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ORIGINAL ARTICLE

Comparative investigation and optimization of cutting tools performance during milling machining of titanium alloy (Ti6Al4V) using response surface methodology

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Abstract

The purpose of this paper is to study the optimization of the cutting performance of three different cutting inserts, during the machining operation of titanium alloy (Ti6Al4V) by making use of the response surface methodology (RSM) on a computer numerical control (CNC) milling. The cutting tools employed for the optimisation of the cutting performance during machining operation are silicon, aluminium, oxygen, nitrogen (SiAlON), cubic-boron nitride and carbide cutting inserts. Scanning electron microscope (SEM) was used for the determination of the tool wear for the cutting inserts being compared during machining of Ti6Al4V, and the cutting parameters, which are cutting speed (V_c), feed per tooth (f_z) and depth-of-cut that were evaluated from the cutting tools as per the manufacturer's design specifications. The determination of the tool wear on the cutting inserts was achieved by using the SEM, while the machining operation for the experimental trails was performed from the CNC milling machine, where face milling operation was executed. The optimization process showed that carbide cutting inserts yielded the best performing results and were considered the most significant choice of cutting insert in machining Ti6Al4V when compared to SiAlON and CBN cutting inserts. This choice was from the cutting tool life obtained where a cutting tool life of 29 min was obtained from a use of carbide cutting inserts; 28 min resulted from a use SiAlON cutting inserts and 26 min from a use of CBN cutting inserts. This work finds appropriate value in assisting the machinists in the selection of the best most performing and cost-effective cutting tool.

Keywords Cutting speed · CNC milling machine · Cutting inserts · Face milling · Tool wear and titanium alloy

1 Introduction

Ti6Al4V alloy is known to be a material difficult to machine, Kull, Diniz [1]. This is due to its strength-to-ratio properties, corrosion resistance and its capability to resist high temperatures. These challenges often lead to long machining times and high production costs [2], which might have resulted due to tool wear [3, 4]. Ti-alloys are widely used in the aerospace, biomedical, petroleum, automotive and marine industries, just to mention a few of its applications [5]. The machinability of this Ti-alloy is determined from the cutting parameters employed, such as the cutting speed, depth-of-cut and the feed rate. In this study, the appropriate selection of these parameters is envisaged to about a tool life that will result in an expected and desirable response parameter. A combination of true cutting parameters should yield good response parameters, while the incorrect cutting parameters will have a negative impact towards the response parameters, and this will lead to a non-competitive cutting process [6]. Ceramic-based cutting inserts are often employed in the machining of difficult-to-cut material due to their ability to withstand high temperature and a good wear resistance [7, 8].

To obtain a developed model, which is statistically and mathematical fit-for-purpose, the RSM technique is employed to give the best fit solutions in improving the

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machining process. This method provides the suitable relationship to each of the factors employed from the experimental design [9–11].

The cutting force and the associated vibration during a cutting exercise directly have an impact to the cutting tool life and the surface quality of the workpiece material being machined. Surface quality of the workpiece material being machined exhibits noticeable deterioration as wear action on the cutting tool is experienced. There for a prolonged tool life and improved surface finish, there is a need for improved cutting forces and vibrations [12, 13]. Milling machining can be optimised via the input cutting parameters, which include the cutting speed, feed rate, cutting depth, tool wear and environmental conditions, e.g. dry cutting or coolant application, among others. The cutting speed, feed rate and depth-of-cut are the most influential input cutting parameters in milling machining operation [14, 15].

A good knowledge of the workpiece material properties plays a vital role in the selection of cutting tools and the cutting parameters to consider thereof. SiAlON-based, CBN and carbides are among the different types of cutting tool materials used in the machining of titanium and its alloy. Carbide cutting tools are mostly used in machining Ti-alloys due to their toughness and hardness properties. Even though ceramic-based cutting tools seem to be harder than the carbide cutting tools, their brittleness and lack of toughness add to its disadvantage of not being fit and suitable choice for machining Ti-alloy. CBNs have the highest hardness among the three mentioned cutting tool materials, and this may lead towards its premature failure due to chipping and fracture [5]. During machining of Ti-alloys, the application of CBN, as material being removed, is too little, and it is generally advised in the finishing operation when compared to the roughening operations, where the depth-of-cuts may lead to the cutting tool breakage. This helps to avoid a shortened tool life.

A study on Nickel-based alloy Inconel 718, which has similar properties as Ti6Al4V, was conducted. From their findings, [7] observed that SiAlON ceramic cutting tool experienced prolonged tool life as compared to carbide cutting tool. However, when the cooling method is adopted, carbide cutting tools outperforms SiAlON-based cutting tools.

The finding reported by [1] in the correlation of the tool life and workpiece surface roughness was that a rigid tool is required. This will result in a minimised cutting vibration, which acts negatively on the tool life and may lead to poor surface finish, resulting from tool wear, if neglected.

During their experimental study on the influence of tool wear on machining Ti6Al4V, the findings observed by [3] showed that the cutter tool life is affected by the cutting temperature. As wearing of the cutting tool increases, the cutting temperature also rises due to the friction generated at the tool-workpiece interface. It was further observed that an increase of the tool wear time also led to increased cutting forces. In a review, [16] concluded that tool life is increased from a use of newly used cutting insert materials, considering their coatings as well. Increased tool wear is often observed due to higher cutting temperatures generated in dry machining when compared to cooling assisted machining [17]. An application of cooling method most likely improves the life of the cutting tool due to reduced cutting temperatures in the cut area [18]. In this study, the performance of cutting tools during Ti6Al4V milling machining is optimised. Cutting parameters affecting the response parameters are further optimised through numerical optimisation in order to keep the results in range and to improve the tool wear, which is beneficial to the prolongation of the tool life, and this leads to a better surface finish [13]. These results will assist in the selection of the best combination of cutting parameters, which will also lead to the determination of production times and costs, *vis-à-vis* the effect of tool life and wear.

The comparison of this nature among these three cutting inserts has not been sufficiently elucidated by the existing literature during titanium machining. Ceramic and carbide cutting tools were compared by [7] in their investigation during the machining of Inconel 718 and stainless steel 316L. Their focus was on tool life while the material being investigated was of difference from Ti6Al4V. [19] compared coated ceramic and CBN cutting inserts during their investigation of hard turning Ti6Al4V where their focus area did not include tool service life of the cutting inserts. They used Taguchi method for their design of experiments (DoE) where the response parameters involved were the surface roughness, cutting force, cutting temperature and cutting vibrations. A comparative study was carried-out for the cutting performance of SiAlON ceramic, CBN and carbide cutting tools during titanium machining [20]. The responses for the comparison were the cutting force, cutting temperature, cutting vibration and surface roughness. In their analysis, the authors did not focus on the cutting tool life, and optimization was also not performed. Hence, this work finds suitable application in Ti6Al4V machining.

