PORT SAID ENGINEERING RESEARCH JOURNAL
Faculty of Engineering - Port Said University
Volume 24 No. 2 September 2020 pp. 114-121
(Mechanical Production Engineering)

Relative Performance of Coated Ceramic and CBN Inserts in Hard Turning of Ti6Al4V Alloy

Al Shimaa Abdelnasser[1], Azza Barakat[2], Samar Elsanabary[3], Ahmed Nassef[4]

Received: 18 June 2020; Accepted: 5 July 2020

ABSTRACT

Characteristics of cutting insert are key factors for the reliability of machining of difficult-to-cut materials such as Ti6Al4V alloy. Therefore, in this paper a comparison between the performance of two different materials, ceramic insert coated by (Al_2O_3+TiNC) and CBN, when turning Ti6Al4V alloy in dry environment. Effect of process parameters, feed rate, cutting speed and depth of cut, and their interactions on measured cutting temperature were examined for both inserts. Taguchi method was utilized to design of experiments (L9) and the results were analyzed by analysis of variance (ANOVA). From the results, CBN insert showed a good behavior for heat dissipation during machining compared with coated ceramic insert with a reduction in cutting temperature by 28%. Moreover, it was found that cutting temperature increased by increase in cutting speed and depth of cut and decrease in feed rate when using the two types of insert. In addition, it was observed that cutting temperature was affected by varying process parameters when machining by CBN insert more than the case of coated ceramic tool. The significant parameter affected cutting temperature in the case of CBN was feed rate followed by cutting speed. While at coated ceramic insert, the most significant parameters effect on cutting temperature was cutting speed.

KEYWORDS: Ti6Al4V alloy, cutting temperature, coated ceramic insert, CBN insert, hard turning

1. INTRODUCTION

Titanium alloys have been widely used in aerospace industry, marine, automotive, biomedical and defense applications [1-2] hardness and strength at high temperatures without damaging and high wear resistance [3, 4]. This is due to their excellent mechanical and physical properties such as low density, maintaining However, machining of super alloys such as nickel alloys and titanium alloys is considered to be problematic and one of the most challenging issue that still needs addressing [5, 6]. Low thermal conductivity is one of the main reasons for low machinability of titanium alloys due to low effective dissipation of temperature generated during process and concentrate a large amount of cutting temperature in the cutting zone and chip [7]. This causes damage on cutting tool and negatively affects the quality of machined surface [8, 9]. Many studies have been carried out on optimizing machining conditions to prevent high temperature generated by machining titanium-based alloys in order to improve their machinability. Ren et al. [10], conducted turning tests of titanium-based alloy on measuring cutting temperature by varying process parameters. The results showed that cutting temperature increased by increasing cutting speed and decreased by increasing feed rate. Similar results were found by Balaji et al. [11] who investigated turning of titanium-based alloys by finite element analysis and experimental work. Different results about the effect of feed rate on cutting temperature was found by Li et al. [12] which reported that increasing feed rate increased cutting temperature, also, the study showed that higher depth of cut resulted in raising temperature. Li et al. [13] examined the effect of tool geometries on cutting temperature, it was found that increasing cutting edge radius resulted in low temperature. Balaji et al. [11], investigated turning of titanium-based alloys by finite element analysis and experimental work. The results showed that positive rake angle gave a better result with high speed machining as it results in low cutting force and cutting temperature. Devin et al. [14] stated that cutting temperature increased by increasing machining time. As the high temperature generated is the main problem during machining titanium-based alloys, selection of appropriate cutting tool is important factor for high reliability levels [15]. Tool materials used in machining titanium-based alloys must have a capability of retaining hardness at very high cutting temperatures to avoid failure of tool [3]. Besides, high compressive strength, high thermal conductivity, good

[1]*Lecturer assistant in Production Engg. Dept., Faculty of Engg., Port Said University, corresponding author, email: Alshymaa.gamal@eng.psu.edu.eg*

[2]*Professor of production engineering, Helwan University, Egypt, email: barakatazza5@hotmail.com*

[3]*Lecturer, Production Engg. Dept., Faculty of Engg., Port Said University. email: samar.abaas@eng.psu.edu.eg*

[4]*Professor of Production Engg., Faculty of Engg., Port Said University. email: nassef12@eng.psu.edu.eg*

DOI: 10.21608/pserj.2020.32842.1044

chipping resistance and low chemical affinity to prevent reactions during machining titanium [6]. Some studies aimed to comparable between different tool materials for higher machining performance of titanium-based alloys. Ren et al. [10] compared between the performance of PCD and PCBN inserts when machining titanium alloy. The results showed PCD tools showed better performance on tool wear and tool life more than PCBN tool. Priarone et al. [16], studied machinability of titanium-based alloy by different cutting tool materials namely; PCD, CBN, uncoated and coated carbide tool. It was found that PCD tool showed excellent results in tool life compared other tool materials. Khan et al. [17], investigated using untreated and cryogenically treated carbide tools by turning titanium alloy. Cryogenically treated tool showed a better result in term of tool wear more than another tool. You et al. [10], studied the machining performance of three type of insert in cutting performance on turning Ti6Al4V namely; uncoated and CVD coated carbide tool and cermet tool Carbide tool showed the best results in tool life more than the two other tools. Niknam et al. [18], compared with carbide and CBN insert with varying process parameters, it was found that higher cutting speed resulted in rapid tool wear by using carbide tool.

