Cutting Force in Dry Slot-Milling of Hastelloy X

Nor Aznan Mohd Nor, B. T. Hang Tuah Baharudin, Zulkiflle Leman, and Mohd Khairol Anuar Mohd Ariffin

Abstract Increasing spindle speed accompanied with decreasing feed per tooth during slot-milling of nickel-based superalloys, is a common approach in aircraft manufacturing industry for achieving low cutting force. This is due to nickel-based superalloys is difficult-to-machine materials, thus increase in spindle speed will lead to thermal softening that may reduce cutting force, while decrease in feed per tooth will decrease the amount to shear unwanted material at the tool edge and may avoid excessive cutting force. By considering this approach, an effective validation is vital. This manuscript elucidates the influence of spindle speed and feed per tooth during dry slot-milling of Hastelloy X on cutting force. Conventional-milling and climb-milling are performed experimentally using Kennametal KYS40 solid ceramic end-mill. Experimental results indicate that cutting force firstly decrease and then increase with increase in spindle speed, whereas cutting force increases with increase in feed per tooth. Feed per tooth has significant effect on cutting force. In contrast, spindle speed, and the interaction between spindle speed and feed per tooth have effect on cutting force but not significant. The lowest cutting force can be obtained using medium spindle speed (24,100 rev/min) accompanied with lowest feed per tooth (0.013 mm/tooth), instead of using highest spindle speed (26,800 rev/min) accompanied with lowest feed per tooth (0.013 mm/tooth).

Keywords Dry slot-milling · ASME SB435 Hastelloy X · Cutting force

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1 Introduction

Hastelloy X is increasingly applied in the aircraft manufacturing industry [1, 2], especially in the manufacture of combustion chambers [1]. This is due to the characteristics of nickel-based superalloys that are high resistance to elevated temperature, high resistance to corrosion and oxidation, high feasibility for manufacturing, high resistance to thermal fatigue, low cost, low thermal expansion, low density and low elastic modulus [1], which perfectly suit the working principle of combustion chambers. In the aspect of machinability, Hastelloy X can be categorized as difficult-to-machine material [3]. Due to this, high cutting force will be generated from the use of conventional machining methods.

Machining Hastelloy X using conventional machining methods is very challenging. Which is why increasing spindle speed accompanied with decreasing feed per tooth during milling process becomes a common approach by aircraft manufacturing industry for achieving low cutting force. In addition, this approach can be related to the findings indicated by Masmiati et al. [4], where they claimed that increase in cutting speed and decrease in feed rate, reduces the cutting force. Increasing spindle speed during milling process leads to greater thermal softening of machined material at the tool-chip interface, thus energy requirement is decreased and subsequently reduce cutting force [4, 5]. On the other hand, decreasing in feed per tooth will decrease the amount of unwanted material to be removed during the end-mill slides and bites the machined material [4, 6]. Low cutting force in milling process may restrain vibrations then leads to improve the quality of machinability [7]. Thus. validating the effectiveness of increasing spindle speed accompanied with decreasing feed per tooth during milling of Hastelloy X for achieving low cutting force is vital.

Slot-milling is a versatile form of milling process, which capable of machining slot. In slot-milling, the direction of end-mill rotation is normally constant, while the direction of feed is changing. Therefore, slot-milling can be divided into two distinct processes of removing an unwanted material as depicted in Fig. 1; conventional-milling and climb-milling. Conventional-milling refers to the direction of feed opposed to direction of end-mill rotation, while climb-milling refers to the direction of feed same as direction of end-mill rotation.

In this manuscript, dry slot-milling in conventional-milling and climb-milling are experimentally carried out on Hastelloy X. Apart of this, the influence of spindle speed and feed per tooth on cutting force is elucidated, for the purpose to validate the effectiveness of increasing spindle speed accompanied with decreasing feed per tooth for achieving low cutting force. In addition, dry condition is chosen as this research intends to encourage sustainable manufacturing of nickel-based superalloys. Thus, solid ceramic end-mill is applied due this type of end-mill has excellent thermal resistance which can avoid from the damaging effect of heat. Cutting force behaviour induced by spindle speed and feed per tooth is explicated systematically, subsequently the optimal spindle speed accompanied with feed per tooth for achieving the lowest cutting force is simultaneously proposed.

