INFLUENCE OF TOOL WEAR ON THE CUTTING FORCES IN HIGH SPEED GREEN MILLING OF TITANIUM ALLOYS

[1]HABIBALLAH SAFARI, [2]SAFIAN SHARIF

[1]Mechanical Engineering Department Esfarayen University of Technology Esfarayen 9661998195, Iran
[2]Mechanical Engineering Department UniversitiTeknologi Malaysia, UTM Skudai, 81310, Johor
E-mail: [1]safari@esfarayen.ac.ir, [2]safian@fkm.utm.my

Abstract - The possessions of titanium and its alloy are expressively suitable for extreme working conditions in aerospace industries. Owing to the high affinity of tool materials for titanium, combined with high-strain hardening and low-elasticity modulus deteriorate the machinability of titanium alloys. High-speed machining (HSM) of titanium alloys is not efficient because of extremely high thermal loads developed on the tool material. However, owing to the responsibilities with regard to the social environment and workers' health, the application of conventional cutting fluids in metal cutting requires strict regulation for the disposal of the used fluids. Therefore conducting dry machining is essential for promoting value-added sustainable and green manufacturing. An experimental investigation on the effects of machining parameters on the various machinability aspects of Ti-6Al-4V ELI was conducted, during HSM, using coated and uncoated carbide tools. The study involved the use of various machining parameters, such as cutting speed and feed rate. Machining responses that were evaluated include cutting force during the machining operations. Results show that cutting speed and feed rate significantly affected the cutting force. Meanwhile, uncoated tools outperform the TiAlN+TiN coated tools in all investigated cutting conditions. Results also show that increasing the cutting speed decreases the resultant cutting force during HSM process. Uncoated tools exhibit less cutting force when HSM Ti-6Al-4V ELI as compared to coated tools.

Keywords - Cutting Force; Green Milling; High Speed; Titanium Alloy.

I. INTRODUCTION

High speed machining (HSM) is considered as one of the advanced machining process which leads to higher removal rates, lower cutting force and lower energy consumption[1, 2]. Its advantages include higher efficiency, good surface finish of workpieces and at the same time reduce machining time and cost. HSM is a relative term which varies from one material to another [3]. However, for a specified material it is defined as the speed that able to developed shear localization completely in the primary shear zone. HSM is different from conventional cutting because of high levels of cutting speed involved. Most of the materials show a substantial alteration in cutting machinery. Thermal softening makes softer the deforming material and causing to decrease the cutting forces. Also chip morphology in HSM is significantly different from that in conventional machining [4]. The HSM technology has become more prevalent in recent years in many industries because of development of tougher, more refractory tool materials and of high-speed machining spindles [5]. HSM is an option to eliminate cutting fluid by switching to dry machining. Milling operation is considered as a critical process because it can remove the unwanted part of materials efficiently and create almost all kinds of contour surfaces smoothly. However, milling is considered a very complicated machining process which is a discontinuous cutting process with varying chip load, forces and heat generation. Additionally, the tool geometry in milling is also complex. The combination of titanium alloys and milling process leads to high temperature and high cutting pressure. [6]. The difficulty in milling titanium alloys makes the selection of cutting tool material very critical. Tungsten carbide is suggested to be the most appropriate cutting tool material in machining titanium alloys [6, 7]. The combination of high hardness tungsten carbide grains and the high toughness cobalt binder has proven its superiority in titanium machining process.