Besides optimizing the process parameters and tool properties to prevent high temperature generated by machining titanium alloys, some researchers tended to utilize other techniques such as hybrid machining [19] and cooling system [20]. Liu et al. [21], studied turning of Ti6Al4V alloys using cool air gun cooling system which showed lower values of cutting temperature compared with dry condition. Qin et al. [22], studied machinability of titanium alloy under dry machining and minimum quantity lubrication (MQL). The results showed that turning with MQL gave a better results of machining performance more than dry machining as the cutting force and temperature. Rahman et al. [23], investigated turning of Ti6Al4V with different cooling system namely; dry machining and using minimum quantity lubrication with different nanoparticles types with different concentration, it was found that dry machining gave higher values of cutting temperature more than the case used MQL as well as gave rapidly tool wear. Although the benefits of cooling system in reduction the temperature generated during machining titanium and tool wear [23], softening of target material by concentration of this high temperature at cutting zone found to be better to reduce strength and cutting force during machining and make the cutting process occurs easily [24-25].

The literature review showed many studies aimed at studying tool wear, surface roughness and cutting force by varying process parameters and tool properties. As the cutting temperature is the main problem when machining titanium, selected suitable tool with optimize cutting conditions are important in machining titanium. Therefore, in this study comparable between two inserts of different materials on cutting temperature generated by turning Ti6Al4V material with different cutting conditions in dry environment. The paper is organized as follows, firstly experimental setup and procedure is presented in section 2. Then results of the performance of coated ceramic insert is discussed followed by the results obtained by CBN insert in section 3. Finally, the main points of conclusions are presented in section 4.

2. EXPERIMENTAL WORK

Specimens of Ti6Al4V alloys were conducted under turning tests with 25 mm in diameter and 15 mm in length. All experiments were carried out for 30 mm cutting length. The measured hardness of material was (367 V_{30}).

The experimental tests were conducted by two different inserts. CBN and (AL_2O_3+TiCN) coated ceramic inserts. Both inserts have 0° rake angle, 55° cutting edge angle and 0.8 mm in nose radius. Tool holder (PDJNR 2020 K15) by Taegu Tec was used.

Turning tests were carried out on CNC lathe with 6000 maximum rotational speed of spindle and 5.5 KW spindle motor. The experiments were conducted on measuring cutting temperature under dry condition by varying process parameters. Taguchi method (L9) was used for design of experiments, nine trails were carried out for each insert type for three factors with three level. Variables cutting parameters was feed rate (0.1, 0.2, 0.3 mm/rev), cutting speed (50, 75, 100 m/min) and depth of cut (0.15, 0.2, 0.25). with recorded response as shown in Table 3.

Thermal camera (testo 890) was used to measure cutting temperature (resolution of 640 × 480 pixels, thermal sensitivity < 40 mK, the measuring range can be extended up to 1200°C). Fig. 1 shows the experimental test rig.

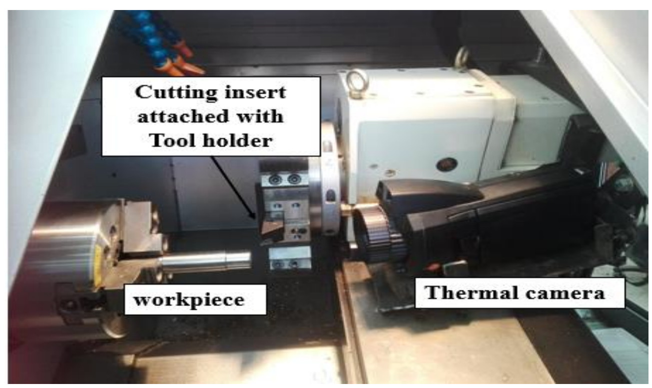

Figure 1: Experimental test rig

3. RESULTS AND DISCUSSION

Analysis of variance (ANOVA) and graphical analysis using MINITAB software were used for analyzed results. Table 1 presents all trails by Taguchi design (L9) and results for both cutting inserts corresponding to process parameters.

Table 1: Design of experiments according to Taguchi method

run	F (mm/rev)	V (m/min)	d (mm)	T (°C) by (coated insert)	T (°C) by (CBN insert)

1	0.1	50	0.15	360	300
2	0.1	75	0.2	390	320
3	0.1	100	0.25	645	350
4	0.15	50	0.2	353	285
5	0.15	75	0.25	431	300
6	0.15	100	0.15	380	300
7	0.2	50	0.25	327	210
8	0.2	75	0.15	352	221
9	0.2	100	0.2	372	250

Figure 2 shows an image taken by thermal camera during turning by coated ceramic and CBN inserts at feed rate (0.2 mm/rev), cutting speed (75 m/min) and depth of cut (0.15 mm). The images show the temperature distribution in the cutting region. It was observed that high cutting temperature concentrated in cutting zone and is carried by chip. That is due to low thermal conductivity of Ti6Al4V material [26] which prevents the effective dissipation of cutting temperature generated during process. By comparison between two inserts of cutting temperature generated at the same cutting conditions, it was found that temperature generated by coated ceramic insert (T= 352 °C) was higher than that obtained by CBN one (T= 221 °C).