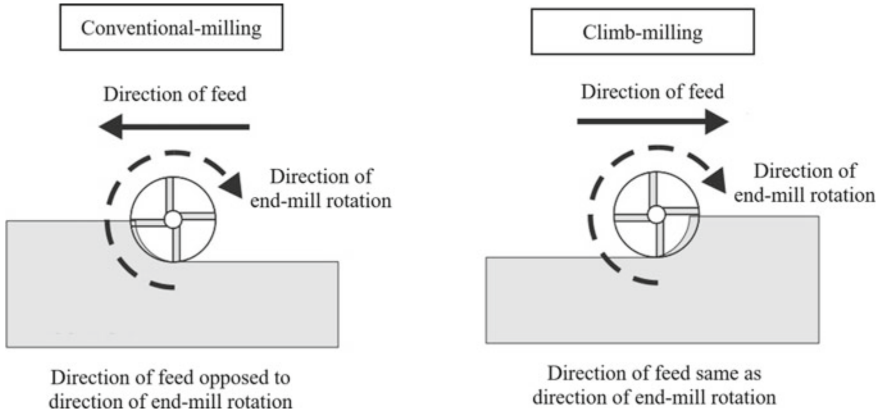


Fig. 1 Schematic illustration of conventional-milling and climb-milling

2 Experimental Setup

Dry slot-milling was carried out on ASME SB435 Hastelloy X 90 × 40 × 10 mm using Mori Seiki NV 4000 DCG vertical machining centre. Conventional-milling and climb-milling were performed with Kennametal KYS40 solid ceramic end-mill diameter of 6 mm. The cutting parameters used in the experimental test are shown in Table 1. In addition, the cutting parameters set in the experimental test were selected by taking into consideration ISO 3002/4 standard as recommended by solid ceramic end-mill manufacturer.

Cutting force components; feed force (F_x), normal force (F_y), and axial force (F_z) at each run were measured simultaneously using Kistler 9129AA dynamometer. The measurements were performed three times at each run to obtain the average value, thus the total sample for 9 runs are 27 samples. The average value was then inserted into the equation below [8] to calculate the cutting force or resultant force (F_r).

$$F_r = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (1)$$

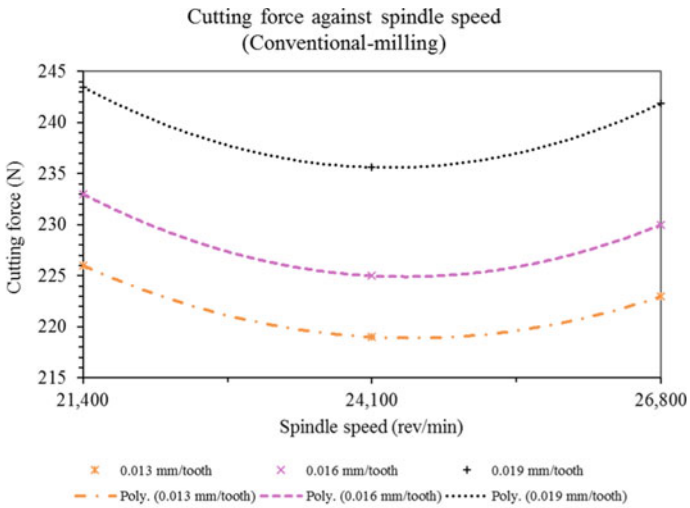
Further, the calculated cutting force was elucidated via main effects plot and Pareto chart of the standardized effects in Minitab software.

Table 1 Cutting parameters used in the experimental test

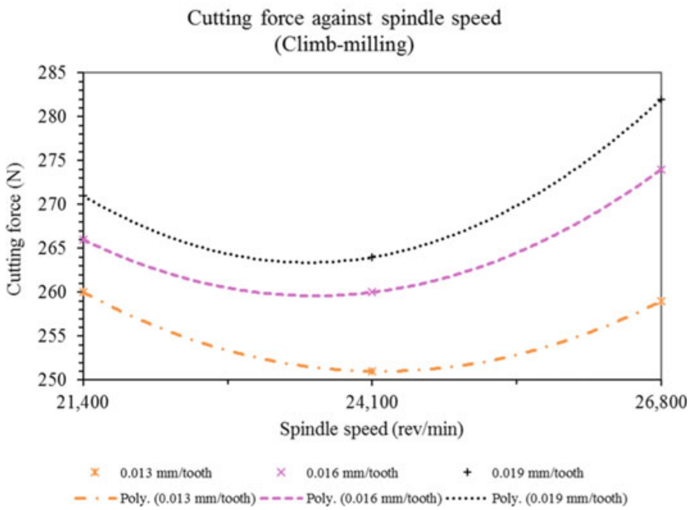
Cutting parameter	Level
Spindle speed (rev/min)	21,400, 24,100 and 26,800
Feed per tooth (mm/tooth)	0.013, 0.016 and 0.019
Axial depth of cut (mm)	0.2