2 Materials and methods

Optimization of the cutting tools performance was carried-out through milling operation via experimental trials. This part of the work expresses the materials and equipment used, including the experimental procedure, the experimental design and data collection along with

Table 1 Chemical composition of Ti6Al4V alloy

Element	Al	Fe	O	Ti	V
Per cent weight (wt. %)	6	0.25	0.2	90	4

Table 2 Mechanical and thermal properties of Ti6Al4V alloy

S/N	Properties	Value
	Mechanical	
1	Density (kg/m^3)	45,000
2	Brinell's hardness	334
3	Yield strength (MPa)	880
4	Ultimate tensile strength (MPa)	950
5	Bulk modulus (GPa)	150
6	Modulus of elasticity (GPa)	113.8
7	Poison's ratio	0.342
8	Shear modulus (GPa)	44
9	Shear strength (MPa)	550
	Thermal	
11	Specific heat capacity (J/g°C)	0.5263
12	Thermal conductivity (W/m K)	6.7
13	Melting point (°C)	1660
14	Coefficient of thermal expansion (K^{-1})	8.70

its analysis. Each cutting insert grade machined 20 workpieces to complete the experimental trial as highlighted in the DoE.

Table 1 presents the chemical composition of the material, while Table 2 presents its mechanical and thermal properties. Ti6Al4V workpiece material was employed to conduct the experiments during a cutting exercise.

Face milling operation was performed on a DMU-80monoBLOCK Deckel Macho CNC milling machine. A two-toothed Sandvik produced a cutting tool of 25 mm in diameter, which accommodated the round-shaped cutting inserts of 12 mm in diameter, and was used for the material removal from the workpiece material employed. The cutting inserts adopted for the optimization of cutting performance in the Ti6Al4V machining were from SiAlON-, CBN- and carbide-based materials.

The cutting parameters for the experimental trials are as indicated in Table 3, as per the manufacturer's design recommendations. Only three dominant factors, viz. the cutting speed, feed per tooth and depth-of-cut, were considered for the data collection, in the execution of the physical experimentation under dry cutting environment [21–23]. Selection of dry cutting environment was from the fact of supporting green environment and to improve cleanliness within a machining environment [16].

Figure 1 represents the flow diagram of the experimental design where the steps followed during data collection are specified.

The RSM procedure was employed for the prediction of the DoE by making use of DesignExpert software package, where 20 experimental trials were generated. The combination of the process parameters response of the cutting inserts was the tool wear, and it was measured from an application of the SEM images. The RSM was employed since it is deemed appropriate for the DoE and in the investigation of the combined effects from the cutting parameters on the DoE response parameter. Additionally, the predictive model that relates to the DoE can be achieved [24]. The face milling operation was over a length of 50 mm, where the cutting took place during a machining operation. The workpiece was securely clamped with dog clamps during a machining operation.

The RSM was applied for the response parameter of the DoE of different cutting inserts that were used, wherein mathematical models were developed. The validation of the numerical experiment was through the machining experiments on the CNC milling machine, which was then, followed by the modelling process, which was used for the predictive model to predict the cutter tool lives from the cutting process parameters. The results of the tool life of the cutting inserts used were derived from the equation previously used by [25] and [26]. The equation applied for the determination of tool life is as follows:

$$T = \left|44.85 - 0.074V_c - 61.77f - 11.29d_a\right| \quad (1)$$

Table 3 Cutting parameters

Parameter	Units	SiAlON		CBN		Carbide	
		Min	Max	Min	Max	Min	Max
Cutting speed	m/min	50	80	70	100	40	65
Feed per tooth	mm/tooth	0.1	0.42	0.08	0.15	0.1	0.2
Depth of cut	mm	0.5	1	0.5	1	0.5	1