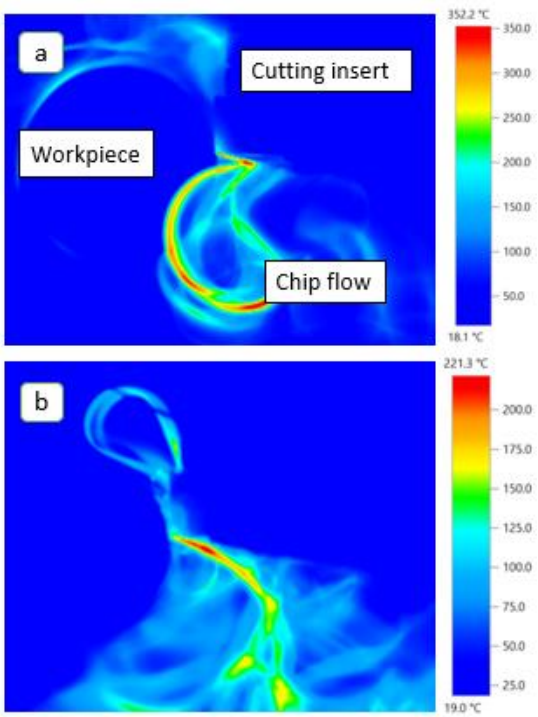

Figure 2: Temperature distribution by thermal camera during process at f=0.2mm/rev, v=75m/min and d=0.15mm a) by coated ceramic insert b) by CBN insert

Figure 3 shows all results of measured cutting temperature when machining by coated ceramic insert and CBN insert. It was found that CBN insert resulted in lower cutting temperature than temperature generated by coated ceramic insert for all trails by 28%. The maximum temperature was found (T= 645°C) by coated ceramic insert and (T= 350°C) by CBN insert at cutting conditions (feed rate =0.1 mm/rev, cutting speed= 100 m/min and depth of cut=0.25 mm). the minimum temperature was found (T= 327°C) by coated ceramic insert and (T= 210°C) at cutting conditions (feed rate =0.2 mm/rev, cutting speed= 50 m/min and depth of cut=0.25 mm).

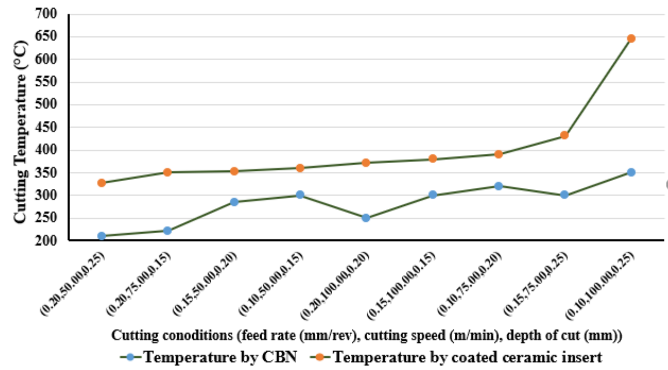

Figure ۳: Results of measured cutting temperature for all trails by CBN and coated ceramic inserts

3.1 Results of Coated Ceramic Insert

The main effect of process parameters on measured cutting temperature. was discussed firstly followed by the effect of interaction of process parameters

Figure 4 presents the effect of feed rate on cutting temperature when turning by coated ceramic insert. it was found inverse relationship between feed rate and temperature. cutting temperature increased obviously at low feed rates. That is due to increased the time which tool tip and target material in contact by low feed rate result in increasing temperature on the tool tip. Moreover, at higher feed rates the chip thickness increases result in take away a large amount of heat generated by chip. These results agree with [10].

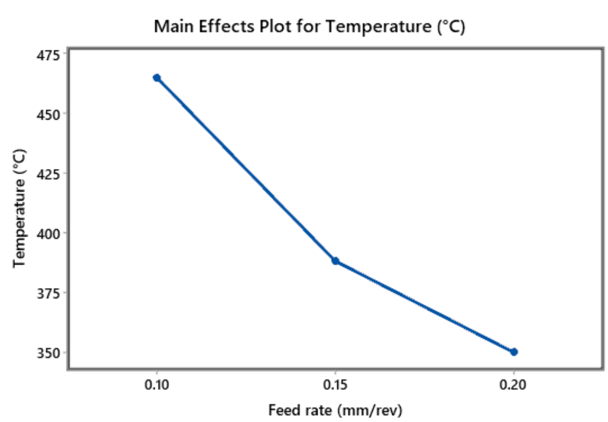

Figure 4: Main effect of feed rate on cutting temperature when turning Ti6Al4V by coated ceramic insert

Figure 5 shows the effect of cutting speed on cutting temperature when turning by coated ceramic insert. It was observed that cutting temperature increased by increasing cutting speed. It is due to high metal removal rate which results in increasing the rate of energy required to cut, thus cutting temperature increases [27].