The material's property is one of the important key factors for improving aircraft engines. The extreme working environment of aerospace engines requires material with good physical properties and wears resistance especially at elevated temperature. In addition, the density and strength of material are significant in manufacture light and small engines. Among all the materials, titanium alloys were the suitable material selected for aerospace industries as well as in other fields such as automotive, offshore, petroleum, sports, chemical and medical purposes. This has attracted many researchers and industrialists to conduct extensive researches related to titanium which also include machining [8]. A lot of effort has been made to improve the machinability of Ti-6Al-4V with using the widespread coolant, which are unreliable with the development of green manufacturing process [9]. However used of cutting fluids raised the issues of ecological, health problems and environmental pollution [10]. Cutting fluids chemically break down due to high cutting temperature in the cutting zone. This can expose the operator to biological hazard due to bacterial growth and breathing of toxins. Furthermore, in terms of economy, additional system is required in order to pump, filter, recycle and storage. At the same time

during the final disposal, water and soil will be contaminated.
Green manufacturing is the theme of manufacturing industry in the 21st century. In order to realize green manufacturing or green machining, it is critical to decrease the usage of cutting fluids in machining as much as possible [11].To realize the implementation of green machining, a technique known as MQL was introduced by previous researchers[12, 13] to overcome the issues of environmental impact and costs. There is a huge difference of lubricant flow rate between MQL and conventional lubrication which are 30 ml/h and 300 000 ml/h respectively.

Practically cutting forces in machining operations can be experimentally measured. The effects of the machining conditions including cutting speed, feed rate and depth of cut are related to measured force components [14, 15]. With larger cutting forces more energy is required for material to be cut causing the tool to experience higher stress during the machining process. Moreover, large cutting forces might result in chatter, tool deflection, and other instability of the cutting system. All these factors affect the tool performance, cutting efficiency, and product quality. Therefore, it is very essential for machinist's researchers to estimate the cutting forces in order to control the machining process and analyse the tool performances. The cutting forces are an important parameter for tool-condition monitoring [16]. Forces can be used as a reference to predict other process output parameters, including tool wear, surface roughness and tool life that will enhance the machining accuracy and efficiency, whereby improved machining can be realized and tool life can be extended.

Previous studies on cutting forces of milling titanium alloys showed that cutting tool as well as cutting conditions such as cutting speed, feed rate, depth of cut, and tool geometry significantly influences the cutting force of machined parts [17-19]. However, limited results have been reported cutting forces of titanium alloys during HSM. In this study, the effect of different HSM conditions on cutting force of Ti-6Al-4V ELI alloy using PVD coated and uncoated carbide tools were investigated. Cutting forces during the machining process under dry condition were analyzed.

II. DETAILS EXPERIMENTAL

2.1. Materials and Procedures

High speed milling process was conducted under dry condition. Different cutting speeds of 200, 250, and 300 m/min, feed rates of 0.03 and 0.06 mm/tooth together with axial depth of cut 5.0 mm, and radial depth of cut 1.5 mm were employed as the cutting parameters. The milling experiments were carried out on a MAHO DMC 835 V CNC milling machine with the maximum spindle speed of 18000 rpm and feed rate ranges up to 20000 mm/ min. as well as high rapid traverse speeds of 30000 mm/ min.

A Kistler type 9123C four-component rotary dynamometer, amplifier, data acquisition card and a computer were used to measure the cutting forces (Fx, Fy, Fz) during the HSM trials. The rotary dynamometer placed on the Spindle and held end mill bit to measure forces in three directions and torque during machining process. Figure 1 shows the HSM experimental setup. Cutting test was performed on Ti-6Al-4V ELI workpiece under down milling mode using a single carbide cutter at different cutting parameters.