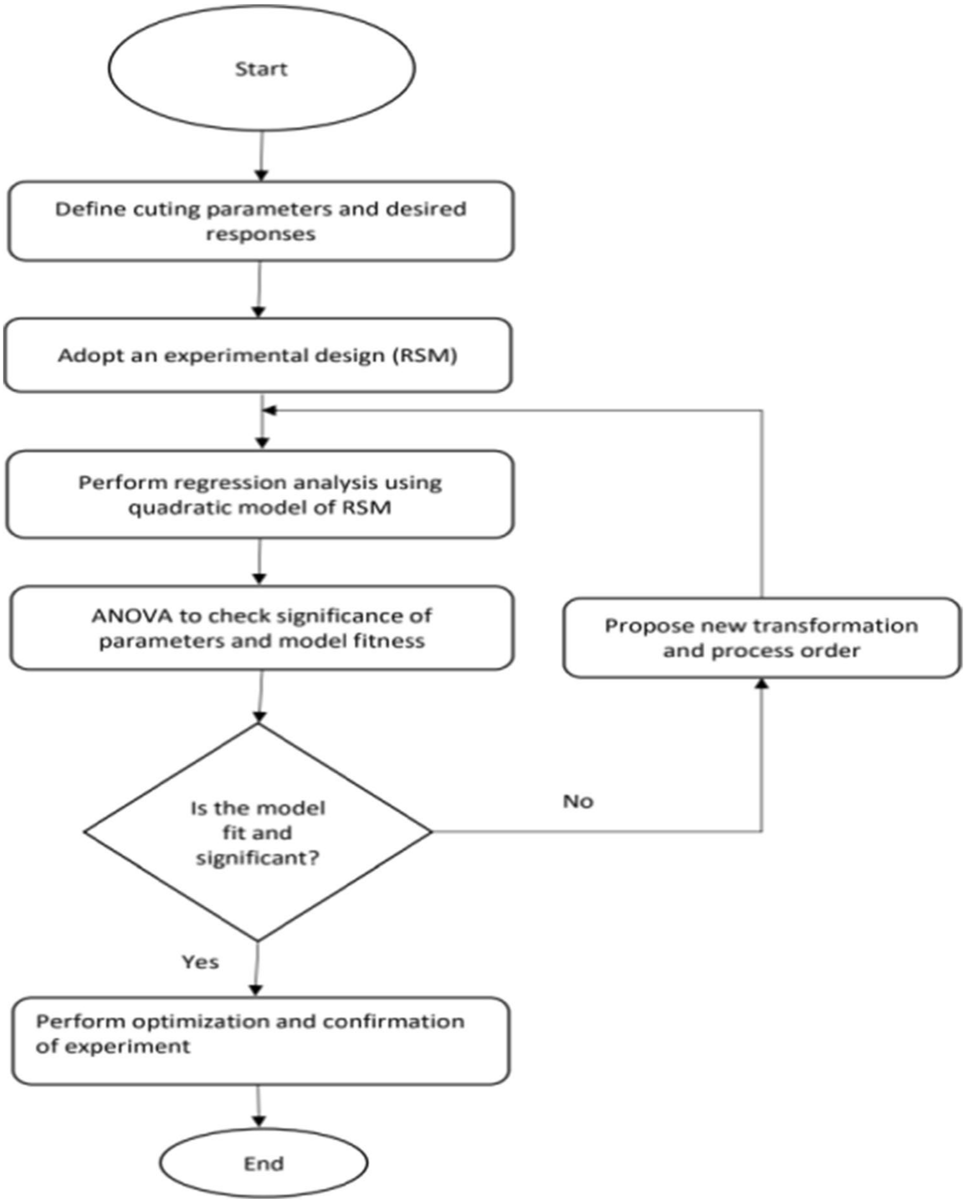


Fig. 1 Experimental design flowchart

where T represents the cutter tool life in minutes, V_c is cutting speed in m/min, f is the feed rate in mm/rev and d_a represents the axial depth-of-cut in mm.

3 Results and discussion

Data analysis, analysis of variance (ANOVA) mathematical modeling and response analysis of cutting tool life were presented in this section. The experimental results conducted were also discussed in this section.

A mathematical model was developed to determine the relationship of cutting tool life and the cutting parameter during a cutting operation for predictive purposes. Tables 4, 5 and 6 present the RSM process parameters of the SiAlON, CBN and carbide cutting inserts, where 20 experimental runs were performed for each of the cutting insert materials for the determination of the response parameter tool life. The results are further compared in Fig. 2 where the CBN cutting inserts showed shortened tool life results in most instances during experimental trials when compared to that of SiAlON and carbide cutting inserts. A general trendline was used on all three cutting inserts to show their best fit. Microscopic analysis was later conducted on the cutting inserts after experiments were completed for the determination of tool wear by using the LeicaTM stereo optical microscope. Chemical elements contained in the cutting inserts were identified and analysed using a SEM, equipped with an X-ray spectroscopy

Table 4 RSM process parameters of the SiAlON cutting inserts

Experimental trials	Factors			Response
	Cutting speed	Feed per tooth	Depth of cut	Tool life
	m/min	mm/tooth	mm	min
1	70	0.15	1	19.115
2	85	0.115	0.75	22.989
3	85	0.115	0.75	22.989
4	100	0.15	0.5	22.54
5	100	0.15	1	16.895
6	85	0.115	0.75	22.989
7	70	0.08	1	23.438
8	59.7731	0.115	0.75	24.856
9	85	0.115	0.75	22.989
10	85	0.173863	0.75	19.353
11	100	0.08	1	21.218
12	70	0.15	0.5	24.76
13	85	0.0561373	0.75	26.265
14	110.227	0.115	0.75	21.122
15	100	0.08	0.5	26.863
16	85	0.115	0.75	22.989
17	85	0.115	1.17045	18.242
18	85	0.115	0.329552	27.736
19	70	0.08	0.5	29.083
20	85	0.115	0.75	22.989

(EDX) device to achieve high-resolution images. Clear and well-resolved images were collected from an accelerating voltage of 20.0 kV at a working distance of 10 mm and a 34.9° take-off angle.

Figure 3 depicts the structural analysis of an unused carbide cutting insert, while that of a used carbide insert is shown in Fig. 4. The cutting edge is, therefore, represented, respectively in both figures, where there were no experimental cuts on the unused cutting inserts, while all the 20 experimental trials were performed by using a single cutting edge from the used cutting inserts. The SEM/EDX scanning line, from the cutting edge to the core of the carbide cutting insert, follows the cutting insert as presented in the figure, whereas the variation of chemical composition follows the SEM/EDX scanning line. This is presented in the form of a flow diagram by making use of an arrow as highlighted in Figs. 3 and 4 for both the unused and used cutting inserts. The chemical compositions from this cutting insert are carbon (C), nitrogen (N), oxygen (O), titanium (Ti), aluminium (Al) and tungsten (W). An unused cutting insert was covered with a coat of 25 µm of aluminium and oxygen. A discontinuous presence of aluminium and a complete absence of oxygen were revealed from the scanning line, and a tool wear of ~ 160 µm was measured on a used carbide cutting insert, relative to the unused carbide cutting insert.

Table 5 RSM process parameters of the CBN cutting inserts

Experimental trials	Factors			Response
	Cutting speed	Feed per tooth	Depth of cut	Tool life
	m/min	mm/tooth	mm	min
1	50	0.1	1	23.683
2	65	0.26	0.75	15.512
3	65	0.26	0.75	15.512
4	65	0.26	0.75	15.512
5	65	0.26	0.75	15.512
6	80	0.1	1	21.463
7	65	0.26	1.17045	10.765
8	80	0.1	0.5	27.108
9	65	0.529087	0.75	1.109
10	50	0.42	1	3.917
11	80	0.42	0.5	7.342
12	50	0.1	0.5	29.328
13	65	0.1	0.75	25.396
14	80	0.42	1	1.697
15	50	0.42	0.5	9.562
16	65	0.26	0.75	15.512
17	90.2269	0.26	0.75	13.646
18	65	0.26	0.329552	20.259
19	39.7731	0.26	0.75	17.379
20	65	0.26	0.75	15.512

Table 6 RSM process parameters of the carbide cutting inserts

Experimental trials	Factors			Response
	Cutting speed	Feed per tooth	Depth of cut	Tool life
	m/min	mm/tooth	mm	min
1	45	0.15	0.75	23.787
2	40	0.2	0.5	23.891
3	36.591	0.15	0.75	24.409
4	53.409	0.15	0.75	23.165
5	50	0.1	0.5	29.328
6	45	0.15	0.329552	28.534
7	45	0.15	0.75	23.787
8	45	0.15	1.17045	19.04
9	40	0.2	1	18.246
10	40	0.1	1	24.423
11	50	0.2	0.5	23.151
12	40	0.1	0.5	30.068
13	45	0.15	0.75	23.787
14	45	0.0659104	0.75	28.981
15	45	0.15	0.75	23.787
16	50	0.1	1	23.683
17	45	0.23409	0.75	18.593
18	50	0.2	1	17.506
19	45	0.15	0.75	23.787
20	45	0.15	0.75	23.787

