]. They showed that surface roughness was reduced about 2-20% by using wiper tool compared to conventional one.
By reviewing previous works, it was revealed that very limited studies have been proposed focusing on the turning of Monel copper-nickel super-alloy. Therefore, the author of this study aims to represent a comprehensive study including all machinability factors (surface roughness, cutting force, and tool wear) in turning of Monel K500 super-alloy by using conventional and wiper ceramic tools. This aim is carried out by implementation of analysis of variance (ANOVA) to find he effective parameters and to find the optimum conditions. The main novelty of this study is finding the correlation between wiper geometry and cutting parameters when output data are investigated.

2. Experimental Preparation

Based on Figure 1, ceramic inserts (DNGA 12-04-08 from SANDVIK catalogue) with two kinds of noses: conventional (C) and wiper (W) were used.

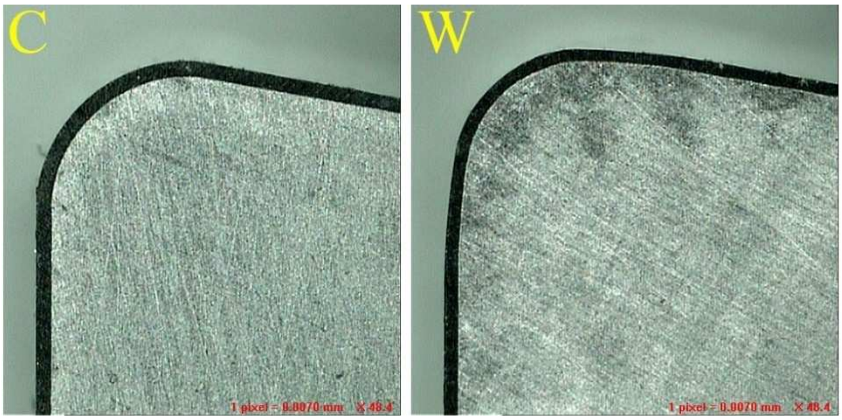

Figure1. C and W inserts

As it is seen in Figure 2, the wiper edge is located in nose radius where it is about 5 degrees. This edge can change the cutting conditions during turning operation.

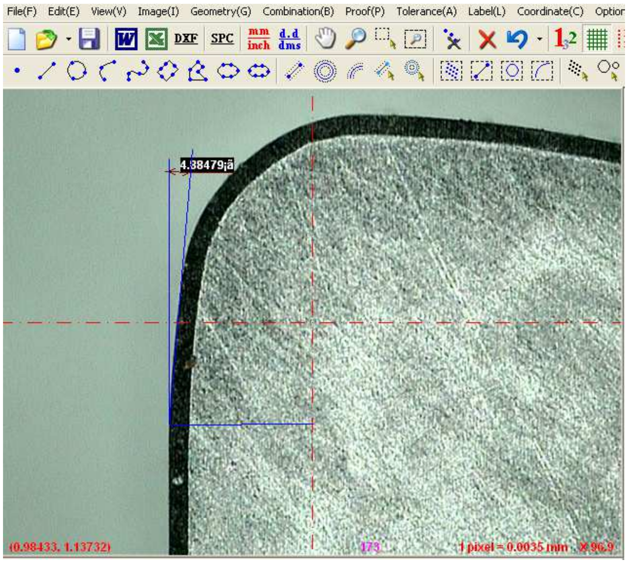

Figure2. The nose of wiper inserts

A Monel K500 copper-nickel super-alloy bar with 60 mm in diameter is used. To find the cutting length for considering worn tools, at first, some trial-and-error tests have been conducted considering ISO-standard (0.3 mm for Average flank wear (VB)) [13, 14]. Consequently, 80 mm has been defined. Following measurement devices have been applied:

1- A Kistler dynamometer-9257B type (to measure cutting forces during the operation).

2- A Mahr roughness tester (Mar Surf PS1) (to measure the roughness of machined surfaces).

3- A vision measuring microscope (VMM-Easson c-3020 type) (to investigate tool wear).

Figure 3 shows the experimental set-up prepared on a universal lathe machine (Tabriz-TN50A).

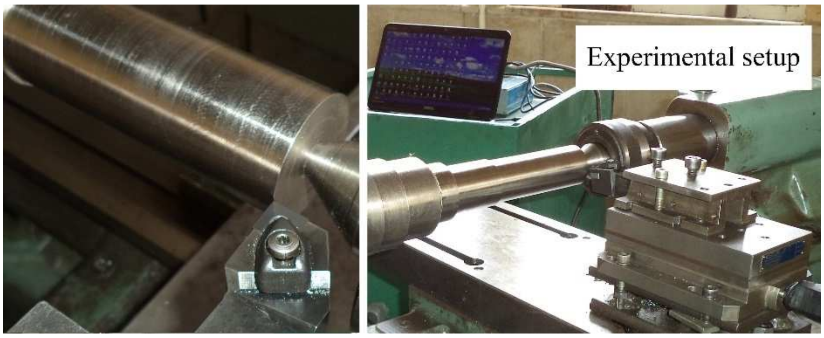

Figure3. The set-up

3. Experimental Design

Response surface method (RSM) is known as an empirical modeling approach which is based on the polynomial and linear equations. This method is created by making a relation between input values (the variables) and output values (measured values in experiments). In RSM, at least three distinct values are required to design the experiment for each particular variable. Therefore, central composite design (CCD) is used to avoid running 3^k factorial design. Note that, a CCD includes a 2^k factorial, 2k axial points and center point [15]. In this study, the independent variables are depth of cut, cutting speed and feed rate. The output data are cutting force, surface roughness, and tool flank wear. The cutting parameters and CCD design are given in Tables 1 and 2, respectively. All statistical analyses are done by using Design Expert software.