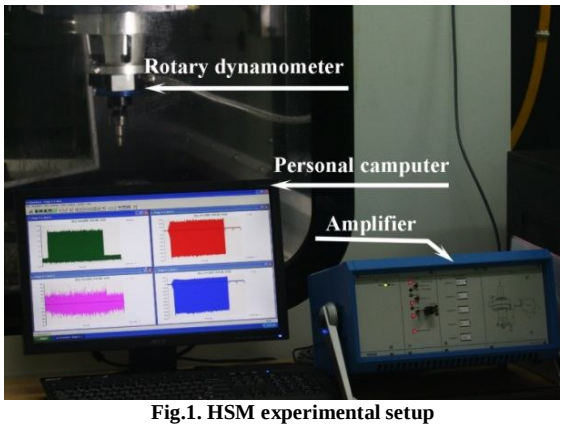


Fig.1. HSM experimental setup

Two type of coated and uncoated rhombus cemented carbide insert from SECO with designation XOMX090308TR-ME06 were chosen for milling Ti-6Al-4V ELI. The uncoated type grade is H25 and the coated type grade is F40M which is PVD coated with (TiAlN+TiN). Both insert has the same dimension and geometry as follow: cutting edge length of 9.9 mm, width of 6.35 mm, thickness of 3.65 mm, 0.8 mm corner radius, a 24° rake angle, and a 90° major cutting edge angle. The cemented carbide insert was rigidly mounted on a tool holder type R217.69-1612.3-09-1AN with one effective insert installation capacity, the Shank diameter of Ø16mm and the cutter diameter of Ø12mm.

Workpiece of titanium Ti-6Al-4V ELI alloy with dimensions 100 mm × 100 mm × 450 mm, was used for the experimental trials. Table 1 show the composition and mechanical properties of the investigated material which was received as annealed forging block.

Table 1 Chemical compositions and mechanical properties of Ti-6Al-4V ELI

Chemical compositions (%wt)								Mechanical properties		
Ti	Al	V	Fe	C	N	H	O	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
Bal.	5.85	4.1	0.10	0.05	0.02	0.001	0.08	905	815	10

III. RESULTS AND DISCUSSION

3.1. Results of Fresh Tools Cutting Forces at Various Cutting Conditions

Cutting forces evidence is essential to distinguish the mechanical output of a machining process. In HSM of Ti-6Al-4V ELI alloys, extremely high compressive stresses act upon the tool tip, which results in remarkable tool wear and high cutting forces.The variation of resultant cutting forces as a function of cutting speed during, feed rate HSM is explained as followed.

3.2Effect of the Cutting Speed on the Cutting Forces

The effect of the cutting speed on the resultant cutting forces in HSM of Ti-6A1-4V ELI under different feed rates, using different types of insert is shown in Fig.2.

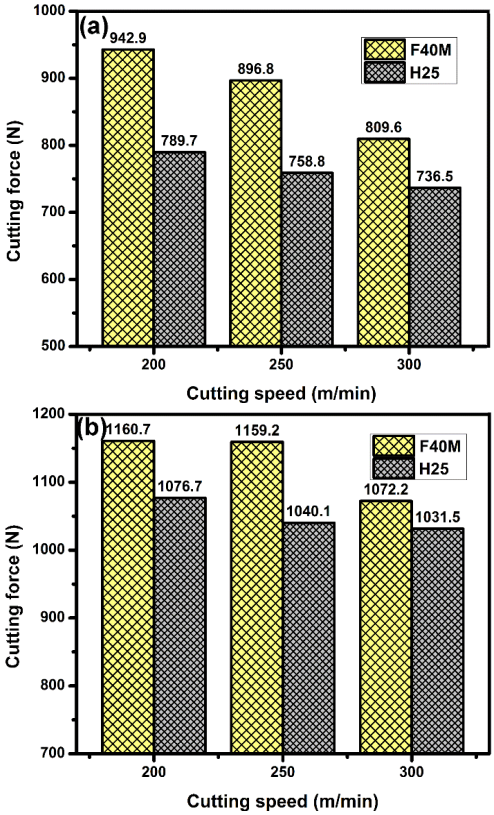


Fig.2. Effect of the cutting speed on the resultant cutting forces in HSM of Ti-6A1-4V ELI alloy for different feed rates, combined with different insert tools under dry cutting condition: (a) f=0.03 mm/tooth (b) f=0.06 mm/tooth.

As seen from graph (a–b), the resultant cutting force decreased as the cutting speed increased at varying feed rates, for both coated and uncoated carbide tools. For the effect of the cutting speed, the lowest resultant cutting force of 809.6 N was recorded as at 300 m/min, while the highest cutting force was 942.9 N at 200 m/min, when using coated tool under dry environment at feed rate of 0.03 mm/tooth.