3 Results and Discussion

Figure 2 depicts the overall experimental results of dry slot-milling on Hastelloy X during conventional-milling and climb-milling. X-axis and Y-axis represent spindle speed and cutting force respectively, while orange trend-line, lavender trend-line

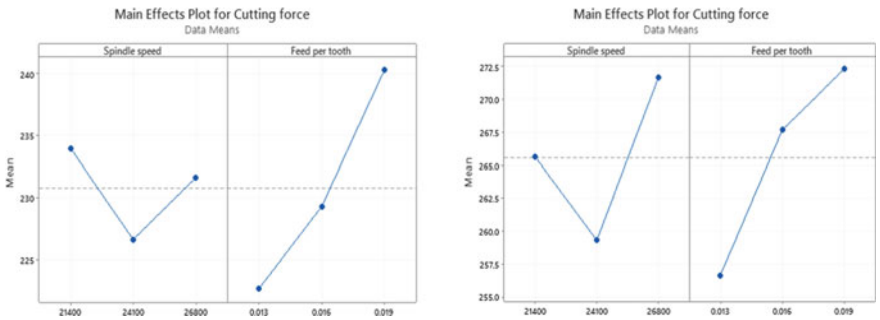


(a)



(b)

Fig. 2 Overall experimental results: **a** conventional-milling and **b** climb-milling



(a) (b)

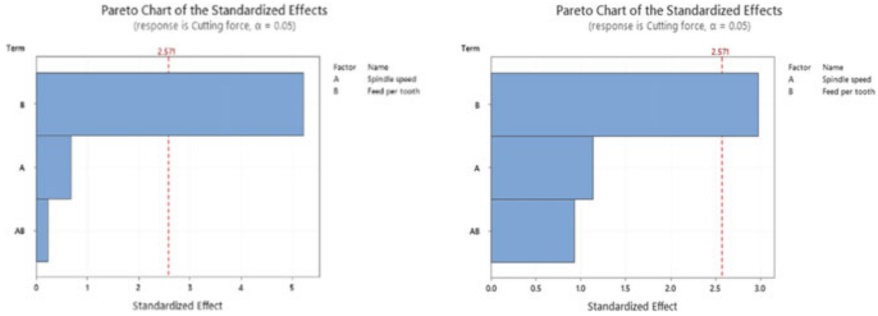
Fig. 3 Main effects plot: **a** conventional-milling and **b** climb-milling

and black trend-line represent feed per tooth 0.013 mm/tooth, 0.016 mm/tooth and 0.019 mm/tooth, respectively.

As presented in Fig. 3, main effects plot is used to quantitatively assess the influence of spindle speed and feed per tooth on cutting force. The dotted line represents the overall mean cutting force.

In both conventional-milling and climb-milling, cutting force firstly decreased when spindle speed was increased from 21,400 to 24,100 rev/min, and then increased with increase in spindle speed higher than 24,100 rev/min. This cutting force behavior is contradictory to the cutting force behaviour observed by Masmiati et al. [4] where cutting force decreases with increased in spindle speed. The behavior of cutting force firstly decreases and then increases after reaching a specific spindle speed is in line with the research conducted by Mohd Nor et al. [9], where it can be associated with ductile-to-brittle transition, in which Hastelloy X undergoes brittle cutting mode at spindle speed 24,100 rev/min and subsequently leads to fluctuation in cutting force. As expected, cutting force increased when feed per tooth was increased from 0.013 to 0.019 mm/tooth. This can be associated with the increase amount of unwanted Hastelloy X to be sheared during dry slot-milling [4, 6]. Another factor that can be associated is due to the increase in feed per tooth which causes the strain hardening effect, and consequently increases cutting force [10]. Therefore, the higher the feed per tooth, the higher the cutting force. Figures 2 and 3 confirm that using spindle speed 26,800 rev/min accompanied with feed per tooth 0.013 mm/tooth will not achieve low cutting force. Therefore, the approach of increasing spindle speed accompanied with decreasing feed per tooth for achieving low cutting force is non-effective. The good rule of thumb for achieving the lowest cutting force during dry slot-milling of Hastelloy X is to use spindle speed 24,100 rev/min accompanied with feed per tooth 0.013 mm/tooth, instead of the maximum spindle speed (26,800 rev/min) accompanied with the minimum feed per tooth (0.013 mm/tooth).