Table1. The cutting parameters

Parameters	Unit	Levels		
		-1	0	+1
Vc	(m/min)	100	150	200
f	(mm/rev)	0.12	0.18	0.24
ap	(mm)	0.5	1	1.5

Table2. The CCD Design

Run	*ap (mm)*	*f (mm/rev)*	*Vc (m/min)*
1	0.5	0.12	100.00
2	1.5	0.12	100.00
3	0.5	0.24	100.00
4	1.5	0.24	100.00
5	0.5	0.12	200.00
6	1.5	0.12	200.00
7	0.5	0.24	200.00
8	1.5	0.24	200.00
9	0.5	0.18	150.00
10	1.5	0.18	150.00
11	1	0.12	150.00
12	1	0.24	150.00
13	1	0.18	100.00
14	1	0.18	200.00
15	1	0.18	150.00

3. Results

Experimental tests were carried out based on the Table 2. During each particular cutting test, the cutting force has been measured by dynamometer. Furthermore, after completing the cutting process, surface roughness of machined surface and tool wear have been measured by roughness tester and VMM, respectively. Accordingly, the results of cutting tests for conventional and wiper ceramic inserts were listed in Table 3.

Table3. The experimental results

Run	*ap* (mm)	*f* (mm/rev)	*Vc* (m/min)	Conventional			Wiper		
				Ra (μm)	*Fz* (N)	*VB* (mm)	*Ra* (μm)	*Fz* (N)	*VB* (mm)
1	0.5	0.12	100.00	1.41	536	0.32	1.17	501	0.314
2	1.5	0.12	100.00	1.1	475	0.297	0.91	512	0.334
3	0.5	0.24	100.00	1.23	523	0.313	1.28	525	0.319
4	1.5	0.24	100.00	1.3	500	0.304	0.79	471	0.311
5	0.5	0.12	200.00	1.35	513	0.309	0.91	481	0.289
6	1.5	0.12	200.00	1.17	518	0.305	0.73	513	0.323
7	0.5	0.24	200.00	1.62	535	0.329	1.09	441	0.292
8	1.5	0.24	200.00	1.6	503	0.288	0.76	469	0.291
9	0.5	0.18	150.00	1.47	515	0.318	0.76	444	0.295
10	1.5	0.18	150.00	1.53	512	0.298	0.77	488	0.315
11	1	0.12	150.00	1.33	489	0.31	1.06	451	0.287
12	1	0.24	150.00	1.19	508	0.3	0.74	466	0.295
13	1	0.18	100.00	1.04	499	0.303	0.42	423	0.269
14	1	0.18	200.00	1.68	494	0.301	0.49	435	0.266
15	1	0.18	150.00	1	478	0.281	0.47	453	0.277

3.1. Statistical Models

Based on obtained results and cutting parameters (independent variables), the mathematical models of surface roughness, cutting force, and flank wear were developed. Based on the analysis of variance, following models are represented to predict output data.

- **Surface roughness:**

$$Ra\ (\text{conventional}) = +0.44325 - 0.252\ ap + 6.4125\ f + 1.375E - 003\ Vc - 2.04167\ ap\ f - 1.5E - 004\ ap\ Vc - 2.91667E - 003\ f\ Vc + 0.34\ ap^2 - 6E - 006\ Vc^2 \quad (1)$$

$$Ra\ (\text{wiper}) = -0.14967 + 0.208\ ap + 4.38333\ f - 1.6E - 004\ Vc \quad (2)$$

- **Cutting force:**

Fz (conventional) $= +454.53333 + 37.6\, ap + 110\, f - 0.036\, Vc$ (3)

Fz (wiper) $= +397.13333 + +69\, ap + 145\, f - 0.138\, Vc$ (4)

- **Flank wear:**

VB (conventional) $= +0.29007 + 0.0216\, ap + 0.058333\, f - 1.14E - 004\, Vc$ (5)

VB (wiper) $= +0.11537 - 0.027411\, ap + 1.91903\, f - 6.91667E - 005Vc - 0.20417ap\, f - 1.05E - 004\, ap\, Vc + 2.08333E - 004\, f\, Vc + 0.059556\, ap^2 - 4.61420\, f^2 + 5.55556E - 007\, Vc^2$ (6)

To evaluate the developed models, an extra experimental test was carried out and its results were compared by the predicted values. The cutting condition was: *Vc*= 175 m/min, *f*= 0.14 mm/rev, and *ap*= 0.8 mm. Table 4 shows the results. It is seen that the errors are in an acceptable range.

Table4. Verification test

Type	Conventional			Wiper		
	Ra (µm)	*Fz*(N)	*VB* (mm)	*Ra* (µm)	*Fz*(N)	*VB* (mm)
Actual	1.22	498	0.311	0.54	455	0.280
Predicted	1.092	493.713	0.295	0.602	448.483	0.282
Error (%)	10.4	0.8	5.1	11.4	1.4	0.7

3.2. Effect of Cutting Parameters

Regarding the analysis, whenever the value of Prob.>F is less than 0.05, it means that the parameter is effective on output data. The more the value to be less than 0.05, it means it is more effective.

- **Surface roughness:**

For conventional insert, feed rate, cutting speed, and interaction of depth of cut and feed rate were significant in which the effect of feed rate on surface roughness was more significant as its value is lower than other parameters (< 0.0001) (Table 5). Furthermore, their effects are graphically shown in Figure 4 for better understanding. Accordingly, by increase of feed value, surface roughness was significantly increased. It was slightly decreased by increase of cutting speed.

Table5. ANOVA results of Ra for conventional insert

Source	Sum of Squares	Degree of Freedom	Mean Square	F value	Prob. > F	Significant
Model	0.64	9	0.071	77.95	< 0.0001	-
A-ap	3.610E-003	1	3.610E-003	3.94	0.1040	-
B-f	0.56	1	0.56	607.70	< 0.0001	significant
C-Vc	0.030	1	0.030	33.01	0.0022	significant
AB	0.030	1	0.030	32.75	0.0023	significant
AC	1.125E-004	1	1.125E-004	0.12	0.7403	-
BC	6.125E-004	1	6.125E-004	0.67	0.4508	-
A^2	0.019	1	0.019	20.27	0.0064	-
B^2	0.000	1	0.000	0.000	1.0000	-
C^2	5.786E-004	1	5.786E-004	0.63	0.4629	-
Residual	4.583E-003	5	9.165E-004	-	-	-
Total	0.65	14	-	-	-	-

For wiper insert, Table 6 indicates that depth of cut and feed rate were effective on surface roughness in which feed parameter was more significant. Furthermore, Figure 4 shows that surface roughness was increased by an increase in depth of cut and feed values. Cutting speed variations was almost ineffective.