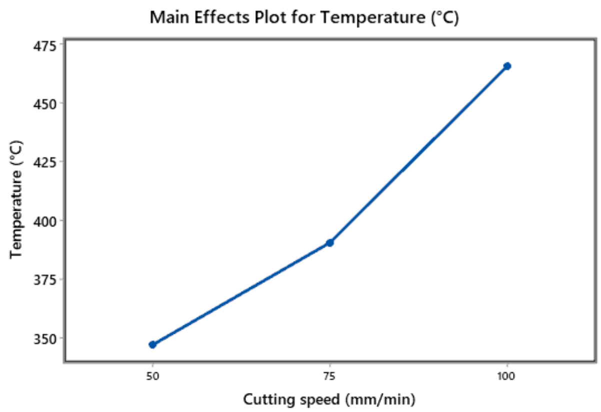

Figure 5: Main effect of cutting speed on cutting temperature when turning Ti6Al4V by coated ceramic insert

Figure 6 illustrates the effect of depth of cut on cutting temperature when turning by coated ceramic insert. It was found that cutting temperature slightly increased with increasing depth of cut from 0.15 mm to 0.2 mm, then a higher raising in cutting temperature was found at depth of cut 0.25 mm. That is due to high metal removal rate by higher depth of cut which increases temperature. Also, increasing cutting force by high depth of cut results in increasing friction and generation high cutting temperature [28].

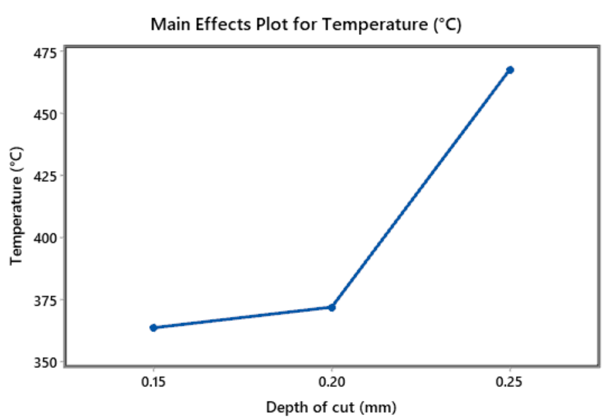

Figure 6: Main effect of depth of cut on cutting temperature when turning Ti6Al4V by coated ceramic insert

Owing to the effect of interactions between process parameters, Fig. 7 shows surface plot of temperature in relation to cutting speed and depth of cut in the case of coated ceramic insert. It was found that the higher effect of depth of cut on cutting temperature was occurred at cutting speed of 100 m/min and this effect became insignificant toward reduction of cutting speed. Also, a significant impact of cutting speed on cutting temperature was found at the highest value of depth of cut (0.25 mm) while a slight effect of cutting speed observed at lower depths of cut. Therefore, the combined of higher depth of cut and cutting speed resulted in high cutting temperature.

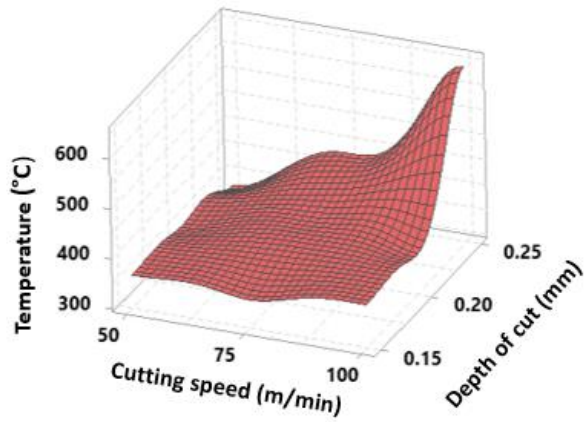

Figure ٧: Surface plot of temperature in relation to cutting speed and depth of cut when using coated ceramic insert

Similarly, Fig. 8 shows the surface plot of temperature in relation of depth of cut and feed rate in the case of coated ceramic insert. It was found that highest variation on temperature by feed rate was occurred at depth of cut 0.25 mm while the highest variation on temperature by depth of cut was found at feed rate of 0.1 mm/rev. it was observed obvious reduction on cutting temperature at depth of cut 0.25 mm and feed rate 0.2 mm and the maximum cutting temperature was found by combination of low feed rate and high depth of cut.