Many researchers investigated the effect of a high cutting speed on the cutting forces. Their results showed that the cutting force generated at higher cutting speeds are lower in magnitude than those generated at the lower cutting speed [20, 21]. This can be attributed to the increased in cutting temperature which decreases the required force for plastic deformation, and reduces the rubbing acting of the chip-tool contact area. This result reveals a relationship between cutting speed and cutting force, which is in agreement with the theory proposed by Oxley [22].

3.3Effect of Feed Rate on Cutting Forces

Fig. 3 shows the effect of the feed rate on cutting forces in HSM of Ti-6A1-4V ELI, at cutting speed of 200 m/min and under dry conditions. As seen, the cutting force increases significantly as the feed rate increases when using both coated and uncoated carbide tools. This is in line with previous results reported by other researchers [23]. This is due to the thicker chip formation caused by higher feed rate, which induced higher pressure on the surface, and resulted in an increased strain hardening process, and consequently in a significant rise in cutting forces.

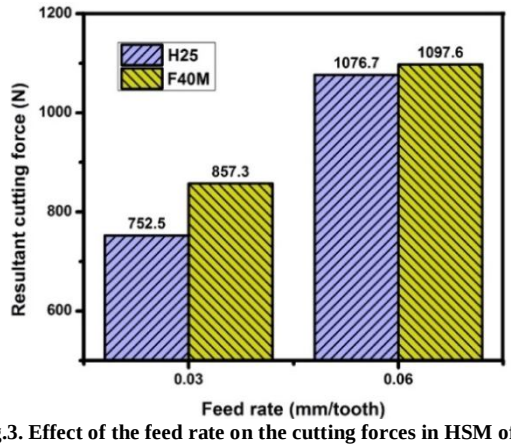
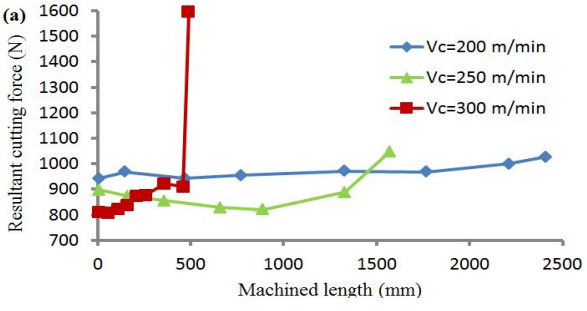


Fig.3. Effect of the feed rate on the cutting forces in HSM of Ti-6A1-4V ELI at Vc=200 m/min and dry conditions

3.4Effect of Tool Wear on the Cutting Forces

Results of cutting force measurements for coated and uncoated carbide tools at different cutting speeds and feed rates during HSM of Ti-6Al-4V ELI alloy are illustrated in Fig.4 The graph shows the variation in cutting forces after each cutting length interval in force measurements, under various cutting speeds and different feed rates during HSM Ti-6Al-4V ELI with PVD-coated (F40M grade type) carbide tools.



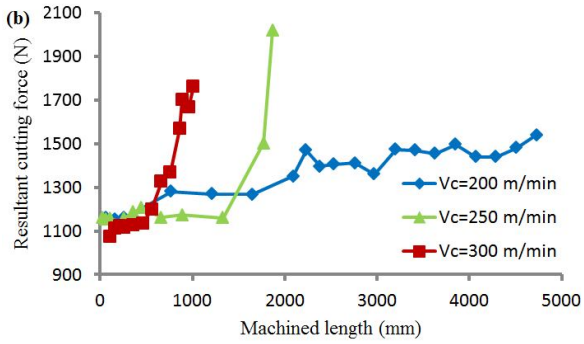


Fig.4. Variation in resultant cutting force versus cutting speed, using coated carbide tool at: (a) f=0.03 mm/tooth; and (b) f=0.06 mm/tooth