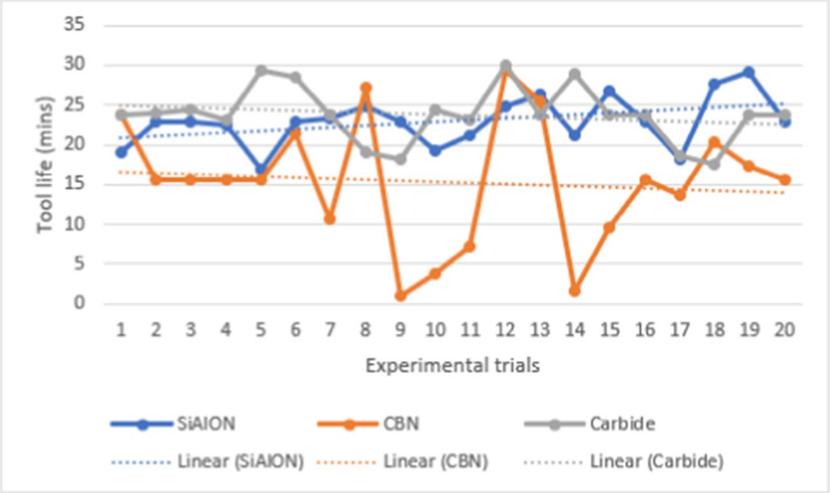


Fig. 2 Comparison results for the tool life

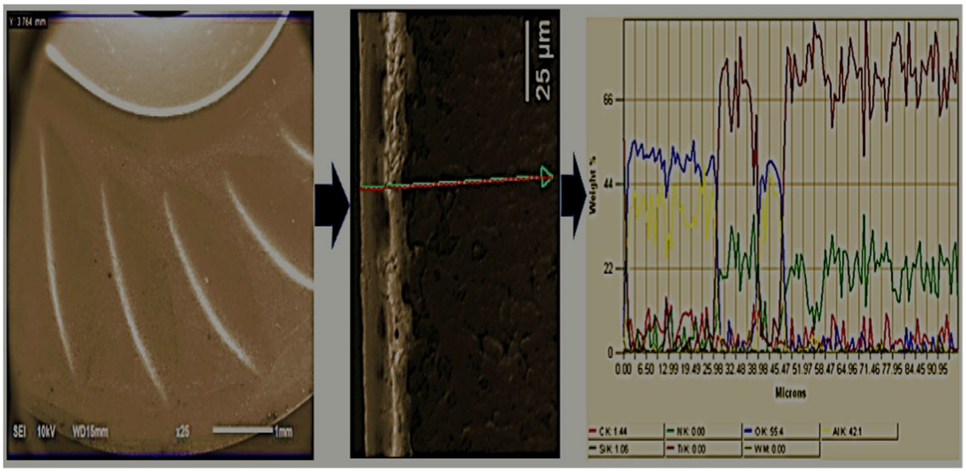


Fig. 3 Structural analysis of an un-used carbide cutting insert

Structural analysis of an unused CBN cutting insert is presented in Fig. 5, while that of a used counterpart for the first 10 (1–10) experimental trials is shown in Fig. 6, and the last 10 trials (11–20) are shown in Fig. 7, respectively. The SEM/EDX scanning line from the cutting edge to the core of the cutting insert and the variation content in a form of C, N, O, Ti, Al and W from the cutting edge are also presented in Fig. 5 for the unused cutting insert, while Fig. 6

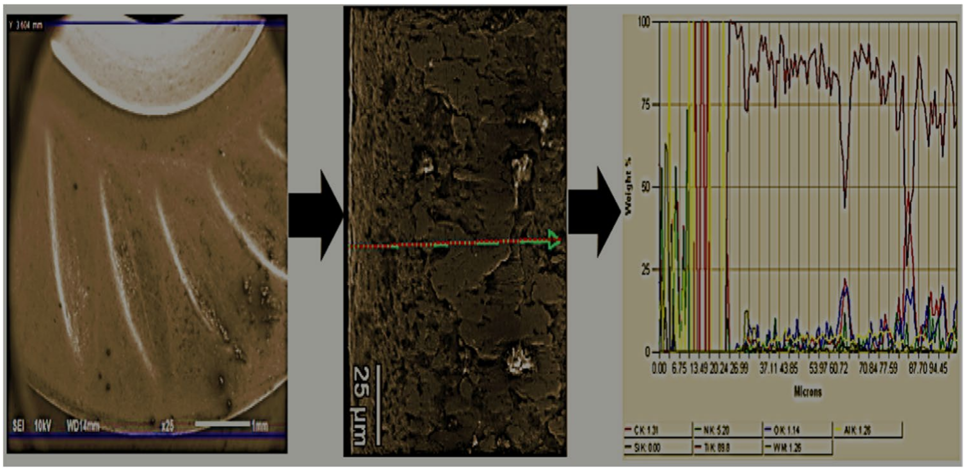


Fig. 4 Structural analysis of a used carbide cutting insert for the experimental trials 1–20

