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ORIGINAL ARTICLE

Comparative analysis of the cutting performances of SiAlON ceramic, cubic boron nitride and carbide cutting tools for titanium machining

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Abstract
The efficiency of machining operation is partly a function of the cutting parameters, such as the cutting speed, depth of cut and cutting feed rate. With an effective cutting performance of any cutting tool, manufacturing industries will remain competitive and hence strive to meet the dynamic service and functional requirements expected of the material. Hence, the purpose of this research is to experimentally perform a comparative analysis of the cutting performances of SiAlON, a ceramic alloy consisting of the elements: silicon, aluminium, oxygen and nitrogen; cubic boron nitride (CBN) and carbide cutting tools, during a titanium machining process. A face milling operation was performed on a computer numerical control (CNC) milling machine from these three different types of cutting tools, for the determination of the cutting forces, cutting temperatures, cutting vibrations produced and the surface roughness, achieved during the machining of titanium (Ti-6Aℓ-4 V) alloy. The response surface methodology was adopted for the possible combination of the cutting parameters for the determination of the practical experimental results of the cutting responses.

Keywords Cutting force · Cutting temperature · Cutting vibration · CNC machining · Titanium alloy

1 Introduction

For effective cutting operation during a machining process, a relative motion between the cutting tool and the workpiece material is required. A compressive force is usually applied on the workpiece material, by the cutting tool during a cutting operation, resulting in the development of residual stress in the material. Cutting takes place when the stress induced in the material exceeds its yield point. Thus, the temperature on the workpiece material and the cutting tool generates heat at the workpiece-tool interface during the cutting operation [1]. An increase in the temperature of the cutting tool softens the cutting tool, and this can lead to the gradual failure of the cutting tool [2]. The distortion or failure of the cutting tool is due to temperature increase during the cutting operation. This often results in an adverse effect on the cutting process, in terms of increase in energy consumption, poor surface finish of the workpiece and increase in the time required for the cutting process, amongst other drawbacks. Hence, in order to address the challenge of tool distortion or damage during the cutting process, many machining industries have developed and are developing special tools that can cope with the dynamic requirements of the cutting process without failure.

To achieve quicker machining times and better surface finish on machined part, the use of ceramic tools in the machining industry has increased.

It has been noted that better results are achievable when making use of ceramics over tools made of steels during machining of hard workpiece materials [3]. For effective machining process, the cutting tool material must be harder than that of the part to be machined, so that it can easily penetrate the workpiece without distortion. Another type of cutting tool that boasts of hardness is the carbide cutting tool. These tools are usually preferred when cutting

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hardened materials. When compared to high-speed steel tools, they perform better at high temperatures during the cutting process. One of the demerits of the carbide tool is that its performance often deteriorates with increase in the material hardness, and this can lead to a poor surface finish as a result of the wear of the cutting material, which may also impact negatively on the tool life.

Due to the characteristics of their microstructure, over the years, Ti-alloys are regarded to be a difficult-to-cut material even with the successful development of improved cutting tool materials. Due to their excellent strength-to-weight ratio, ability to retain their strength at high temperatures and their good corrosion resistance profiles [4], Ti-alloys, e.g. Ti-6Al-4 V, are widely used in the aerospace, automotive, biomedical and mining industries, amongst others [5]. The challenges faced on the workpiece material when machining Ti-alloy, include poor surface finish at low cutting speeds and feeds, high chances of vibrations at higher cutting speeds and high thermal loads and residual stress developments, amongst others [6]. From these challenges, high tool wear rates may lead to poor quality work and therefore renders the cutting process less effective, in terms of time and cost requirements. To overcome these challenges solutions, such as high pressure and cryogenic cooling, hybrid machining and thermally enhanced machining, amongst other approaches, have been adopted [7–9].

The low thermal conductivity of Ti-alloy also makes it to be prone to temperature rise when it is in contact with the cutting tool during a cutting operation. This may lead to a premature tool failure and a decrease in the tool life [10]. In their experimental and numerical studies on the performance of alloyed carbide tool, [11] reported that the machinability of Ti-alloys is weakened due to the low modulus of elasticity and the sustained high strength at elevated temperatures.

One of the most important parameters in a machining operation is temperature. This is because temperature changes determine the changes in workpiece's mechanical behaviour, microstructure, surface finish and cutting tool performance. The tool life of any cutting tool often decreases when cooling is not applied during a cutting operation, which may affect the sustainability of the cutting process, in terms of energy consumption and subsequently, poor surface finish of the workpiece. To overcome this challenge, cooling should be employed to improve the quality of the workpiece and increase the tool life [12, 13]. Over the years, technologies that integrate temperature sensors into the computer numerical controlled machines for capturing and monitoring temperatures in real time have evolved. The essence is to keep the temperature of the cutting process within the permissible limits.

Some of the influential factors in the machining and behavioural change of Ti-alloy are the cutting parameters and the tool geometry. The cutting tool selection, suitable for machining Ti-alloy can, therefore, be made from the optimum range of the process parameters. Added to that, appropriate cutting force should be estimated for the determination of the material removal rate and the cycle time for the cutting operation. To achieve this, researchers have employed methods, e.g. the RSM and Taguchi approaches [14, 15].

In a study, during the milling of cold-work tool steel, [16] investigated the performance and wear behaviour of a tungsten carbide tool with different coatings, namely cermet, ceramic and CBN. The combination of the cutting tool material and coating contributed towards the cutting tools' wear formation. Factors such as workpiece condition, cutting operation performed, generated chip, machine tool capability, cutting tool and workpiece rigidity, fixturing used for securing workpiece, selected speed and feed rates and the cutting conditions resulting from the applied cutting forces and temperatures played a vital role in the selection of a cutting tool material for a cutting operation [17].