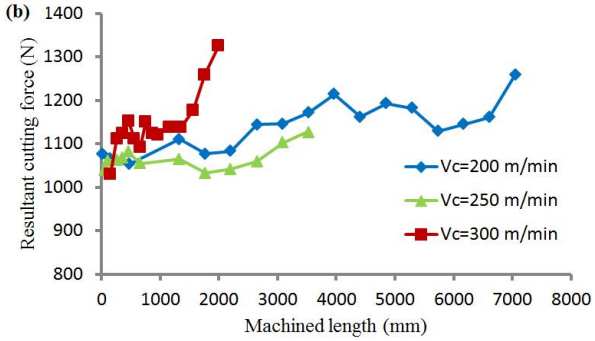


Fig.5. Variation in resultant cutting force versus cutting speed with H25 grade type carbide tool at: (a) f=0.03 mm/tooth; and (b) f=0.06 mm/tooth

As shown in the Fig. 4, the cutting force increases as the machined (cutting) length progresses. The forces remain constant or decrease or increase slightly at the initial cutting intervals, and then start to increase gradually as the machined length increases. This is more significant at the higher cutting speeds. The main reason for the gradual increase in the cutting force against the cutting length is the effect of tool wear [23]. The graph also shows that the resultant cutting force is lower when machined at high cutting speed at the beginning of the cutting, when the tool is fresh [20, 21]. This is due to the interaction between material strain hardening and thermal softening characteristics. However, it increased with the cutting length and higher cutting forces were recorded at higher cutting speed. This is a result of severe flank wear and chipping marks on the tool wear area [24]. These situations tend to increase the friction at the tool and workpeice contact area which resulted in abrupt increase in cutting force.

Fig. 5 reveals the variation in forces after each cutting length interval versus the cutting speed at different feed rates during HSM Ti-6Al-4V ELI, with uncoated H25-grade carbide insert. The graph shows different trend for the resultant cutting force when using uncoated carbide tool, which are much related to the cutting-edge conditions such as chipping, built-up edge and wear properties. However, the performance of this tool was much better than the coated one.

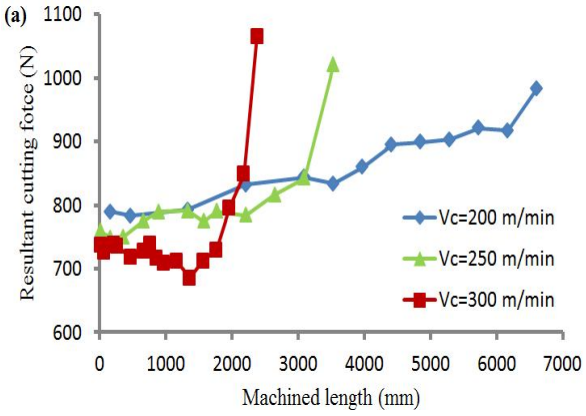


Fig. 6 shows the cutting-edge wear at different cutting lengths when machining with H25 insert, cutting speed 250 m/mim and feed rate 0.06 mm/tooth. Fig. 6 (a–b) shows the cutting edge after 60mm and 110 mm cutting length, respectively. At this machined length, the wear was less obvious and the built-up edge is the main reason for the cutting-force variations. The adhered material on the cutting edge affected the cutting edge with a slight change in rake angle and edge radius which adversely influence the cutting force. With prolong machining, the wear progresses slowly at the cutting edge. As shown in Fig. 6 (c), after 460 mm cutting length the wear starts to form, but it was in the initial stage.