In search of determining the magnitude and the importance of the effects, Pareto chart of the standardized effects is used as depicted in Fig. 4. Factor that crosses the dotted line is statistically significant.



(a) (b)

Fig. 4 Pareto chart of the standardized effects: **a** conventional-milling and **b** climb-milling

From Fig. 4, feed per tooth was the dominant factor affecting cutting force in both conventional-milling and climb-milling, followed by spindle speed and the interaction between spindle speed and feed per tooth. Since feed per tooth extended past the dotted line, thus it can be considered that feed per tooth had significant effect on cutting force at 0.05 significance level. Whereas, spindle speed and the interaction between spindle speed and feed per tooth both had effect on cutting force but not statistically significant. It can be claimed that the variation of cutting force behavior during dry-slot milling of Hastelloy X is closely related to the increasing and decreasing feed per tooth, when compared to the increasing and decreasing spindle speed. Therefore, a precise selection of feed per tooth value is crucial in order to prevent cutting force catastrophe.

4 Conclusion

Dry slot-milling of Hastelloy X was performed by conventional-milling and climb-milling using Kennametal KYS40 solid ceramic end-mill. The following conclusions can be drawn from this experimental test:

- Cutting force firstly decreased as spindle speed was increased from 21,400 to 24,100 rev/min, then cutting force increased as spindle speed increased higher than 24,100 rev/min.
- Cutting force increased with the rise of feed per tooth from 0.013 to 0.019 mm/tooth.
- Increasing spindle speed accompanied with decreasing feed per tooth for achieving low cutting force is non-effective approach.
- Spindle speed 24,100 rev/min (medium spindle speed) accompanied with feed per tooth at 0.013 mm/tooth (lowest feed per tooth) were found to achieve the lowest cutting force, instead of spindle speed 26,800 rev/min (highest spindle speed) accompanied with feed per tooth 0.013 mm/tooth (lowest feed per tooth).

- Feed per tooth is the most influential cutting parameters for the cutting force generated during dry slot-milling, while spindle speed and the interaction between spindle speed and feed per tooth have effect but not significant.
- Future research should be focused on surface integrity of Hastelloy X and tool wear of KYS40 solid ceramic end-mill.

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References

1. Romero-Jabalquinto A, Velasco-Téllez A, Zambrano-Robledo P, Bermúdez-Reyes B (2016) Feasibility of manufacturing combustion chambers for aeronautical use in Mexico. J Appl Res Technol 14(3):167–172
2. Han Q, Gu Y, Huang J, Wang L, Low KWQ, Feng Q, Yin Y, Setchi R (2020) Selective laser melting of Hastelloy X nanocomposite: effects of TiC reinforcement on crack elimination and strength improvement. Compos B Eng 202:108442
3. Şirin E, Kıvak T, Yıldırım ÇV (2021) Effects of mono/hybrid nanofluid strategies and surfactants on machining performance in the drilling of Hastelloy X. Tribol Int 157:106894
4. Masmiati N, Sarhan AAD, Hassan MAN, Hamdi M (2016) Optimization of cutting conditions for minimum residual stress, cutting force and surface roughness in end milling of S50C medium carbon steel. Measurement 86:253–265
5. Bhirud NL, Gawande RR (2017) Measurement and prediction of cutting temperatures during dry milling: review and discussions. J Braz Soc Mech Sci Eng 39(12):5135–5158
6. Grzesik W (2017) Chapter fifteen—Advanced machining processes, 2nd edn. Elsevier
7. Ducroux E, Fromentin G, Viprey F, Prat D, D'Acunto A (2021) New mechanistic cutting force model for milling additive manufactured Inconel 718 considering effects of tool wear evolution and actual tool geometry. J Manuf Process 64:67–80
8. Shixiong W, Wei M, Bin L, Chengyong W (2016) Trochoidal machining for the high-speed milling of pockets. J Mater Process Technol 233:29–43
9. Mohd Nor NA, Baharudin BTHT, Ghani JA, Leman Z, Mohd Ariffin MKA (2020) Effect of chip load and spindle speed on cutting force of Hastelloy X. J Mech Eng Sci 14(1):6497–6503
10. Danish M, Yasir M, Mia M, Nazir K, Ahmed T, Rani AMA (2020) Chapter 10—High speed machining of magnesium and its alloys. Academic