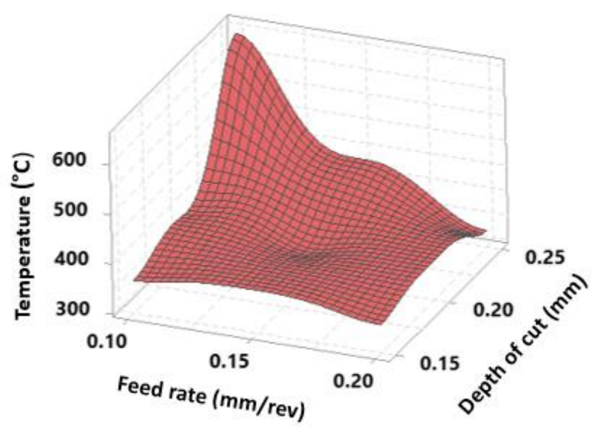

Figure 8: Surface plot of temperature in relation to feed rate and depth of cut when using coated ceramic insert

Figure 9 shows the surface plot of cutting temperature in relation of feed rate and cutting speed at the case of coated ceramic insert. The significant impact of cutting speed on cutting temperature was found at low feed rate of 0.1 mm/rev and the effect of cutting speed decrease gradually by increasing feed rate. Also, it was observed obvious increase on cutting temperature by combination of cutting speed of 100 m/min and feed rate of 0.1 mm/rev while slight variation on temperature was found when feed rate changed from 0.15 to 0.2 mm/rev at cutting speed 100 m/min.

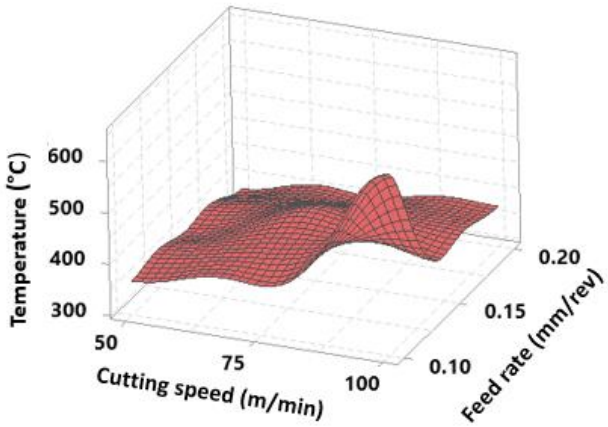

Figure 9: Surface plot of temperature in relation to cutting speed and feed rate when using coated ceramic insert

3.2. Results by CBN Insert

The main effect of process parameters on measured cutting temperature. was discussed firstly followed by the effect of interaction of process parameters.

Figure ١0 shows the main effect of feed rate on cutting temperature using CBN insert. Same trend of relationship between feed rate and cutting temperature by coated ceramic insert was found when using CBN insert. Cutting temperature decreased with increasing feed rate.

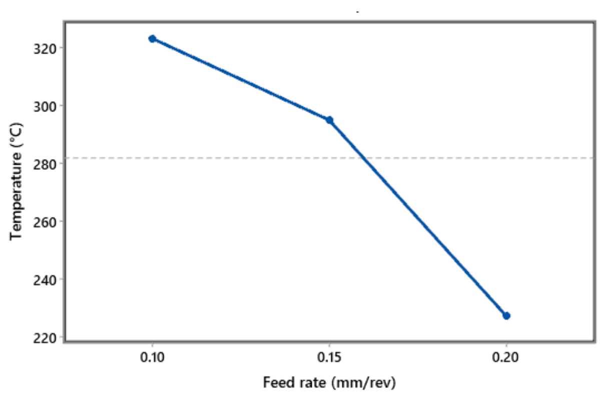

Figure ١0: Main effect of feed rate on cutting temperature when turning Ti6Al4V by CBN insert

Figure ١1 shows the main effect of cutting speed on cutting temperature when using CBN insert. It was found that cutting temperature increased with increasing cutting speed. that is agreement with the results obtained when using coated ceramic insert.

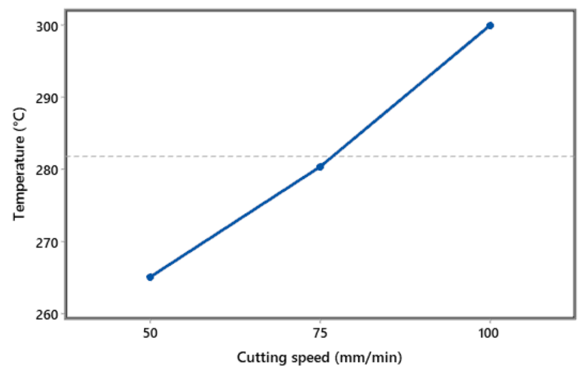

Figure ١1: Main effect of cutting speed on cutting temperature when turning Ti6Al4V by CBN insert

Figure ١2 shows the main effect of depth of cut on measured cutting temperature when using CBN insert. It was found high increase in cutting temperature when depth of cut changed from 0.15 mm to 0.2 mmm, followed by a slight increase in cutting temperature toward maximum value of depth of cut.