Fig. 6 (d) illustrates the cutting-edge wear after 1330 mm of cutting length. At this stage the wear developed and localised chipping started to occur on the cutting edge. Localised chipping is another reason for increasing the cutting forces during the process. Rubbing of the cutting edge against the machined surface causes an increase in flank wear owing to the abrasive or attrition wear. As a result of the continuous contact with the workpiece, this wear mechanism was more obvious at the outer cutting edge because of rubbing action between workpiece and the flank face. Finally, causing the rounding of the cutting edge and localized chipping become smoother which contributed to the reduction of cutting force. In other words, localized chipping tends to increase the cutting force with prolong machining and rubbing action at the developed flank wear along the cutting edge. With increasing tool wear, the effect of localized chipping was reduced through the smoothing effect. This phenomenon can be seen in Fig. 6 (e). Fig. 6 (f–g) shows the progression of the flank wear, especially in the localised chipping areas, which results in an increase in the cutting force. While smooth wear has taken place at the cutting edge, and the development of the flank wear was localised at the partial of the cutting edge, the cutting force was not increased significantly at the final machined distance, which is shown in Fig. 6 (h). Tool rejection criterion of VBmax=0.2 mm, occurred at the 3530 mm cutting length.

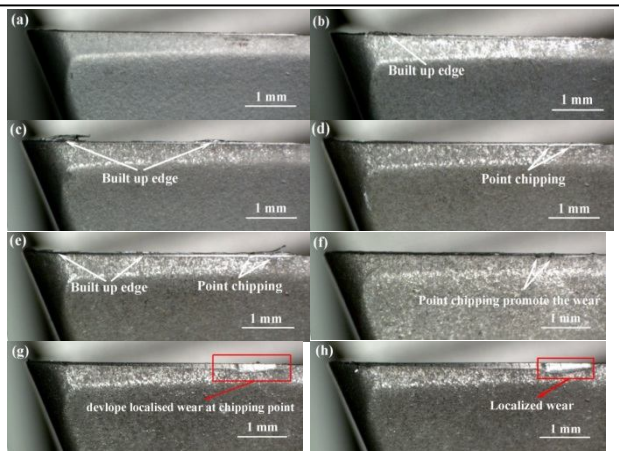


Fig.6. Cutting-edge wear when dry machining with H25 insert tool grade, Vc=250 m/min and f=0.06 mm/tooth at different cutting lengths: (a) 60 mm; (b)110 mm; (c) 460 mm; (d) 1330 mm; (e)1770 mm; (f) 2210 mm; (g) 3090 mm; and (h) 3530 mm

CONCLUSIONS

Based on the investigation conducted on the influence of tool wear on the cutting forces in high speed green milling of titanium alloys, the following conclusions can be drawn:

1. Increasing cutting speed decreased the resultant cutting force when employing new tool at varying feed rates, for both coated and uncoated carbide tools. Cutting force value was declined by means of tools types particularly at lower cutting speeds and feed rates.
2. For both uncoated H25 grade and PVD coated F40M grade type of insert tools cutting force increased as the machined length proceeded. The forces remained constant or decreased or increased slightly at the initial cutting intervals, and then started to increase gradually as the machined length increased.
3. Different trend for the resultant cutting force after each cutting length interval was observed. The main reasons for the cutting-force variations which are much related to the cutting-edge conditions were localised chipping, chipping, built-up edge and wear properties.

REFERENCES

[1] Fang, N. and Wu, Q. (2009). A comparative study of the cutting forces in high speed machining of Ti–6Al–4V and Inconel 718 with a round cutting edge tool. Journal of materials processing technology. 209 (9): 4385-4389.

[2] Dudzinski, D., Devillez, A., Moufki, A., Larrouquere, D., Zerrouki, V. and Vigneau, J. (2004). A review of developments towards dry and high speed machining of Inconel 718 alloy.International Journal of Machine Tools and Manufacture. 44 (4): 439-456.

[3] Hamade, R. and Ismail, F. (2005). A case for aggressive drilling of aluminum.Journal of materials processing technology. 166 (1): 86-97.

[4] Al-Ghamdi, K. A., &Iqbal, A. (2015). A sustainability comparison between conventional and high-speed machining. Journal of Cleaner Production, 108, 192-206.

[5] Hong, S. Y. (2001). Economical and ecological cryogenic machining.Journal of manufacturing science and engineering. 123 (2): 331-338.