Table6. ANOVA results of Ra for wiper insert

Source	Sum of Squares	Degree of Freedom	Mean Square	F value	Prob. > F	Significant
Model	0.80	3	0.27	30.37	< 0.0001	-
A-ap	0.11	1	0.11	12.31	0.0049	significant
B-f	0.69	1	0.69	78.73	< 0.0001	significant
C-Vc	6.400E-004	1	6.400E-004	0.073	0.7922	-
Residual	0.097	11	8.786E-003	-	-	-
Total	0.90	14	-	-	-	-

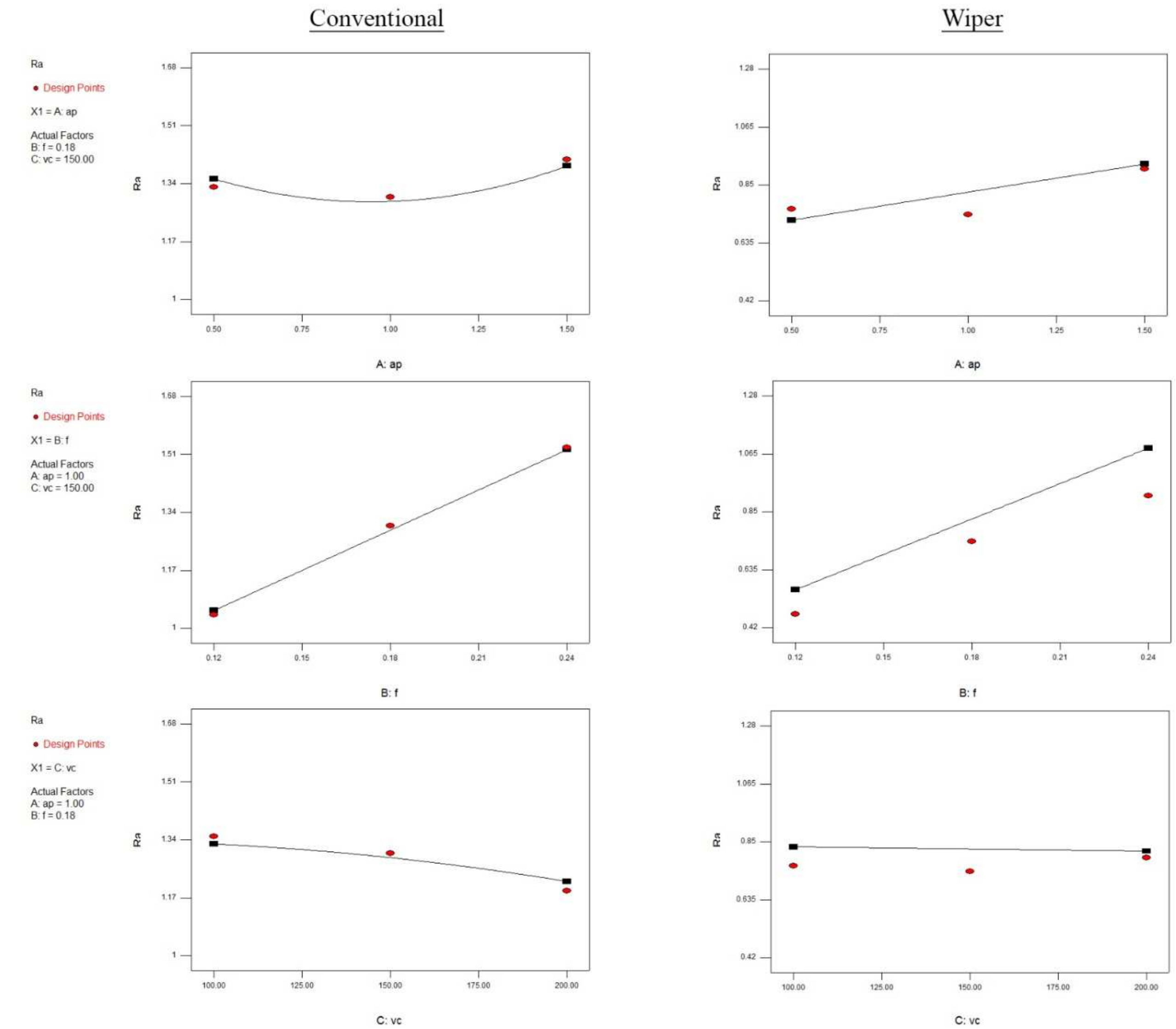

Figure4. Effect of cutting parameters on surface roughness

- **Cutting force:**

For conventional insert, it is seen that depth of cut and feed rate was effective in which the effect of depth of cut was more significant (Table 7). Its related illustrations (Figure 5) show that in both depth of cut and feed rate, by increase of these factors, cutting forces were increased. However, the slope of the graph is more when depth of cut increases.

Table7. ANOVA results of Fz for conventional insert

Source	Sum of Squares	Degree of Freedom	Mean Square	F value	Prob. > F	Significant
Model	4002.40	3	1334.13	24.08	< 0.0001	-
A-ap	3534.40	1	3534.40	63.80	< 0.0001	significant
B-f	435.60	1	435.60	7.86	0.0171	significant
C-Vc	32.40	1	32.40	0.58	0.4605	-
Residual	609.33	11	55.39	-	-	-
Total	4611.73	14	-	-	-	-

For wiper insert, it is seen that depth of cut was the most effective factor. After depth of cut, feed rate and cutting speed were effective on cutting force, respectively (Table 8). According to Figure 5, cutting force decrement is happened by increase of depth of cut and feed rate. This condition is reverse when increase of cutting speed decreased cutting force, slightly.