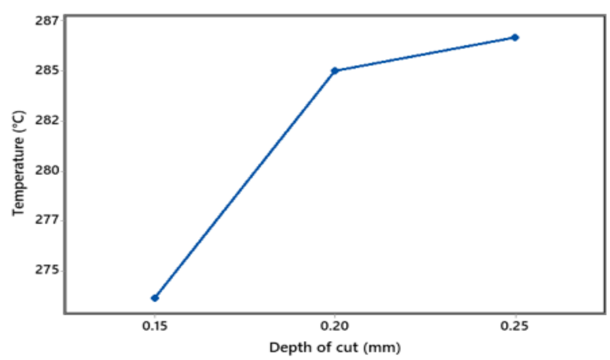

Figure ١2: Main effect of depth of cut on cutting temperature when turning Ti6Al4V by CBN insert

Regards to the effect interaction between process parameters on cutting temperature using CBN insert, Fig. 13 shows the surface plot of cutting temperature in relation of cutting speed and depth of cut. it was observed that the proportional relationship between cutting speed and cutting temperature was achieved at the depth of cut of 0.25 mm while different trends of cutting speed were found at depth of cuts 0.2 and 0.15 mm. it was observed that the combination between low cutting speed (50 m/min) and lower values of cut depths targeted high cutting temperature. At low cutting speed (50 m/min), it was found increasing in cutting temperature also, that is may be occurred due to increase resistance forces and stresses at the tip of the cutting tool which increase coefficient of friction tool-chip contact length and friction [29], as the result, the tool-chip interface temperature increases. That is occurred at smaller depth of cut due to ploughed and rubbing action occurred at low depth of cut as the material gets ploughed rather than form chips lead to increase in cutting temperature.

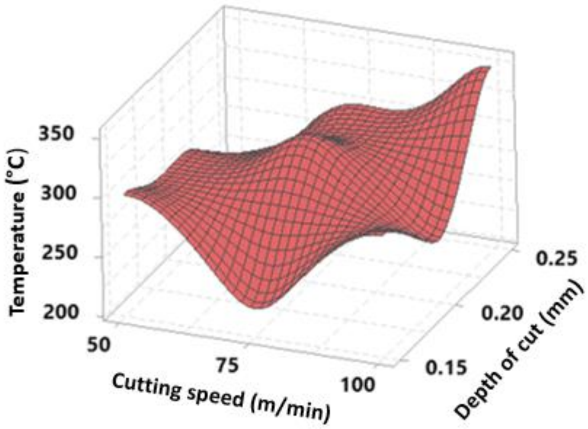

Figure 13: Surface plot of temperature in relation to cutting speed and depth of cut when using CBN insert

Figure 14 shows the surface plot of cutting temperature in relation of depth of cut and feed rate by CBN insert. It was found obvious inverse relationship between feed rate and cutting temperature for all cut depths. The proportional relationship between depth of cut and cutting temperature was found at lower feed rates while no significant effect of depth of cut was found at higher values of feed rate. From graphs, it was observed that the maximum cutting temperature was tacked place at combination of high depth of cut and low feed rate.

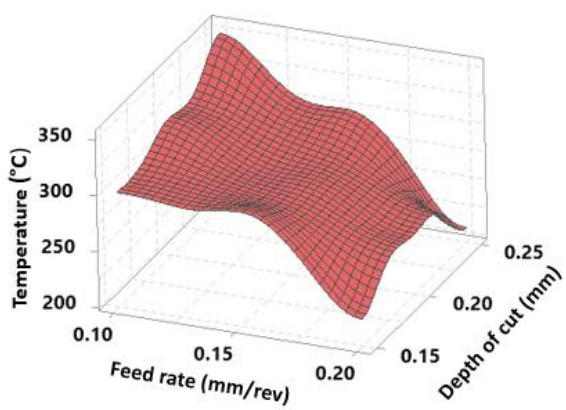

Figure 14: Surface plot of temperature in relation to feed rate and depth of cut when using CBN insert

Figure 15 shows the surface plot of temperature in relation of feed rate and cutting speed when machining by CBN insert. It was observed that cutting temperature was decreased by increasing feed rate for all values of cutting speeds. owing to the effect of cutting speed on temperature, it was found fluctuant trends of cutting speed at higher values of feed rate while a proportional trend between cutting speed and temperature was found at low feed rate. The maximum cutting temperature was found at combination of low feed rate and high cutting speed while minimum values of cutting temperature was found at combination of high feed rate and low cutting speed.

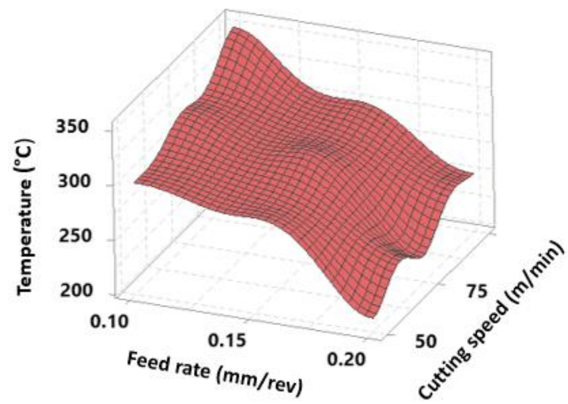

Figure 15: Surface plot of temperature in relation to cutting speed and feed rate when using CBN insert

Table (2 and 3) present ANOVA results to find the most significant parameters on cutting temperature by two inset types. It was observed that the three process parameters have close results in p-value, the most significant parameter affected cutting temperature was cutting speed (p-value= 0.342) followed by feed rate (p-value= 0.353) and depth of cut (p-value= 0.359) in the case of coated ceramic insert. While the results found by CBN insert showed that feed rate has the most significant effect on cutting temperature (p-value= 0.008) followed by cutting speed (p-value= 0.63) and depth of cut (p-value= 0.292).