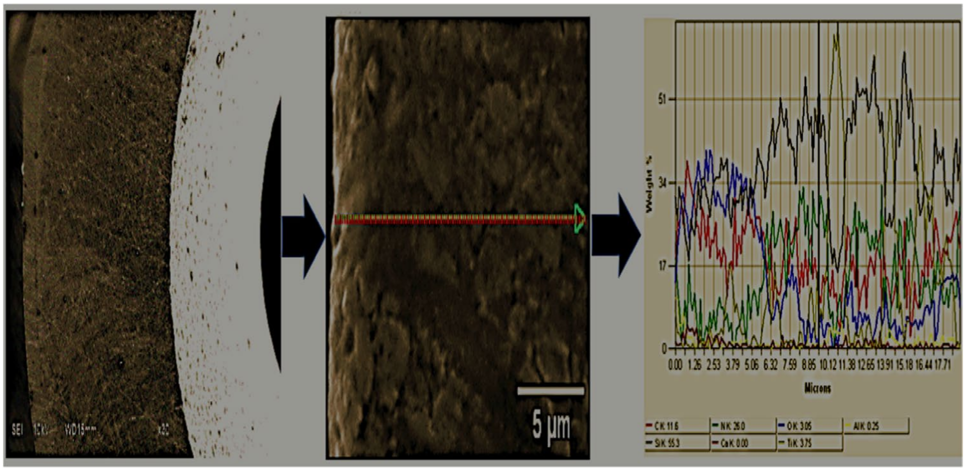


Fig. 5 Structural analysis of an un-used CBN cutting insert

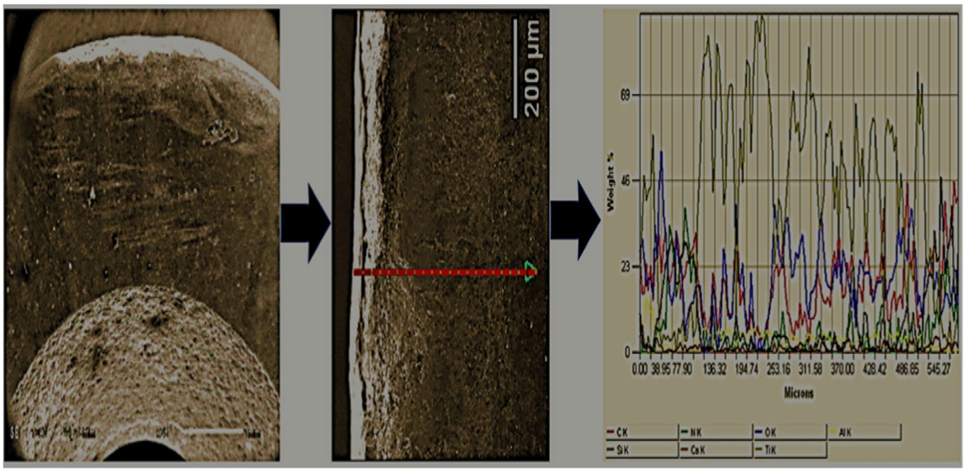


Fig. 6 Structural analysis of a used CBN cutting insert for experimental trials 1–10

is for that used for the first 10 cutting exercises, and lastly, the last 10 exercises are presented in Fig. 7. Predominant wear is observed in the last 20 experimental trials, and these could have resulted from the higher cutting temperatures produced during the cutting exercise. A coat of ~ 6 μm from C, Si and Al covered the unused cutting inserts, while the used cutting inserts show from the scanning a decrease in C and Si. Approximately 160 μm of wear was measured on

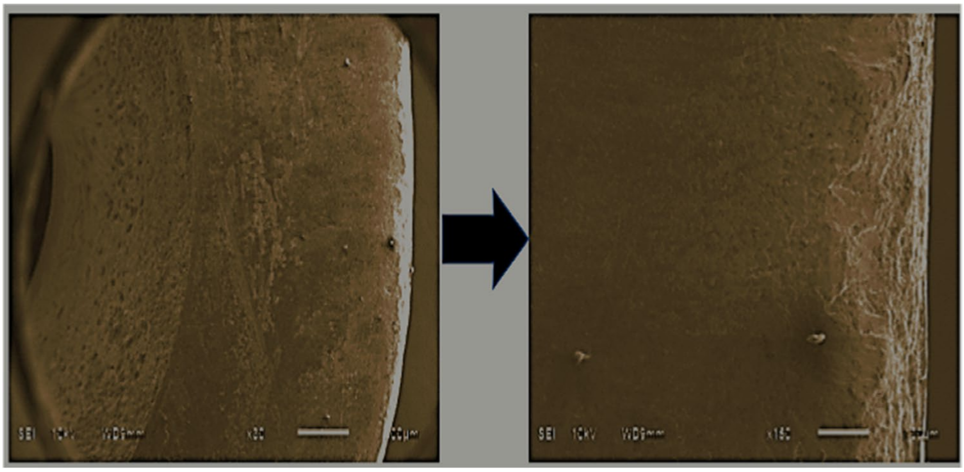


Fig. 7 Structural analysis of a used CBN cutting insert for experimental trials 11–20

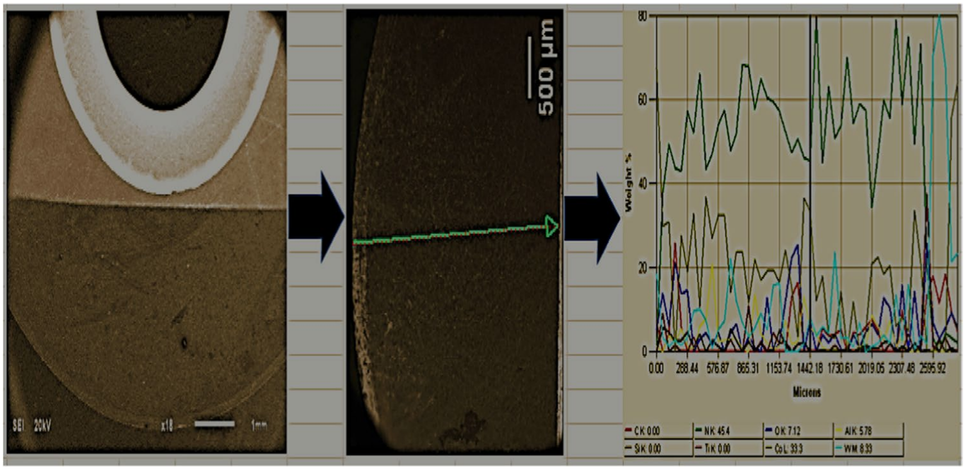


Fig. 8 Structural analysis of an un-used SiAlON ceramic cutting insert

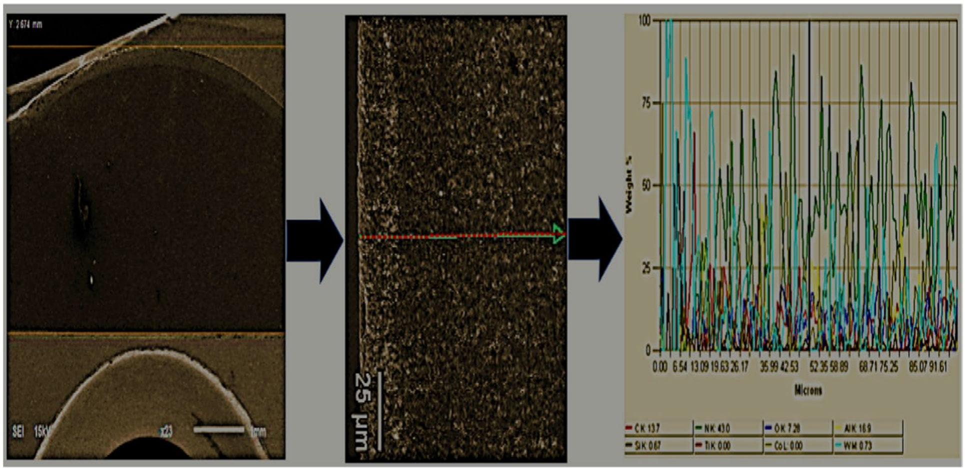


Fig. 9 Structural analysis of a used SiAlON cutting insert for experimental trials 1–14