Table8. ANOVA results of Fz for wiper insert

Source	Sum of Squares	Degree of Freedom	Mean Square	F value	Prob. > F	Significant
Model	13135.50	3	4378.50	97.85	< 0.0001	-
A-ap	11902.50	1	11902.50	265.99	< 0.0001	significant
B-f	756.90	1	756.90	16.91	0.0017	significant
C-Vc	476.10	1	476.10	10.64	0.0076	-
Residual	492.23	11	44.75	-	-	-
Total	13627.73	14	-	-	-	-

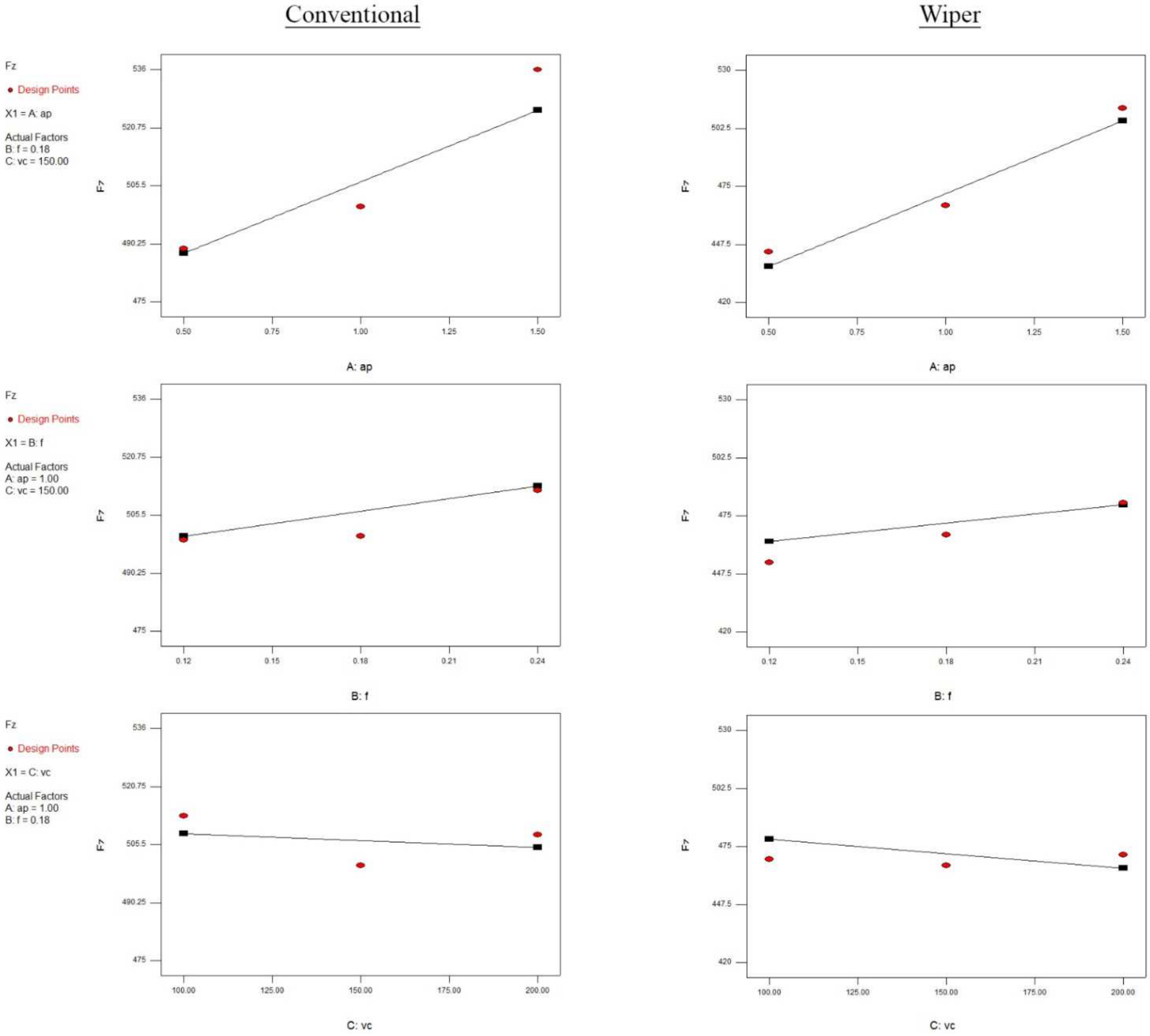

Figure5. Effect of cutting parameters on cutting force

- **Flank wear:**

For conventional insert, Table 9 shows that depth of cut and cutting speed were effective on flank wear in which the effect of depth of cut was more significant. Its related illustrations are also given in Figure 6. Accordingly, by increase of depth of cut, surface roughness was increased while it was decreased by increase of cutting speed.

Table9. ANOVA results of VB for conventional insert

Source	Sum of Squares	Degree of Freedom	Mean Square	F value	Prob. > F	Significant
Model	1.614E-003	3	5.379E-004	12.20	0.0008	-
A-ap	1.166E-003	1	1.166E-003	26.45	0.0003	significant
B-f	1.225E-004	1	1.225E-004	2.78	0.1238	-
C-Vc	3.249E-004	1	3.249E-004	7.37	0.0201	significant
Residual	4.851E-004	11	4.410E-005	-	-	-
Total	2.099E-003	14	-	-	-	-

For wiper insert, Table 10 shows that depth of cut and its interaction with feed rate were significant. As it is seen in Figure 6, at first, increase of depth of cut was ineffective on flank wear, but by further increment, flank wear was dramatically increased. It can be explained by wiper edge. In other words, by increase of depth of cut, the wiper edge is passed and the straight edge of insert is engaged with workpiece. Consequently, the cutting condition becomes close to the condition that conventional insert is used. Apart from the depth of cut, increase of feed rate caused to increase of flank wear.