[18] concluded that during machining of AISI 4340 with coated carbide tools, there was an increase in the surface roughness, and this made the feed rate to be more influential when compared to other cutting parameters.

It is a known fact that Ti-alloys are difficult-to-cut material; hence, the objective of this study is to comparatively analyse the cutting performance of the three cutting insert materials, namely SiAlON ceramics, CBN and carbide cutting tools. This is to guide in the selection of the best performing and cost-effective cutting tool, during the machining of Ti-alloy. To achieve this, different approaches, such as statistical and mathematical model, were executed in this study, in order to investigate the performance of the different cutting tools.

2 Methodology

In this study, a comparative investigation was undertaken through an experimental milling operation, involving trial runs. This section describes the materials, equipment used for this study, the experimental procedure, the design of experiments, data collection and the data analytical approach, employed to achieve the objectives of this research. It also describes the types of equipment, which include both the hardware and software used to conduct the experiments of this study. The research methodology is discussed together with the data analysis method applied during the experiments so that the envisioned objectives are attained. Figure 1 illustrates the machine tool (5-axis Deckel Maho CNC milling machine) and equipment used for the experimental setup. The material employed, i.e. Ti-6Aℓ-4 V alloy workpiece, is presented in Fig. 2. The equipment used is schematically highlighted in Fig. 3.

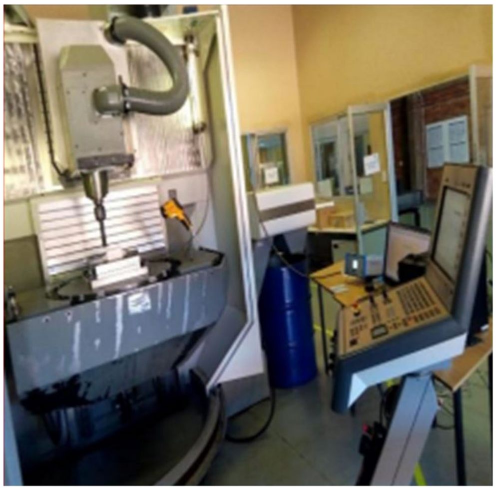

Fig. 1 Experimental setup

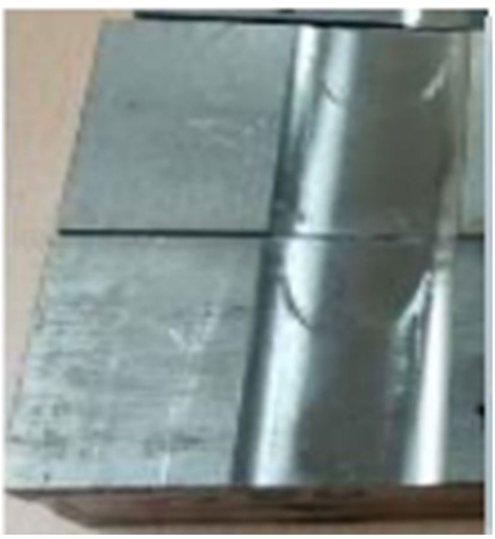

Fig. 2 Ti-6Al-4 V workpiece material

Ti-6Al-4 V, which is an α-β titanium alloy, was used as a test material during the cutting operation. This particular alloy was chosen because it is the most widely used in the industry. In this work, 20 workpieces per insert grade in comparison were machined. The chemical composition of this material is presented in Table 1, while its properties are presented in Table 2.

2.1 Experimental procedure

The physical experimentation was conducted by performing a face-milling operation on a Ti-6Al-4 V workpiece material for the comparative analysis of the cutting performances of SiAlON, CBN and carbide cutting tools. Cutting operation was carried out on a 5-axis CNC milling operation with a maximum spindle speed of 18,000 rpm and a power output of 55 kW.

A SANDVIK cutting tool with a diameter of 25 mm (R200-020A25-12 M), suitable for 12-mm round-shaped cutting inserts, was used to perform the cutting exercise through the material removal from the workpiece. Face-milling operation was completed for the physical experimentation, by making use of cemented carbide, SiAlON-based ceramics and CBN cutting inserts for the comparison of their cutting performances of the machining of Ti-6Al-4 V.

The cutting forces produced were measured from The Kistler 9257A dynamometer during the cutting operation, and the values obtained were recorded by making use of the DynoWare software. To complete the process of the cutting forces, the workpiece was clamped on the dynamometer, and the dynamometer was connected to the multichannel charge amplifier used as an analogue data wave. A KISTLER DAQ device, connected to the multichannel charge amplifier, was used for the collection of data for the cutting forces. A Major Tech IRR video thermometer was used to measure and record the cutting temperature for each cutting operation, while a vibration accelerometer was used for data acquisition that relates to the cutting vibration. The LabVIEW software was employed for measuring the magnitude of the vibration. The average roughness of the machined surface was determined with the aid of a Mitutoyo roughness tester, by running three tests along the machined area of the workpiece. The cutting parameters for the experimental trials are presented in Tables 3, 4, and 5 as per the cutting inserts employed in this study.

Figure 3 shows the schematic diagram of the experimental setup, where A represents the machine spindle, B represents a cutting tool, C is the Ti-6Aℓ-4 V workpiece material, D is the dynamometer, E represents the machine table, while F is an accelerometer.