a used cutting insert of the first 10 experimental trials, and the second set of cutting inserts for the last 10 used cutting operation shows wear of ~ 261 µm, relative to the unused cutting insert.

Figure 8 indicates the structural analysis of an unused SiAlON cutting insert, while the used cutting inserts for the first 14 cutting operations are shown in Fig. 9, and lastly, the inserts for the last six experimental trials are shown

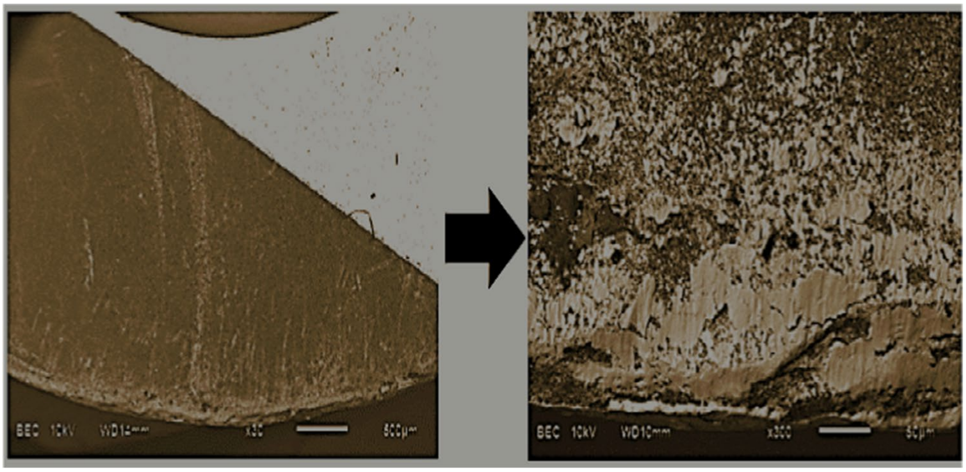


Fig. 10 Structural analysis of a used SiAlON cutting insert for experimental trials 15–20

Table 7 Selected optimised results from the listed 100 solutions

SiAlON	Parameters	Cutting speed	70.000	(m/min)
		Feed per tooth	0.080	(mm/tooth)
		Depth of cut	0.500	(mm)
	Response	Tool life	28.649	(min)
CBN	Parameters	Cutting speed	50.000	(m/min)
		Feed per tooth	0.100	(mm/tooth)
		Depth of cut	1.000	(mm)
	Response	Tool life	26.005	(min)
Carbide	Parameters	Cutting speed	40.000	(m/min)
		Feed per tooth	0.100	(mm/tooth)
		Depth of cut	0.500	(mm)
	Response	Tool life	29.689	(min)

in Fig. 10. The SEM/EDX scanning line from the cutting edge to the core of the of the insert and its variation content of C, N, O, Ti, Al and W are presented in Fig. 8 for the unused cutting insert, while the used cutting insert for the first 14 cutting trials is shown in Fig. 9. The last six experiments (15–20) shown in Fig. 10, which were conducted by using a second set of cutting inserts, show a prevalent wear of ~ 276 µm, while the first set (of experiments, i.e. 1–14), shows an approximate tool wear of ~ 124 µm relative to the unused SiAlON cutting insert. The cutting edge of the unused cutting insert was covered with a coat of ~ 6 µm emanating from C, Si and Al.

For the improvement of quality, increased productivity and cost reductions of cutting, an optimization method has to be implemented to achieve best cutting parameter results [27]. As a result, response parameters are increased at minimized cutting parameters. Optimized results of the cutting performance for response process parameters of these cutting inserts are presented in Table 7, where the best results are selected from the listed solutions to optimize tool life. Numerical optimization method was analysed for the selected cutting response within a selected range to avoid

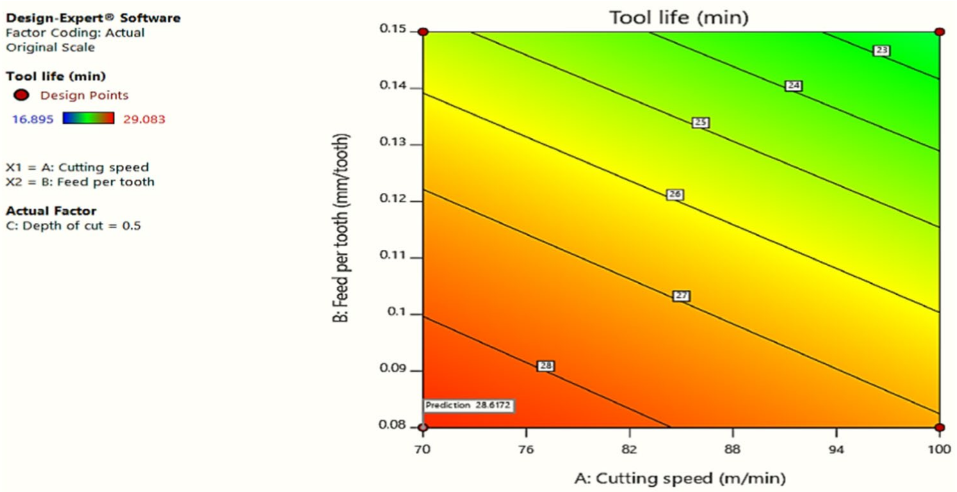


Fig. 11 Optimised 2D contour plot of the tool life for the SiAlON cutting inserts