Table10.ANOVA results of VB for wiper insert

Source	Sum of Squares	Degree of Freedom	Mean Square	F value	Prob. > F	Significant
Model	5.482E-003	9	6.091E-004	15.08	0.0041	-
A-ap	3.842E-003	1	3.842E-003	95.12	0.0002	significant
B-f	2.601E-004	1	2.601E-004	6.44	0.0520	-
C-Vc	2.250E-005	1	2.250E-005	0.56	0.4890	-
AB	3.001E-004	1	3.001E-004	7.43	0.0415	significant
AC	5.512E-005	1	5.512E-005	1.36	0.2954	-
BC	3.125E-006	1	3.125E-006	0.077	0.7920	-
A^2	5.700E-004	1	5.700E-004	14.11	0.0132	significant
B^2	7.095E-004	1	7.095E-004	17.57	0.0086	significant
C^2	4.960E-006	1	4.960E-006	0.12	0.7403	-
Residual	2.019E-004	5	4.039E-005	-	-	-
Total	5.684E-003	14	-	-	-	-

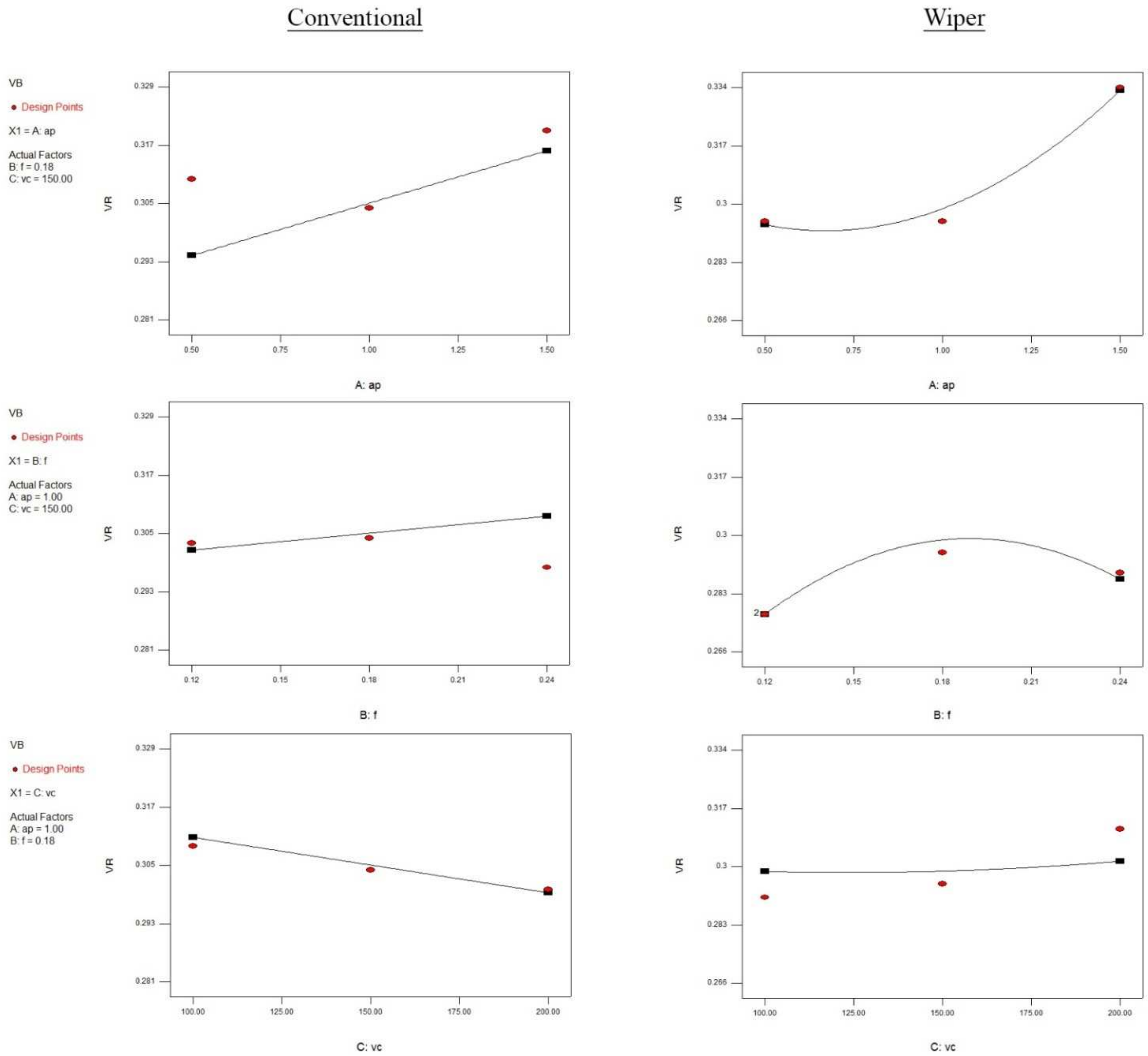

Figure6. Effect of cutting parameters on flank wear

3.3 Optimization

To optimize the turning operation of Monel K500 with conventional and wiper ceramic inserts, the target should be defined. In this study, the target is to minimize all three outputs (surface roughness, cutting force, and flank wear). Based on this target, the optimization process was carried out by using Design Expert software. The most optimized condition is happened when the value of desirability is equal to 1. Therefore, the more the value is near the value of 1, the more cutting condition is optimal. According to (Figure 7), the optimal condition for conventional insert was happened when:

- Conventional: *ap*=0.5 mm, *f*= 0.12 mm/rev, and *Vc*=200 m/min
- Wiper: *ap*=0.5 mm, *f*= 0.12 mm/rev, and *Vc*=178.49 m/min.

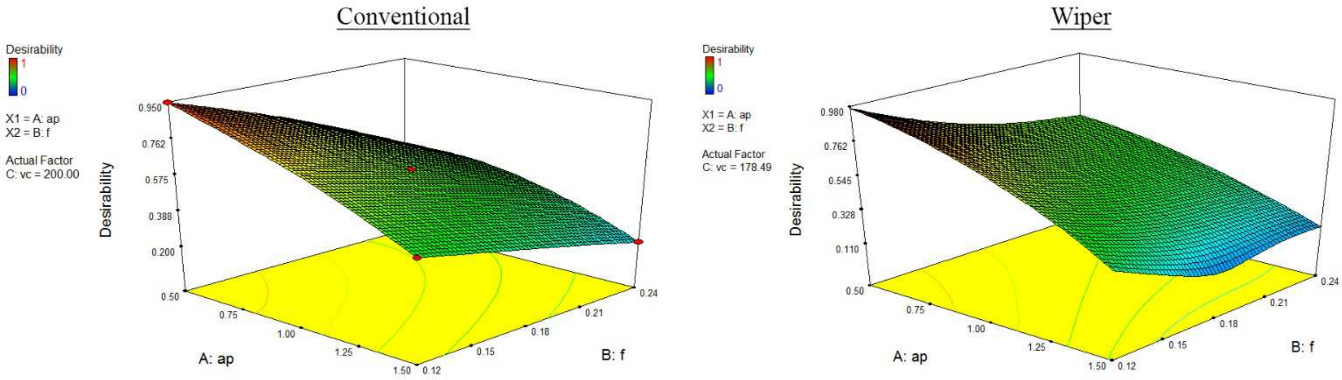

Figure7. 3D surface of desirability results

4. Comparison and Discussion

In this section, the results of conventional and wiper tools are compared with each other.