[6] Ezugwu, E. and Wang, Z. (1997). Titanium alloys and their machinability—a review. Journal of Materials Processing Technology. 68 (3): 262-274.

[7] Zelinski, P. (2004). The Right Tool For Milling Titanium. Modern Machine Shop. 76 (8): 80-85.

[8] Sharma, V. S., Dogra, M. and Suri, N. (2009). Cooling techniques for improved productivity in turning.International Journal of Machine Tools and Manufacture. 49 (6): 435-453.

[9] Liang, X., & Liu, Z. (2018). Tool wear behaviors and corresponding machined surface topography during high-speed machining of Ti-6Al-4V with fine grain tools. Tribology International, 121, 321-332.

[10] Paul, S. and Chattopadhyay, A. (2006). Environmentally conscious machining and grinding with cryogenic cooling.Machining science and technology. 10 (1): 87-131.

[11] Zhong, W., Zhao, D. and Wang, X. (2010). A comparative study on dry milling and little quantity lubricant milling based on vibration signals. International Journal of Machine Tools and Manufacture. 50 (12): 1057-1064.

[12] Braga, D. U., Diniz, A. E., Miranda, G. W. and Coppini, N. L. (2002). Using a minimum quantity of lubricant (MQL) and a diamond coated tool in the drilling of aluminum–silicon alloys. Journal of Materials Processing Technology. 122 (1): 127-138.

[13] Attanasio, A., Gelfi, M., Giardini, C. and Remino, C. (2006). Minimal quantity lubrication in turning: effect on tool wear. Wear. 260 (3): 333-338.

[14] Yang, X. and Richard Liu, C. (1999). Machining titanium and its alloys.Machining Science and Technology. 3 (1): 107-139.

[15] Shi, Q., Li, L., He, N., Zhao, W. and Liu, X. (2013). Experimental study in high speed milling of titanium alloy TC21. The International Journal of Advanced Manufacturing Technology. 64 (1-4): 49-54.

[16] Cui, X., Zhao, J. and Tian, X. (2013). Cutting forces, chip formation, and tool wear in high-speed face milling of AISI H13 steel with CBN tools. The International Journal of Advanced Manufacturing Technology. 64 (9-12): 1737-1749.

[17] Brinksmeier, E., Preuss, W., Riemer, O., &Rentsch, R. (2017). Cutting forces, tool wear and surface finish in high speed diamond machining. Precision Engineering, 49, 293-304.

[18] Safari H, Sharif S, Izman S, Jafari H (2012) High speed dry end milling of Ti-6Al-4V alloy towards nano-scale surface roughness. J ApplSci Res 8(11):5280-5284.

[19] [19] Guillemot N, Mawussi BK, Lartigue C, Billardon R (2013) A first approach to characterize the surface integrity generated by ball-end finishing milling. Int J AdvManufTechnol 64:269–279.

[20] Nalbant, M., Altın, A. and Gökkaya, H. (2007). The effect of cutting speed and cutting tool geometry on machinability properties of nickel-base Inconel 718 super alloys.Materials & design. 28 (4): 1334-1338.

[21] Sutter, G., Faure, L., Molinari, A., Delime, A. and Dudzinski, D. (1997). Experimental analysis of the cutting process and chip formation at high speed machining. Le Journal de Physique IV. 7 (C3): 33-38.

[22] Oxley, P. (1989). Mechanics of Machining: an Analytical Approach to Assessing Machinability.(Retroactive Coverage). United Kingdom: Ellis Horwood Limited

[23] Li, H., Zeng, H. and Chen, X. (2006). An experimental study of tool wear and cutting force variation in the end milling of Inconel 718 with coated carbide inserts. Journal of Materials Processing Technology. 180 (1): 296-304.

[24] Zhang, S., Li, J., Sun, J. and Jiang, F. (2010). Tool wear and cutting forces variation in high-speed end-milling Ti-6Al-4V alloy. The International Journal of Advanced Manufacturing Technology. 46 (1-4): 69-78.

★★★