2.2 Design of experiments

Twenty experimental trials were conducted for each grade of the cutting inserts used in this comparative analysis. A cutting length of 50 mm was used for the face-milling operation on the workpiece material during machining process. The workpiece was securely clamped on the dynamometer with dog clamps, for safety reason.

RSM was employed for the experimental design to predict the experimental results of the cutting force, cutting temperature, cutting vibration and the surface roughness for the establishment of necessary mathematical models. The relationship of the responses and their factors, during the machining operation, are determined by the mathematical model, for future work purposes.

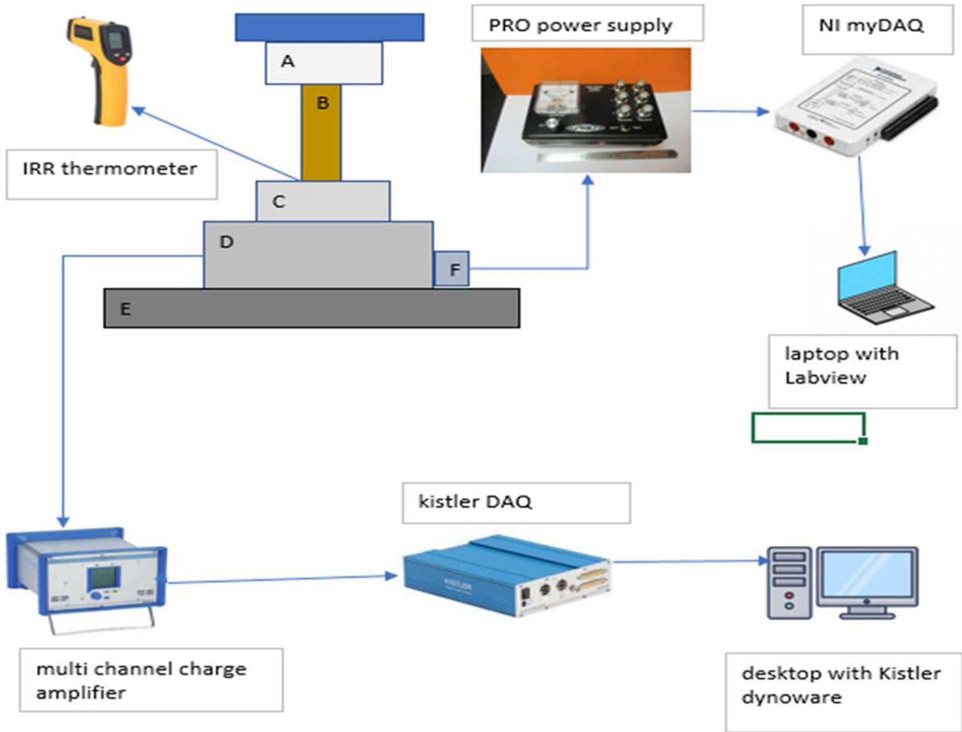

Fig. 3 Schematic diagram of experimental set-up

Table 1 Chemical properties of Ti-6Al-4 V

Chemical constituent	Carbon	Nitrogen	Aluminium	Vanadium	Hydrogen	Iron	Titanium
Symbol	C	N	$A\ell$	V	H	Fe	Ti
%Mass	0.05	0.01	6.15	4.4	0.005	0.09	89.295

Table 2 Physical properties of Ti6Al4V

Physical properties	Strength	Yield point	Ductility	Hardness	Modulus of Elasticity	Density	Thermal conductivity
Unit	MPa	MPa	%	HB	GPa	kg/m^3	W/m K
Value	950	850	10	340	113	4430	7.56

Table 3 CBN cutting parameters

Name	Units	Low	High
Cutting speed	m/min	70	100
Feed per tooth	mm/tooth	0.08	0.15
Depth of cut	mm	0.5	1

Table 4 SiAlON cutting parameters

Name	Units	Low	High
Cutting speed	m/min	50	80
Feed per tooth	mm/tooth	0.1	0.42
Depth of cut	mm	0.5	1

Table 5 Carbide cutting parameters

Name	Units	Low	High
Cutting speed	m/min	40	65
Feed per tooth	mm/tooth	0.1	0.2
Depth of cut	mm	0.5	1

RSM was applied for the design of experiment (DoE) in order to develop the mathematical models of the three cutting tools that are being compared in this study. This is critical to predict the experimental results of the responses. RSM was selected because it can study the cross effect of the process parameters on the measured responses of the experiment [19]. The cutting parameter values selected were reasonable as recommended by the cutting inserts supplier, SANDVIK Coromant. The designed experiment generated 20 trials whose responses were determined experimentally.

RSM was employed in the DesignExpert software package (ver. 11, StatEase Inc.,) environment that was used to carry out the DoE for the possible combination of the process parameters. Validation of the numerical experimentation results was through physical experimentation, followed by the modelling process for the predictive models of the experimental responses, which are the cutting force, cutting temperature, cutting vibration and surface roughness as the function of the independent process parameters, which are the cutting speed, feed/tooth and depth of cut.