4.1 Surface Roughness

The effect of wiper insert on surface improvement can clearly be seen in Figure 8 where the values are remarkably reduced. In general, during each feed motion, some parts of workpiece material are remained when conventional insert is used. Increase of feed motion causes more remained material resulting increment of roughness height.

In such conditions, wiper edge with more engagement leaves lower material causing lower surface roughness. Figure 9 can clarify the discussion. It is ascertained from figure that the feed marks in conventional turning were eliminated when wiper tool was used in the same cutting conditions.

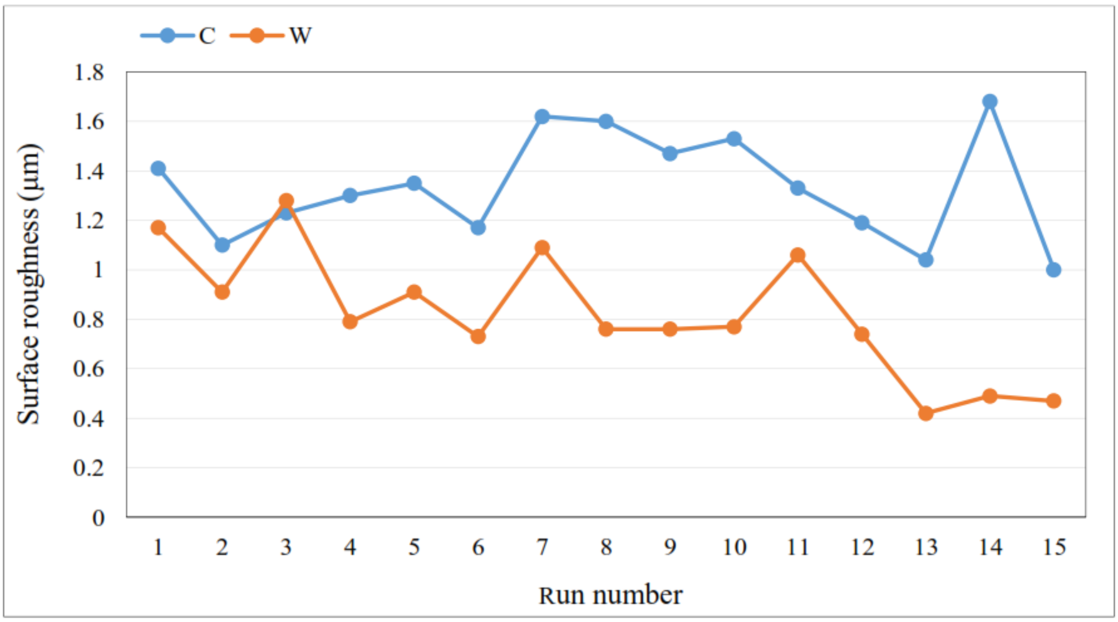

Figure8. Comparison of Surface roughness turned by C and W inserts

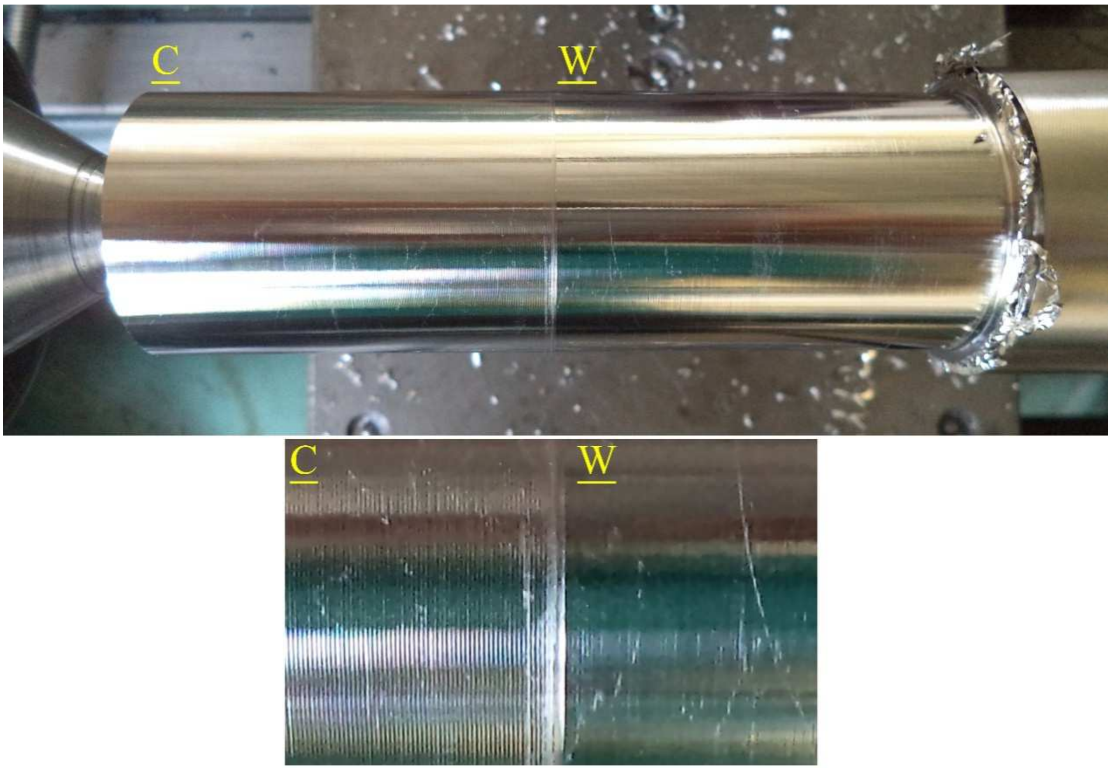

Figure9. Surfaces turned by C and W inserts

4.2 Cutting Force

With respect to Figure 10, the cutting forces were reduced by using wiper inserts compared to conventional ones. However, this decrement was not as significant as it was happened for surface roughness.