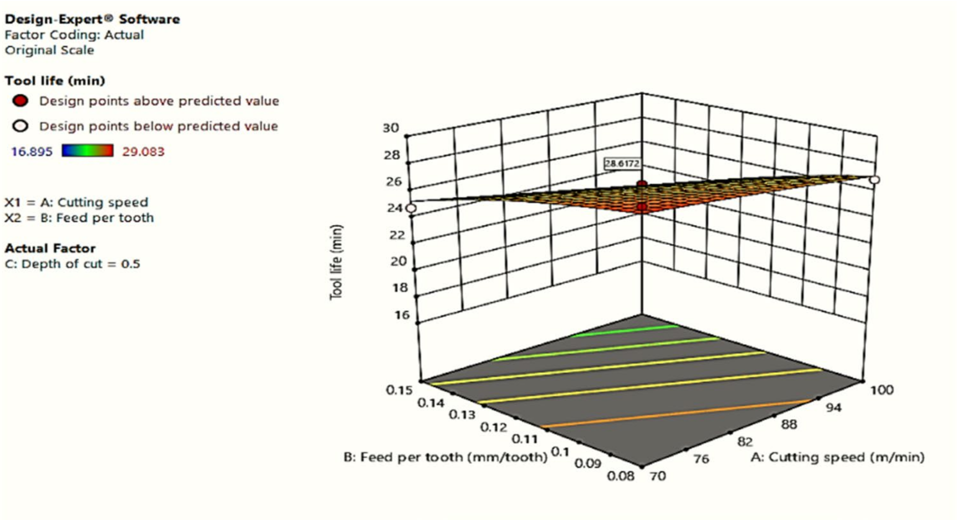


Fig. 12 Optimised 3D contour plot of the tool life for the SiAlON cutting inserts

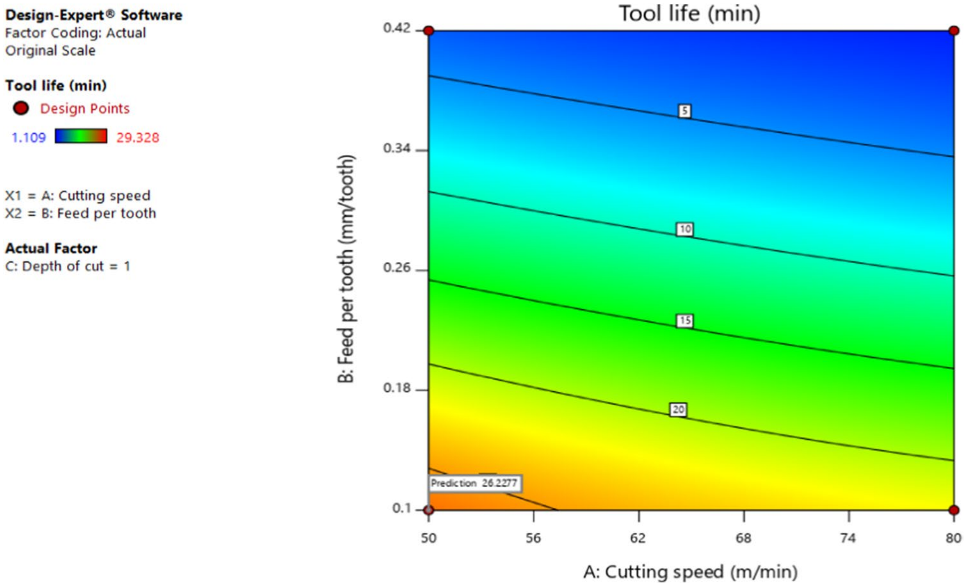


Fig. 13 Optimised 2D contour plot of the tool life for the CBN cutting inserts

causing problems. The optimized range of process parameter and their experimental response were tabulated for different cutting tool material used as shown in Table 7. These results were selected from the 100 listed solutions of numerical optimization for the selection of optimal results, and the best optimised value of them all was being selected and tabulated as per cutting insert material. The desirability for all optimised values is 1. These solutions from Table 7 further showed improved cutting performance results, whereby the cutting tool life also increased.

Optimized results of the cutting tool life of SiAlON cutting inserts are presented in Figs. 11 and 12 in the form of 2D and 3D contour plots. Figures 13 and 14 depict the 2D and 3D contour plots for the CBN cutting inserts, while carbide cutting inserts contour plots are shown in Figs. 15 and 16. The figures highlight the relationship of the feed per tooth and the cutting speed towards the cutting tool life. From the graphs, it is observed that a shortened tool life resulted from the lower feed per tooth and increased cutting speeds, and it is further observed that an increase in the feed per tooth and the cutting speed also led to a shortened tool life [28]. Furthermore, it is observed that low cutting speeds and increased feed per tooth led to a shortened tool life, while increased cutting