2.2.1 Analysis of results for responses of cutting inserts

Tables 6, 7 and 8 present the significant values from the analysis of variance (ANOVA) of the model developed for the experimental responses: cutting force, cutting temperature, surface roughness, cutting vibration and the tool life for experimental results obtained from the SiAlON, CBN and carbide cutting inserts. The results show that the model *F*-value of the responses is significant. The *P*-value of the overall model parameters is less than 0.05, which means that the models for all the responses are statistically significant. The significant

Table 6 Significant values from the ANOVA of SiAlON cutting inserts

Cutting force	Significant parameter	C	ABC	A^2C	
	F-value	13.19	15.74	8.04	
	P-value	0.0027	0.0014	0.0132	
	Model type	Reduced Cubic			
Cutting temperature	Significant parameter	C^2	ABC	A^2B	A^2B^2
	F-value	37.29	5.07	5.23	20.27
	P-value	< 0.0001	0.0423	0.0396	0.0006
	Model type	Reduced quartic			
Surface roughness	Significant parameter	B			
	F-value	6.63			
	P-value	0.0191			
	Model type	Reduced linear			
Cutting vibration	Significant parameter	AC			
	F-value	5.43			
	P-value	0.0316			
	Model type	Reduced 2FI			

Table 7 Significant values from the ANOVA of CBN cutting inserts

Cutting force	Significant parameter	A	B	AB	B^2	
	F-value	7.9	15.74	8.04	10.52	
	P-value	< 0.0001	0.0014	0.0132	0.0055	
	Model type	Reduced cubic				
Cutting temperature	Significant parameter	BC	ABC			
	F-value	6.69	4.67			
	P-value	0.0199	0.0461			
	Model type	Reduced cubic				
Surface roughness	Significant parameter	B	AB	B^2	ABC	A^2B
	F-value	36.64	15.91	21.77	5.47	8.27
	P-value	< 0.0001	0.0013	0.0004	0.0347	0.0122
	Model type	Reduced cubic				
Cutting vibration	Significant parameter	B	AC	A^2B		
	F-value	7.3	10.79	5.51		
	P-value	0.0164	0.005	0.0331		
	Model type	Reduced cubic (aliased)				

Table 8 Significant values from the ANOVA of carbide cutting inserts

Cutting force	Significant parameter	B	C	AB	A^2	ABC		
	F-value	8.57	6.11	10.20	4.94	8.74		
	P-value	0.011	0.0269	0.0065	0.0431	0.0104		
	Model type	Reduced Cubic						
Cutting temperature	Significant parameter	C	AB	AC	C^2	A^2B	A^2C	
	F-value	28.17	7.17	27.39	8.26	9.08	26.64	
	P-value	0.0018	0.0366	0.002	0.0283	0.0236	0.0021	
	Model type	Cubic (Aliased)						
Surface roughness	Significant parameter	B	AC	BC	A^2	B^2	C^2	ABC
	F-value	6.63	7.61	6.43	5.74	11.26	10.71	5.88
	P-value	0.0191	0.0186	0.0277	0.0355	0.0064	0.0074	0.0337
	Model type	Reduced Cubic						
Cutting vibration	Significant parameter	C						
	F-value	16.1						
	P-value	0.001						
	Model type	Linear						

Table 9 Fit statistics values of SiAlON cutting inserts

	Parameter	R^2	Adjusted R^2	Predicted R^2	Adeq precision
Cutting force	Value	0.7245	0.6261	0.6263	10.2409
Cutting temperature	Value	0.833	0.7559	0.5964	14.4477

Table 10 Fit statistics values of CBN cutting inserts

	Parameter	R^2	Adjusted R^2	Predicted R^2	Adeq precision
Cutting force	Value	0.7829	0.725	0.5538	12.1934
Surface roughness	Value	0.8556	0.804	0.663	14.2567
Cutting vibration	Value	0.6798	0.5944	0.5295	11.1164

Table 11 Fit statistics values of carbide cutting inserts

	Parameter	R^2	Adjusted R^2	Predicted R^2	Adeq precision
Cutting force	Value	0.7336	0.6385	0.5581	10.8322
Cutting temperature	Value	0.9275	0.7704	0.6779	14.0583
Surface roughness	Value	0.8696	0.7747	0.6533	11.2823
Cutting vibration	Value	0.5187	0.4284	0.3291	8.1654

parameters are A, which is the cutting speed in m/min; B is the feed per tooth in mm/tooth and C is the depth of cut in mm. These are also indicated in Tables 6, 7 and 8, respectively.

Tables 9, 10 and 11 show the statistical fits of the model developed for the experimental responses' predictions. Their predicted R^2 is in reasonable agreement with their adjusted R^2 with a difference of less than 0.2. This implies that the model is suitable for predictive purposes. Furthermore, the magnitude of "Adeq Precision", which measures the signal-to-noise ratio of greater than 4, is desirable, as it indicates an adequate signal. Therefore, these models can be used to navigate the design space.

2.2.2 Equations for cutting force models

Equation 1 presents the model equation for the prediction of the magnitude of the cutting force, as a function of the independent process parameters, namely the cutting speed, feed per tooth and depth of cut. The final equation is in terms of the coded factors, and this equation is useful in identifying the relative impact of the factors by comparing the factor coefficients. This is the initial equation determined by software codes using impact factor levels before calculation could be completed:

$$Cutting\ force = 564.65 + 145.24C - 64.99AB + 68.31AC + 133.41ABC - 148.09A^2C \quad (1)$$

The final equation, in terms of coded factors, is presented in Eq. 2, while Eq. 3 presents the final equation in terms of the actual factors for the prediction of the cutting force of the CBN cutting inserts. Final equation in terms of actual factors refers to the equation that uses physical factor values to the factors of consideration. Furthermore, Eq. 2 is useful in identifying the relative impact of the factors by comparing the factor coefficients.