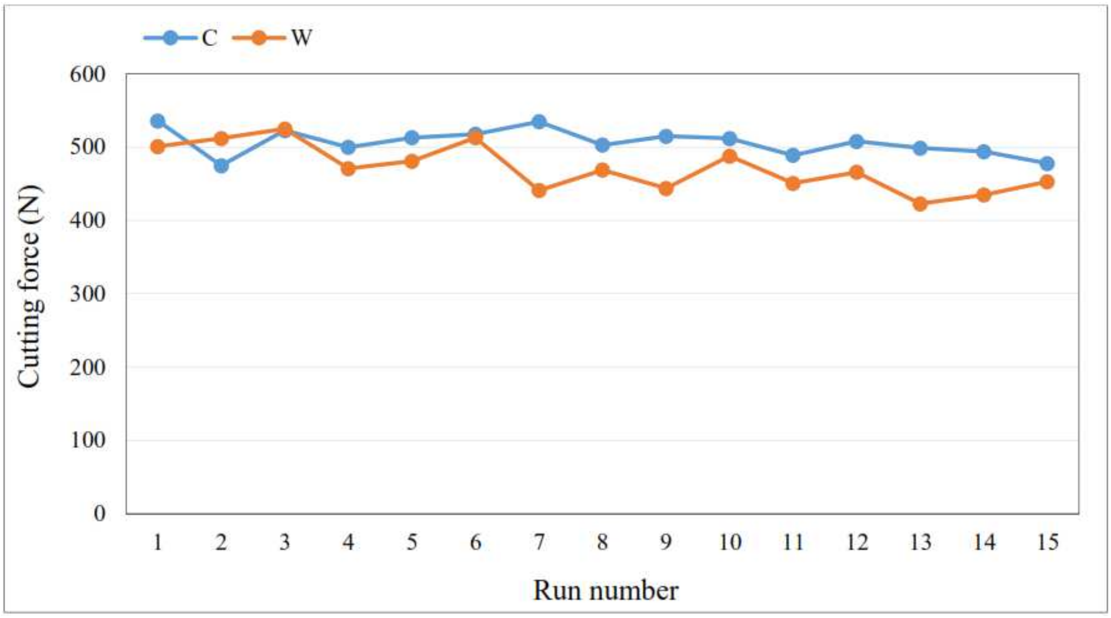

Figure10. Comparison of cutting force produced by C and W inserts

4.3 Flank Wear

The comparison of flank wear results are shown in Figure 11. In some cutting conditions wiper insert outperformed the conventional one and vice versa. With more precise investigation, it is found that almost in the condition that depth of cut value was equal or less than 1 mm (0.5 or 1 mm in run numbers like 1, 5, 7, 9, 11, 13, 14, and 15), flank wear was reduced by using wiper tool, while it became inverse in the value of 1.5 mm (run numbers like 2, 6, and 10). It can be explained by passing the wiper edge in higher depth of cut. In other words, in higher depth of cut, wiper tool acts somehow the same as conventional one, because its straight edge does the shearing action simultaneous with its wiper edge. These explanations can be seen in microscopic images of Figure 12. Based on the figure, the pattern of tool wear is the same in both wiper and conventional insert. Furthermore, it is seen that in low depth of cut condition, flank wear is lower in wiper insert compared to conventional one.

As shown in Section 2 by microscopic images, wiper edge produces 5 negative angles in cutting edge angle (Kr). When the holder is set in 90° with conventional tool, this becomes 85° when wiper tool is used instead of conventional one. Therefore, as reported by Jahanbakhsh et al. reduction in cutting edge angle causes to reduction of cutting force and also flanks wear [16].