Table 2. Analysis of variance results by coated ceramic insert

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Feed rate (mm/rev)	2	20700	10350	1.83	0.353
Cutting speed (mm/min)	2	21743	10871	1.93	0.342
Depth of cut (mm)	2	20171	10085	1.79	0.359
Error	2	11287	5643		
Total	8	73901			

Table 3. Analysis of variance results by CBN insert

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Feed rate (mm/rev)	2	14706.9	7353.44	119.03	0.008
Cutting speed (mm/min)	2	1846.9	923.44	14.95	0.063
Depth of cut (mm)	2	300.2	150.11	2.43	0.292
Error	2	123.6	61.78		
Total	8	16977.6			

By comparison between two types of insert in term of generated cutting temperature and the effect of process parameters and their interaction on it, it was observed that machining by coated ceramic insert resulted in higher cutting temperature compared that CBN one, see Fig. 3. Nevertheless, the temperature generated when machining by CBN has higher affected by process parameters. Moreover, it was found that the most significant parameter affected temperature by coated ceramic insert was cutting speed especially at low feed, that resulted in a high heat generated. Therefore, it is not recommended to machining with coated ceramic insert under high cutting speed especially at low feed rates to avoid the negative effect of generation high temperature during cutting. CBN insert showed low cutting temperature at higher feed rates for all values of cutting speed with an acceptable increase in temperature with combination between high cutting speed and low feed rate. CBN showed a good behavior to dissipation temperature during machining and it is suitable for cutting with high cutting speed more than coated ceramic insert.

4. CONCLUSION

Turning operations were conducted for the comparison between two different insert materials in term of generated cutting temperature. Taguchi method was used in experimental design and ANOVA analysis was used to examine the effect of process parameters on the results. The variable process parameters were feed rate, cutting speed and depth of cut. The main conclusions are as follows

1. CBN insert showed a good behavior for dissipation temperature during machining compared to coated ceramic insert with a reduction of temperature by 28%
2. Cutting temperature increased with the increase in cutting speed and depth of cut and decrease in feed rate when using the two types of insert.
3. It was observed that cutting temperature was affected by varying process parameters when machining by CBN insert more than the case of coated ceramic tool.
4. The most significant parameter affected cutting temperature when machining by coated ceramic insert was cutting speed and combination of low feed rate and high cutting speed generated high cutting temperature. Therefore, CBN is more suitable to machine Ti6Al4V under high cutting speed than coated ceramic one.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Al Shimaa Abdelnasser: Methodology, Investigation, Formal analysis, Writing – Original Draft **Azza Barakat**: Conceptualization, Methodology, Writing – review editing, Supervision **Samar Elsanabary:** Methodology, Writing – review & editing, Supervision, **Ahmed Nassef** : Writing – review & editing, Supervision

DECLARATION OF COMPETING INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

ACKNOWLEDGMENTS

The authors would like to thank Prof. Assistant Ahmed Elkaseer from Faculty of Engineering, Port Said University for the scientific support he provided and the knowledge he shares with us to pursue this research.

REFERENCES

[1] G. Hou, A. Li, X. Song, H. Sun, and J. Zhao, “Effect of cutting parameters on surface quality in multi-step turning of Ti-6Al-4V titanium alloy”, The International Journal of Advanced Manufacturing Technology (98), 2018, pp. 1355–1365

[2] S. A. Khan, M. Z. Afzal, M. Q. Saleem, K. H. Hashmi and Z. Ghulam, “Performance evaluation of novel chamfered inserts in high-feed turning of Ti-6Al-4V alloy”, The International Journal of Advanced Manufacturing Technology (97), 2018, pp. 2319–2329

[3] J. P. Davim, “Machining of Titanium Alloys”, Springer, 2014.

[4] J. E. Abu Qudeini, A. I. Mourad, A. Ziout, M. H. Abidi and A. Elkasser. “Electric discharge machining of titanium and its alloys: review”, The International Journal of Advanced Manufacturing Technology (96), 2018, pp. 1319:1339

[5] I. Cascón, J. A. Sarasua and A. Elkaseer, “Tailored Chip Breaker Development for Polycrystalline Diamond Inserts: FEM-based Design and Validation”, Appled Scencei.(9) 4117, 2019.

[6] H. A. Kishawy and S. A. Hosseini, “Machining Difficult-to-Cut Materials”, Springer, 2019.

[7] S. H. You, J. H. Lee and S. H. Oh, “A Study on Cutting Characteristics in Turning Operations of Titanium Alloy used in Automobile”, International Journal of Precision Engineering and Manufacturing (20), 2019, pp. 209–216

[8] J. Sun, S. Huang, T. Wang and W. Chen, “Research on surface integrity of turning titanium alloy TB6”, Procedia CIRP (71), 2018, pp. 484-489.

[9] A.M.A. Elkaseer, S.S. Dimov, K.B. Popov and R. Minev, “Tool Wear in Micro-Endmilling: Material Microstructure Effects, Modelling and Experimental Validation”, Journal of Micro and Nano-Manufacturing 2(4): 044502, 2015.