Predictions about the response for a given level of each factor can be made by making use of Eq. 3, and this equation should not be used to determine the relative impact of each factor because the coefficients are scaled to accommodate the units of each factor, and the intercept is not the centre of the design space:

$$\sqrt{Cuttingforce} = 24.74 + 1.61A + 3.53B - 2.76AB - 2.28B^2 \quad (2)$$

$$\sqrt{Cutting\ force} = -10.42832 + 0.406466A + 143.15752B - 1.15136AB - 88.95603B^2 \quad (3)$$

Equation 4 presents the final equation in terms of the coded factors for the prediction of the cutting force of the carbide cutting inserts. This equation is useful in identifying the relative impact of the factors by comparing the factor coefficients. Given the similar cutting conditions and process parameters, the model equations can be employed to determine the magnitude of the cutting force. This will assist the machinist to save cost and time in running similar experiments:

$$1/(Cutting\ force) = 0.002 - 0.0002B - 0.000C + 0.0003AB - 0.0002A^2 - 0.0003ABC \quad (4)$$

2.2.3 Equations for cutting temperature models

Equation 5 presents the final equation in terms of the coded factors for the prediction of the cutting temperature of the SiAlON cutting inserts. The usefulness of this equation is to identify the relative impact of the factors by comparing the factor coefficients:

$$\sqrt{Cutting\ temperature} = 11.13 - 0.2781C - 0.0808A^2 + 0.9265C^2 + 0.432ABC - 0.439A^2B - 1.25A^2B^2 \quad (5)$$

Equation 6 presents the final equation in terms of the coded factors for the prediction of the cutting temperature of the CBN cutting inserts. The usefulness of this equation is to identify the relative impact of the factors by comparing the factor coefficients:

$$Cutting\ temperature = 155.78 + 12.03A + 21.36BC - 17.86ABC \quad (6)$$

The final equation, in terms of the actual factors for the prediction of the cutting temperature of the carbide cutting tools, is presented in Eq. 7. This equation should not to be used to determine the relative impact of each factor because the coefficients are scaled to accommodate the units of each factor and the intercept is not the centre of the design space:

$$\begin{aligned} log(Cutting\ temperature) &= ln\left[(Cutting\ temperature - 80.89)/(137.59 - Cutting\ temperature)\right] \\ &= -384.01647 + 16.25295A - -3177.62431B \\ &+ 1234.89685C + 144.05102AB \\ &- 53.44259AC - 290.88545BC - 0.167914A^2 \\ &+ 127.74913B^2 - 15.53462C^2 + 6.90655ABC - 1.69823A^2B \\ &+ 0.5819A^2C + 9.08775AB^2 \end{aligned}$$

2.2.4 Equations for surface roughness models

Equation 8 presents the final equation in terms of the coded factors for the prediction of the surface roughness of the SiAlON cutting inserts. The usefulness of this equation is in identifying the relative impact of the factors, by comparing the factor coefficients.

Equation 9 presents the final equation in terms of the actual factors for the prediction of the surface roughness of the SiAlON cutting inserts, and this equation can be used to make predictions about the response for a given level of each factor, and it should not be used to determine the relative impact of each factor because the coefficients are scaled to accommodate the units of each factor, and the intercept is not the centre of the design space:

$$\sqrt{Surface\ Roughness} = 0.9387 + 0.1058B \quad (8)$$

$$\sqrt{Surface\ Roughness} = 0.59102 + 3.02299B \quad (9)$$

The final equation, in terms of the coded factors for the prediction of the surface roughness of the CBN cutting inserts, is illustrated in Eq. 10, and this equation can be used to identify the relative impact of the factors by comparing the factor coefficients:

$$1/(Surface\ roughness) = 0.8193 - 0.76B + 0.2899AB + 0.3613B^2 + 0.17ABC + 0.4173A^2B \quad (10)$$

The final equation, in terms of the coded factors for the prediction of the surface roughness of the carbide cutting inserts, is illustrated in Eq. 11, and this equation can be used to identify the relative impact of the factors by comparing the factor coefficients.

$$\sqrt{Surface\ roughness} = 0.8466 - 0.0125A + 0.0333B + 0.0233AC - 0.0214BC - 0.0151A^2 - 000211B^2 - 0.0206C^2 - 0.0205ABC \quad (11)$$

2.2.5 Equations for cutting vibration models

Equation 12 presents the final equation in terms of the coded factors for the prediction of surface roughness for the SiAlON cutting inserts and the relative impact of the factors, by comparing the factor coefficients that can be identified by using this equation:

$$\ln(Cutting\ vibration) = -12.62 + 0.1995AC \quad (12)$$

The final equation in terms of the coded factors for the prediction of the surface roughness of the CBN cutting inserts is presented in Eq. 13, and the relative impact of the factors, by comparing the factor coefficients, can be identified by using this equation:

$$(Cutting\ vibration)^3 = 4.9143707389431x10^{-15} + 7.7261217686243x10^{-15}B - 5.436543004625x10^{-15}AC + 2.9010584412253x10^{-15}B^2 - 7.7541863169993x10^{-15}A^2B \quad (13)$$

The final equation, in terms of the coded factors for the prediction of the cutting vibration for the carbide cutting inserts, is presented in Eq. 14. This equation is useful in identifying the relative impact of the factors by comparing the factor coefficients.