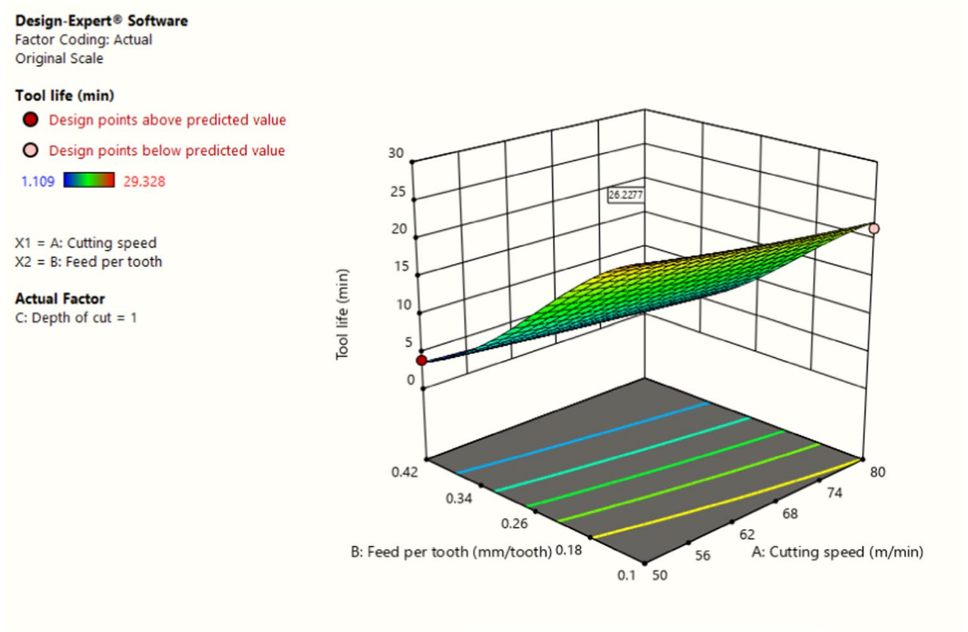
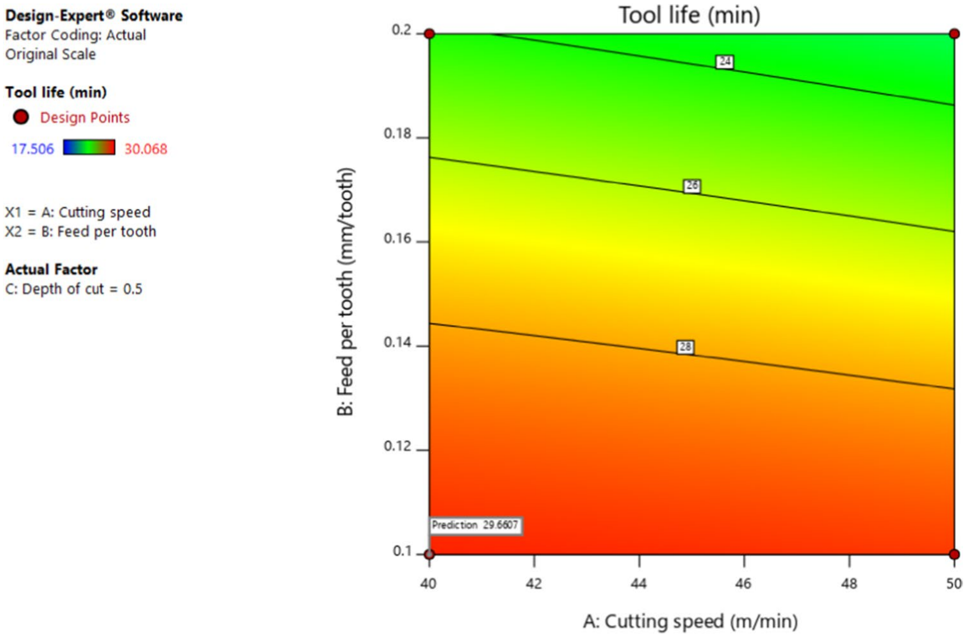


Fig. 14 Optimised 3D contour plot of the tool life for the CBN cutting inserts

Fig. 15 Optimised 2D contour plot of the tool life for the carbide cutting inserts

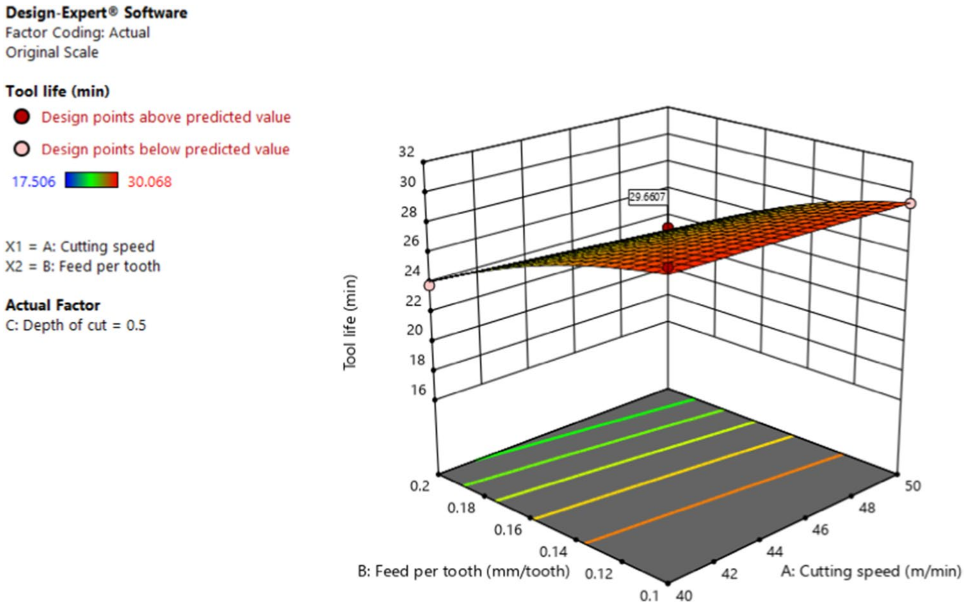


speeds and feed per tooth show similar results. These observations show that both the cutting speeds and feed per tooth have a negative impact on tool life because when either of both parameters is increased, kept a constant or reduced, a reduction in tool life also results. This is due to the friction and heat generated in the cutter-workpiece contact area where cutting operation takes place. Tool life was reduced from ~ 28 to ~ 23 min as the cutting parameters of the cutting speed and the feed per tooth were increased, as shown in Figs. 11 and 12. An increase in the cutting speed and the feed per tooth in the application of the CBN cutting inserts, as shown in Figs. 13 and 14, led to a reduction of the tool life from ~ 26 to ~ 5 min. It is further observed that the tool life was reduced from ~ 29 to ~ 24 min, as presented in Figs. 15 and 16 when carbide cutting inserts were used for the face milling operation on the workpiece material.

4 Conclusion

In this study, cutting tool performance during the Ti6Al4V milling machining has been optimized for three cutting tool insert materials. DoE was performed via the RSM by

Fig. 16 Optimised 3D contour plot of the tool life for the carbide cutting inserts



using the DesignExpert software. The conclusions from the study are as follows:

1. An increase in the input cutting parameters resulted in a shortened tool service life.
2. Input cutting parameters affected negatively the service tool life; therefore, for an increased tool life, the true cutting parameter values should be assigned.
3. The optimized response results recorded are viz. a cutting tool life of 29 min, resulting from the use of carbide cutting inserts, 28 min with SiAlON cutting inserts and 26 min from the CBN cutting inserts.
4. It can, therefore, be concluded that carbide cutting inserts exhibited the best results since they outperformed the SiAlON and CBN cutting inserts.

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Author contribution All authors contributed to the study conception. Material preparation, data collection and analysis were performed by Mr. Solomon Ntshiniki Phokobye. Dr. Kalenda Mutombo performed the tool wear and structural analysis of the cutting inserts. Prof Dawood Ahmed Desai, Mr. Isaac Tlhabadira and Prof Emmanuel Rotimi Sadiku, offered supervision, guidance and editing.

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Declarations

Conflict of interest The authors declare no competing interests.

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