[10] Z. Ren, Shengguan, Y. Zhang, F. Sun, X. Li and C. Yang, “Machining performance of PCD and PCBN tools in dry turning titanium alloy Ti-6Al-0.6Cr-0.4Fe-0.4Si-0.01B”, The International Journal of Advanced Manufacturing Technology (102) 2019, pp. 2649–2661

[11] J. H. Balaji, V. Krisharaj and S. Yogeswaraj, “Investigation on High Speed Turning of Titanum Alloys”, Procedia Engineering (46), 2013, pp. 926-935

[12] T. Li, T Shi, Z. Tanga, G. Liao, J. Han and J. Duan, “Temperature monitoring of the tool-chip interface for PCBN tools using built-in thin-film thermocouples in turning of titanium alloy”, Journal of Materials Processing Tech (275) 116376, 2020.

[13] R. Li and A. J. Shih, “Finite element modeling of 3D turning of titanium”, International Journal of Advanced Manufacturing Technology (29), 2006, pp. 253–261

[14] L. N. Devin, N. E. Stakhniv, A. S. Antoniuk, S. V. Rychev and V. N. Nechiporenko, “The Influence of Cutting Speed on Cutting Temperatures and Forces in Fine Turning of VT1_0 Titanium Alloy by a PCD Tool” Journal of Superhard Materials 4 (2), 2019, pp. 119–125

[15] B. Wang and Z. Liu, "Influences of tool structure, tool material and tool wear on machined surface integrity during turning and milling of titanium and nickel alloys: a review", The International Journal of Advanced Manufacturing Technology (98), 2018, pp. 1925–1975
[16] P. C. Priarone, F. Klocke, M. G. Faga, D. Lung and L. Settineri, "Tool life and surface integrity when turning titanium aluminides with PCD tools under conventional wet cutting and cryogenic cooling", International Journal of Advanced Manufacturing Technology (85), 2016, pp. 807–816
[17] A. Khan and K. Maity, "Comparative study of some machinability aspects in turning of pure titanium with untreated and cryogenically treated carbide inserts", Journal of Manufacturing Processes (28), 2017, pp. 272–284
[18] S. A. Niknam, S. Kamalizadeh, A. Asgari and M. Balazinski, "Turning titanium metal matrix composites (Ti-MMCs) with carbide and CBN inserts", The International Journal of Advanced Manufacturing Technology (97), 2018, pp. 253–265
[19] R. Muhammad, A. Roy and V. V. Silberschmidt, "Finite Element Modelling of Conventional and Hybrid Oblique Turning Processes of Titanium Alloy", Procedia CIRP (8), 2013, pp. 510–515
[20] E. Tascioglu, A. Gharibi and Y. Kaynak, "High speed machining of near-beta titanium Ti-5553 alloy under various cooling and lubrication conditions", The International Journal of Advanced Manufacturing Technology (102), 2019, pp 4257–4271
[21] N. Liu, K. Chiang and C. Hung, "Modeling and analyzing the effects of air-cooled turning on the machinability of Ti–6Al–4V titanium alloy using the cold air gun coolant system", International Journal of Advanced Manufacturing Technology (67), 2013, pp. 1053–1066
[22] S. Qin, Z. Li, G. Guo, Q. An, M. Chen and W. Ming, "Analysis of Minimum Quantity Lubrication (MQL) for Different Coating Tools during Turning of TC11 Titanium Alloy", Materials (9) 804, 2016, pp. 1-13
[23] S. S. Rahman, M. Z. Ibne Ashraf, A. N. Amin, M.S. Bashar, M. F. K. Ashik and M. Kamruzzaman, "Tuning nanofluids for improved lubrication performance in turning biomedical grade titanium alloy", Journal of Cleaner Production (206), 2019, pp. 180-196
[24] S. Sun, M. Brandt and M. S. Dargusch, "Characteristics of cutting forces and chip formation in machining of titanium alloys", International Journal of Machine Tools and Manufacture (49), 2009, pp 561–568
[25] F. Xiuli, L. Wenxing, P. Yongzhi and L. Wentao, "Morphology evolution and micro-mechanism of chip formation during high-speed machining", The International Journal of Advanced Manufacturing Technology (98), 2018, pp 165–175
[26] Q.L. An, Y. C. Fu and J. H. Xu, "Experimental study on turning of TC9 titanium alloy with cold water mist jet cooling", International Journal of Machine Tools and Manufacture (51), 2011, pp. 549–555
[27] D. A. Stephenson and J. S. Agapiou, "Metal Cutting Theory and Practice", Amazon, 2016.
[28] S. L. M. R. Filho, R. B. D. Pereira, C. H. L. and L. C. Brandão, "Investigation and modelling of the cutting forces in turning process of the Ti-6Al-4V and Ti-6Al-7Nb titanium alloys", The International Journal of Advanced Manufacturing Technology (101), 2019, pp. 2191–2203
[29] A. Khan and K. Maity, "Comparative study of some machinability aspects in turning of pure titanium with untreated and cryogenically treated carbide inserts", Journal of Manufacturing Processes (28), 2017, pp. 272–284