The final equation, in terms of the actual factors for the prediction of the cutting vibration for carbide cutting inserts, is presented in Eq. 15, and the predictions about the response for a given level of each factor can be achieved from this equation. However, it should not be used to determine the relative impact of each factor because the coefficients are scaled to accommodate the units of each factor, and the intercept is not the centre of the design space:

$$(Cutting\ vibration)^3 = 1.17\times10^{-16} - 6.531\times10^{-18}A + 2.356\times10^{-18}B + 9.17\times10^{-17}C \quad (14)$$

$$(Cutting\ vibration)^3 = -1.70026\times10^{-16} - 1.30623\times10^{-18}A + 4.71109\times10^{-16}B + 3.66809\times10^{-16}C \quad (15)$$

3 Results and discussion

The possible combinations of the process parameters from the numerical experimentation, involving the use of the RSM and the values of the measured responses for the cutting force, temperature, surface roughness and vibration for the SiAlON, CBN and carbide cutting inserts, are presented in Tables 12, 13 and 14, respectively. The measured responses for the cutting inserts are presented in Figs. 4, 5, 6 and 7, for the comparison of their results.

Figure 4 presents the comparative results for the cutting forces of the SiAlON, CBN and carbide cutting inserts. The results show that the highest cutting forces were produced when cutting with the CBN when compared to the SiAlON and carbide cutting inserts. These high cutting forces experienced with the CBN cutting inserts resulted from the use of low cutting speeds and high cutting depths. [20] also observed that high cutting forces resulted from the reduction of cutting speed when they studied cutting force during laser-assisted machining of near-alpha titanium alloy. The CBN cutting inserts showed the best results of 235.84 N when a cutting speed was set at 50 m/min, feed/tooth at 0.1 mm/tooth and a depth of cut at 0.5 mm. The lowest cutting force for the SiAlON cutting inserts was 285.645 N at a cutting speed of 100 m/min, feed/tooth of 0.15 mm/tooth and a cutting depth of 0.5 mm. The use of carbide cutting inserts experienced the highest cutting force when compared to the other two, namely the SiAlON and CBN inserts. The minimum cutting force results for carbide cutting inserts were 345.337 N at a cutting speed of 40 m/min, feed/tooth of 0.1 mm/tooth and a cutting depth of 0.5 mm. The reason for this was the lower cutting speed when compared to the other cutting inserts. From these results, the CBN exemplified as the best performing cutting inserts that produced the least cutting forces, among the three inserts.

The comparison for cutting temperature data is illustrated in Fig. 5. The CBN inserts also produced high results, in most cases when compared to the other two cutting insert materials. The lowest cutting temperature produced, by employing the CBN cutting inserts, was 89.6 °C when the cutting speed was 65 m/min, feed/tooth of 0.26 mm/tooth at a cutting depth of 0.75 mm. The cutting force produced from these results was at a high of 798.706 N. The minimum cutting temperature produced from the SiAlON cutting inserts was 89.6 °C, at a cutting speed of 70 m/min, feed/tooth of 0.15 mm/tooth and a depth of cut of 1 mm. A cutting force of 364.99 N was produced from these results. The minimum cutting temperature produced for the carbide cutting inserts was 80.9 °C at a cutting speed of 45 m/min, feed per tooth at 0.15 mm/tooth and

Table 12 RSM process parameters for the SiAlON cutting inserts

Run	Factors			Responses			
	Cutting speed	Feed per tooth	Depth of cut	Cutting force	Cutting temperature	Surface roughness	Cutting vibration
	m/min	mm/tooth	mm	N	°C	µm	Hz
1	70	0.15	1	364.99	89.6	1.12	2.51E−06
2	85	0.115	0.75	448.242	116	1.1	2.69E−06
3	85	0.115	0.75	441.621	114.8	1.05	2.6E−06
4	100	0.15	0.5	285.645	114.7	1.5	2.8E−06
5	100	0.15	1	660.278	110.1	1.2	2.96E−06
6	85	0.115	0.75	444.214	141.7	0.9	2.75E−06
7	70	0.08	1	570.557	141.7	0.79	2.75E−06
8	59.7731	0.115	0.75	564.331	117.2	0.83	2.73E−06
9	85	0.115	0.75	510.132	125.4	0.81	5.81E−06
10	85	0.173863	0.75	650.024	134.8	1.19	5.4E−06
11	100	0.08	1	592.163	108.7	1.17	5.48E−06
12	70	0.15	0.5	797.241	109.6	1.4	5E−06
13	85	0.0561373	0.75	730.957	120.3	0.86	2.79E−06
14	110.227	0.115	0.75	602.417	120.3	1.05	3E−06
15	100	0.08	0.5	704.956	138.2	0.5	2.96E−06
16	85	0.115	0.75	708.252	136.8	0.55	3.14E−06
17	85	0.115	1.17045	797.241	168.4	0.75	2.99E−06
18	85	0.115	0.329552	308.716	210.7	0.33	3.13E−06
19	70	0.08	0.5	422.974	111.6	0.51	3.48E−06
20	85	0.115	0.75	688.11	102.9	0.58	3.35E−06

a cutting depth of 1.17 mm. Lowest cutting temperature was observed when carbide cutting insert was used, and this proved the findings of [21] in their study that the biggest influential factor for tool wear and cutting temperature is cutting speed. The cutting force observed from these results was 580.078 N. SiAlON cutting inserts showed the best cutting temperature data.