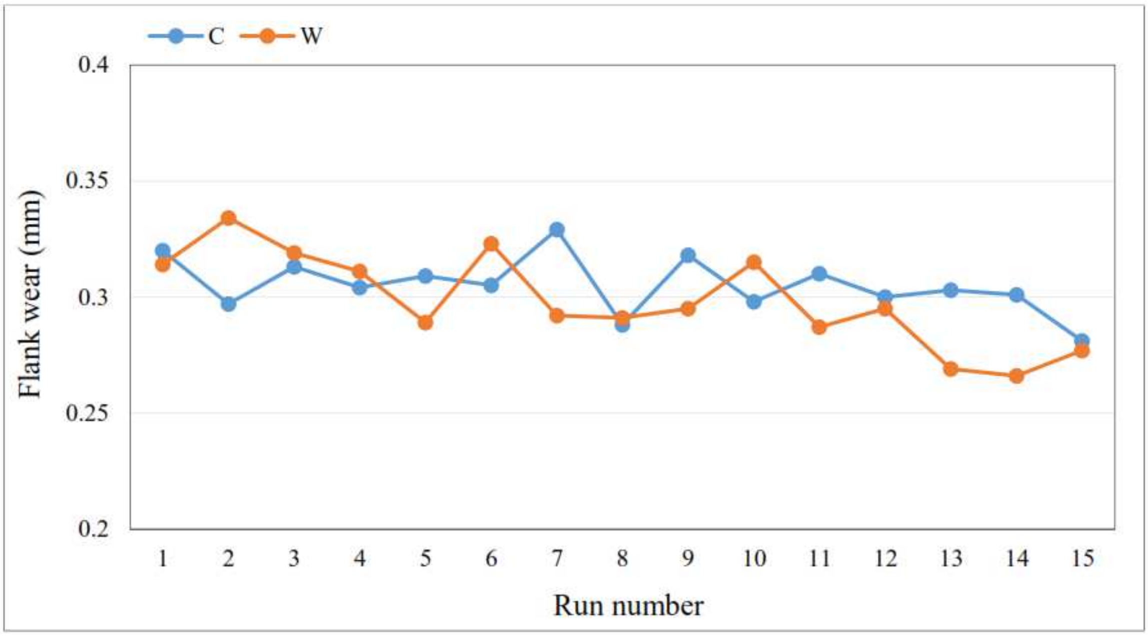

Figure11. Comparison of flank wear of C and W inserts

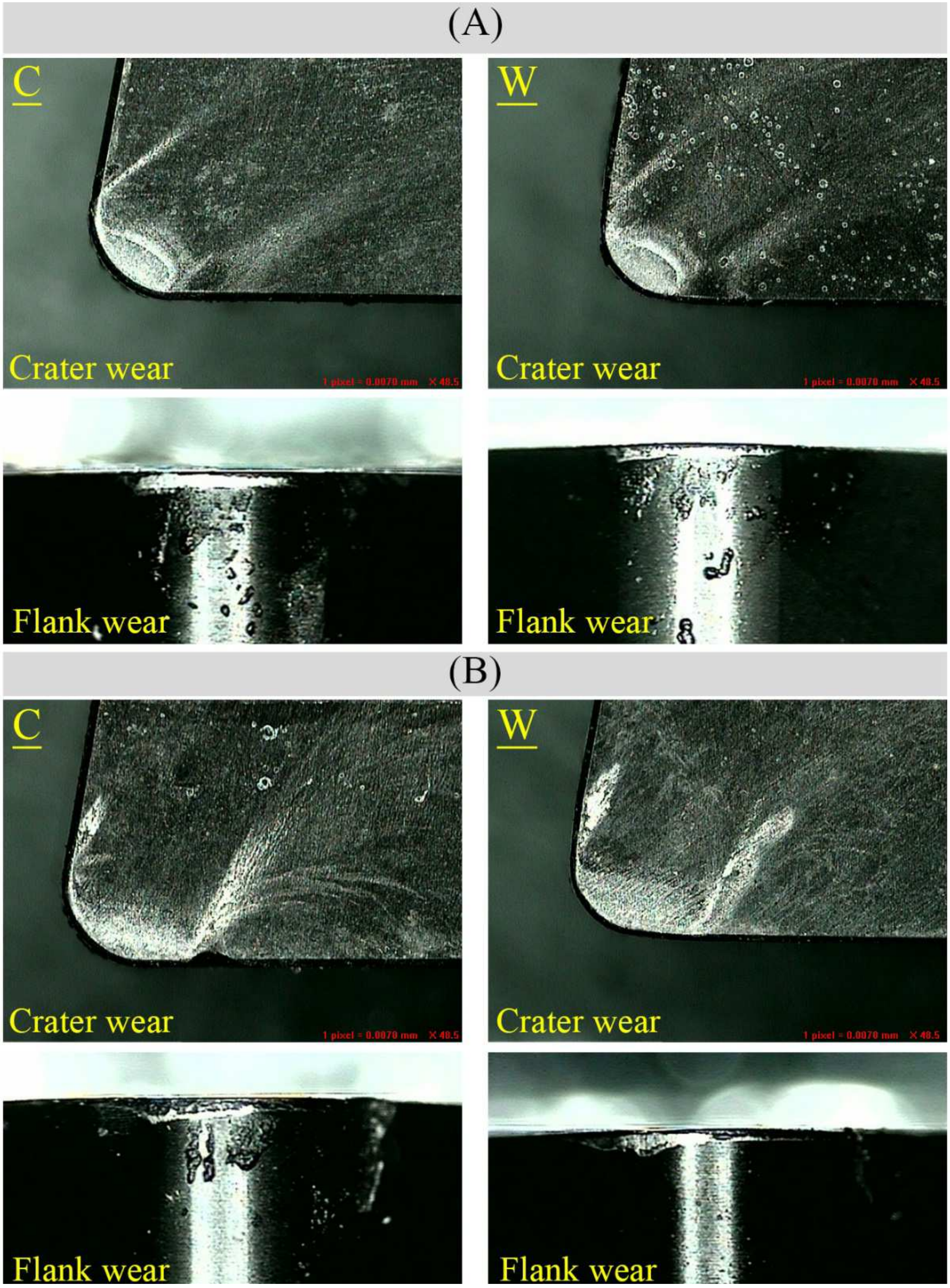

Figure12. Flank and crater wear of C and W inserts at minimum (A) and maximum (B) depth of cut

4. Conclusion

5. Conclusion

In this study, turning operation of Monel super-alloy was investigated by using two kinds of cutting tools, conventional and wiper inserts. After preparation work and design of the experiments by using central composite method, the tests were implemented. After that the results were individually represented for each cutting tool. All effective parameters on turning operation were found for each cutting tool by using analysis of variance. At the end of this analysis, the cutting condition was optimized and the optimal condition in turning of Monel super-alloy was represented for both conventional and wiper inserts. Consequently, following results were obtained:

- The tests of statistical models developed in this study showed that the models could acceptably predict the output values (surface roughness, cutting force, and flank wear).
- Feed and cutting speed were the effective factors on surface roughness by using conventional insert. Increase of feed rate increased the surface roughness, while it was reduced by increase of cutting speed. For wiper tool, feed and depth of cut were effective in which increase of both of them increased surface roughness. In general, feed rate was the most effective factor on surface roughness for both tools.
- Feed and depth of cut were the effective factors on cutting force for both tools where increase of these parameters increases cutting force. In general, depth of cut was the most effective factor on cutting force.
- The optimization analysis showed that lowest values of depth of cut and feed rated produced the most desire condition, but for cutting speed it was a little different. For C type, the highest value was obtained (200 m/min) and for W type, the speed of 178 m/min showed the best conditions.
- The comparison results revealed that the feed marks remained in turning with C type tool, almost were eliminated when wiper tool was used. Therefore, the roughness values were significantly lower in using W type compared to C type.
- The cutting forces were reduced by using wiper inserts compared to conventional ones. However, this decrement was not as significant as it was happened for surface roughness.
- The comparison of flank wear results showed that in some cutting conditions W insert outperformed the C one and vice versa. With more precise investigation, it is found that almost in the condition that depth of cut value was equal or less than 1 mm, flank wear was reduced by using wiper tool, while it became inverse in the value of 1.5 mm. In other words, when the holder is set in 90° with conventional tool, this becomes 85° when wiper tool is used. Therefore, cutting force and flank wear are reduced.

In general, surface roughness is significantly improved by using wiper tool where cutting force and flank wear are also reduced, slightly. Furthermore, ceramic wiper tool can be a good choice for turning of Monel super-alloy when low depth of cut and feed rate coupled with high cutting speed are selected.

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