Figure 6 illustrates the surface roughness comparison data. Poorer surface finish results were observed mostly, when the cutting operation was carried out by using the CBN cutting inserts, as shown in the graph as follows. The minimum results for the surface roughness, observed when cutting with the CBN cutting inserts, are 0.49 µm at a cutting speed of 50 m/min, feed per tooth of 0.1 mm/tooth and depth of cut at 1 mm. The cutting force and temperature for these results were measured to be 364.014 N and 107.9 °C, respectively. The best surface roughness result for SiAlON cutting inserts was 0.33 µm at a cutting speed of 85 m/min, feed per tooth of 0.115 mm/tooth and a cutting depth of 0.33 mm. The cutting force and cutting temperature observed are 308.716 N and 210.7 °C, respectively. The surface roughness produced during the utilization of carbide cutting inserts was at 0.44 µm at a cutting speed of 50 m/min, feed per tooth of 0.1 mm/tooth and cutting depth of 0.5 mm. The observed cutting force and cutting speed from these results of carbide cutting inserts are 588.135 N and 110.9 °C, respectively. The high cutting temperatures softened the cutting tool and that resulted in a shortened tool service life [22]. Therefore, from the observed results, it can be argued that the carbide cutting inserts produced the best and acceptable results when compared to the SiAlON and CBN cutting inserts.

The comparative results for the cutting vibration of SiAlON, CBN and carbide cutting inserts are illustrated in Fig. 7.

CBN cutting inserts The CBN cutting inserts experienced highest vibrations at high depths of cut and feed per tooth. The lowest cutting vibration observed during the cutting operation of the CBN cutting insert was recorded at a frequency of 2.51×10^{-6} Hz, at a cutting speed of 65 m/min, feed per tooth of 0.26 mm/tooth and a depth of cut at 0.3 mm. The responses measured from this resulted in a cutting vibration that was recorded at a cutting force of 799.072 N, cutting temperature of 163.1 °C and a surface roughness of 1.09 µm. A cutting vibration recorded at a frequency of 2.51×10^{-6} Hz was also observed to be the lowest while cutting with SiAlON cutting inserts. This resulted from a cutting speed of 70 m/min, a feed per tooth of 0.15 mm/tooth

Table 13 RSM process parameters for the CBN cutting inserts

Run	Factors			Responses			
	Cutting speed	Feed per tooth	Depth of cut	Cutting force	Cutting temperature	Surface roughness	Cutting vibration
	m/min	mm/tooth	mm	N	°C	µm	Hz
1	50	0.1	1	364.014	107.9	0.49	2.26E – 05
2	65	0.26	0.75	611.572	140.1	0.83	2.22E – 05
3	65	0.26	0.75	803.101	160.3	1.25	2.02E – 05
4	65	0.26	0.75	799.072	171.3	1.52	2.13E-05
5	65	0.26	0.75	800.903	151.1	0.97	2.23E – 05
6	80	0.1	1	800.537	140.1	0.85	2.08E – 05
7	65	0.26	1.17045	802.734	160.3	1.72	2.1E – 05
8	80	0.1	0.5	799.805	171.3	0.85	2.18E – 05
9	65	0.529087	0.75	808.96	151.1	1.96	2.97E – 05
10	50	0.42	1	802.002	207.6	2.02	2.44E – 05
11	80	0.42	0.5	799.805	188.8	1.49	2.54E – 05
12	50	0.1	0.5	235.84	175.5	0.55	6.55E – 06
13	65	0.1	0.75	322.918	140.2	0.54	6.14E – 06
14	80	0.42	1	804.565	171.6	0.68	2.73E – 06
15	50	0.42	0.5	800.537	118.3	1.2	2.91E – 06
16	65	0.26	0.75	798.706	89.6	1.21	2.76E – 06
17	90.2269	0.26	0.75	799.072	188.5	1.3	2.78E – 06
18	65	0.26	0.329552	799.072	163.1	1.09	2.51E – 06
19	39.7731	0.26	0.75	806.763	128	1.49	2.82E – 06
20	65	0.26	0.75	809.326	190.8	1.57	2.71E – 06

Table 14 RSM process parameters for the Carbide cutting tools

Run	Factors			Responses			
	Cutting speed	Feed per tooth	Depth of cut	Cutting force	Cutting temperature	Surface roughness	Cutting vibration
	m/min	mm/tooth	mm	N	°C	µm	Hz
1	45	0.15	0.75	799.435	90.3	0.75	2.54E – 06
2	40	0.2	0.5	799.072	98.8	0.72	2.77E – 06
3	36.591	0.15	0.75	596.924	110.9	0.69	3.03E – 06
4	53.409	0.15	0.75	734.619	110.9	0.63	3.11E – 06
5	50	0.1	0.5	588.135	110.9	0.44	3.15E-06
6	45	0.15	0.329552	384.155	126.7	0.67	3.11E – 06
7	45	0.15	0.75	465.82	126.7	0.74	2.72E – 06
8	45	0.15	1.17045	580.078	80.9	0.6	6.28E – 06
9	40	0.2	1	569.092	112.5	0.67	6.5E – 06
10	40	0.1	1	473.145	112.5	0.56	6.54E – 06
11	50	0.2	0.5	433.228	89.2	0.66	3.22E – 06
12	40	0.1	0.5	345.337	91.2	0.6	3.2E – 06
13	45	0.15	0.75	464.335	91.2	0.73	3.23E – 06
14	45	0.0659104	0.75	419.312	101.4	0.55	3.26E – 06
15	45	0.15	0.75	505.371	87.3	0.7	6.43E – 06
16	50	0.1	1	545.288	108.5	0.66	6.14E – 06
17	45	0.23409	0.75	585.938	137.5	0.72	6.23E – 06
18	50	0.2	1	639.038	119.9	0.63	6.03E – 06
19	45	0.15	0.75	476.074	108.4	0.75	6.16E – 06
20	45	0.15	0.75	529.907	87.2	0.63	3.23E – 06

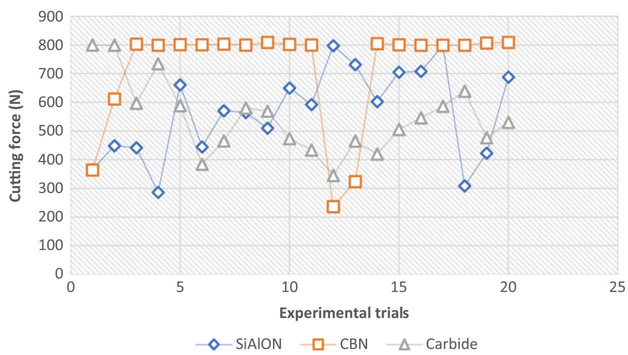

Fig. 4 Cutting force comparison results

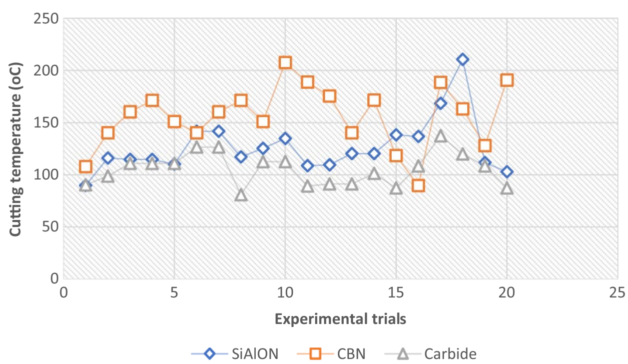

Fig. 5 Cutting temperature comparison results

and a cutting depth of 1 mm. The cutting force from these results was 364.99 N, a cutting temperature of 89.6 °C and a surface roughness of 1.12 µm. The minimum results for the cutting vibration of the carbide cutting tool were measured at a frequency of 2.54×10^{-6} Hz, and this was the highest value when compared to the other two inserts. From this measured cutting vibration of carbide cutting tool, the cutting speed was set at 45 m/min, feed per tooth at 0.15 mm/tooth and

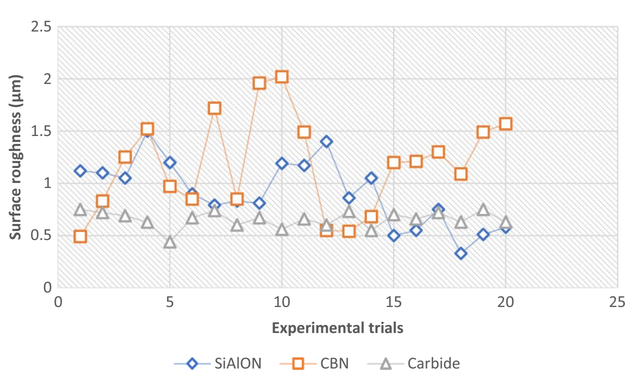

Fig. 6 Surface roughness comparison results

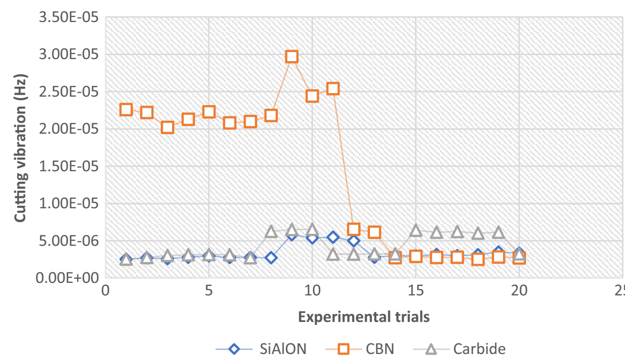

Fig. 7 Cutting vibration comparison results

depth of cut at 0.75 mm. The cutting force, cutting temperature and surface roughness responses were measured to be 799.435 N, 90.3 °C and 0.75 µm, respectively. Taking into consideration the cutting temperature and surface roughness, it can be argued that the carbide cutting inserts produced best vibrational results.

4 Conclusion

This report highlights the selection of the best performing cutting inserts, during Ti-6Al-4 V alloy machining. These inserts include SiAlON, CBN and carbide cutting inserts. The following conclusions are drawn from the study:

1. Feed rate is an essential factor that influences the surface roughness; hence, its increase resulted in a poorer surface finish and at its lowest, and the quality of the machined surface of the workpiece was improved. This was observed from all the cutting inserts compared.
2. Higher cutting forces were experienced during cutting operation with CBN cutting inserts, and these could have resulted from high feed per tooth and high depth of cuts as compared to SiAlON and carbide cutting inserts where cutting parameters employed were much lower.
3. Better results in the cutting force and surface roughness were observed when machining Ti-alloy with CBN cutting inserts. Carbide cutting inserts also performed well and were selected to be the best performing inserts of the three inserts employed in the machining of in Ti-6Al-4 V. This conclusion was arrived at, by considering their cost-effectiveness and the optimal temperature observed during the cutting operation. It was discussed in literature that the cutting temperature affects the material microstructure, which often leads to poor quality finish of the material or the premature tool failure.

Recommendations for future work

1. Comparison on this cutting performance using cooling methods
2. The tool-service life of the cutting inserts employed during the machining process
3. Optimisation of the cutting tool performance

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Declarations

Conflict of interest The authors declare no competing interests.

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