11º Congresso Brasileiro de Engenharia de Fabricação
24 a 26 de maio de 2021, Curitiba, PR, Brasil

COMPARISON BETWEEN HIGH PERFORMANCE AND HSC MACHINING IN THE HARD MILLING OF A CURVED GEOMETRY

Laurence Colares Magalhães
Federal University of Espírito Santo – UFES, Fernando Ferrari Avenue, 514 – Goiabeiras, 29075-210, Vitória – ES, Brazil.
laurence.magalhaes@ufes.br
João Carlos Espíndola Ferreira
Federal University of Santa Catarina – UFSC, João David Ferreira Lima Campus - Trindade, 88040-900, Florianópolis – SC, Brazil.
jcarlos@emc.ufsc.br
Marcelo Tramontin Souza
State University of Santa Cruz – UESC, Rod. Jorge Amado, Km 16 - Salobrinho, 45662-900, Ilhéus – BA, Brazil.
mtsouza@uesc.br
Jairo Wilson
Federal University of Amazonas UFAM. Rodrigo Otávio avenue, 3000 - Coroado, 69080-900, Manaus – AM, Brazil.
wilsjai@gmail.com

Abstract. *Continuous technological advances in machines, cutting tools, numerical controls, and CAM systems have allowed the advent of hard milling in the manufacture of molds and dies. Its objectives comprise obtaining low tolerances and better surface finishes with shorter times and costs. In this work, a high-performance machine was compared with a high-speed cutting (HSC) machine in the manufacture of a curved geometry similar to those found in some molds and dies. The high-performance machine has a cast iron structure with a maximum spindle speed of 8,000 rpm. The HSC machine has a monobloc structure and a maximum spindle speed of 12,000 rpm. The die was machined in AISI H13 steel quenched and tempered to 52 HRC, with CVD multi-layer coated cemented carbide tools. The comparison was made in terms of total processing time and surface quality. For the amount of material removed, it is inferred that, in the finishing stages, the processing time can be reduced by up to 17% by using an HSC machine. The values of surface arithmetic average roughness of the dies with both machines were lower than 0.8 μm, which can contribute to reduce manual polishing significantly. However, the roughness obtained with an HSC machine was slightly less compared to high-performance machine. Chipping was the predominant wear mechanism in the tools in the roughing stage, whereas abrasion was predominant in the finishing stages.*
Keywords*: Hard milling, H13 Steel, High Speed Cutting*

1. INTRODUCTION

Manufacturing of complex surfaces is common to several sectors (Lazoglu et al., 2011; de Souza et al.; 2015; Schützer et al., 2007). Machining is the process used to achieve the required shape of dies, moulds, or blades (Urbanski et al., 2000). A difficult challenge is to produce precise free-form surfaces on difficult-to-cut materials, with narrow tolerances, with good performance (M'Saoubi et al. 2015). Some of the aspects that should be taken into account include: the use of three, four or five-axis machines, the computer-aided manufacturing (CAM) system, the cutting tools, and the skill of programmers and machine operators (Ramesh et al., 2013).

The need to reduce the delivery time of industrialized products is leading to modifications in the sequence of the conventional mold and die manufacturing process (Gaitonde et al., 2009). Traditionally, roughing and pre-finishing operations are performed on annealed steel. Subsequently, in the tempered state, finish milling and removal by electrical discharge machining (EDM) of complex details are performed. Then, a final finishing process such as manual grinding and/or polishing is used (Hassanpour et al., 2016). The milling of steel in the hardened state provides substantial benefits in terms of reducing production time and manufacturing costs when compared to the traditional way (Gaitonde et al., 2016; Magalhães et al., 2019). Nowadays, the use of machining concepts such as high speed cutting (HSC) in five simultaneous axes, in addition to hard milling (HM) are becoming common (Batista et al., 2007; Yao et al., 2018; Sundi et al., 2018. These concepts could be introduced in the production chain due to the technological advances of machines, cutting tools, and computer-aided manufacturing (CAM) systems (Tönshoff et al., 2000; de Lacalle et al., 2002; Toh, 2004).

Surface roughness is one of the most important quality parameters in the high speed machining of molds and dies and in aerospace field (Magalhães et al., 2019; Zhenchao et al., 2018). In some cases, the finishing operation is crucial to determining the life of the mold/die (de Oliveira and Diniz, 2009). Generally, the low roughness obtained with lower feed per tooth produces molds with long life (Axinte and Dewes, 2002; Magri et al., 2013).

Although the gains that HSC and HM can bring are significant (Zanoil and Yazid, 2017; de Lacalle et al., 2002; Pu and Singh, 2013), their application is often limited to the volume of material removed (Dolinšek, 2001) and also to the availability of appropriate machines, which are generally more costly (Huo and Poo, 2013; Ekinovic, 2007).

Usually, some important questions are asked in companies that manufacture dies and moulds: (a) which machine to use when several are available on the shop floor? (b) is the quality of the machined surface significantly worsened in conventional machining, which cannot be compared to that obtained with an HSC machine? (c) with regard to the so-called high performance machines, do their characteristics enable them to achieve a better result? (d) can processing time be reduced to justify this choice? Despite these important questions, few papers are found that seek to answer them. Usually only one machine is used, and the main process parameters are changed.

In this context, this work presents a comparison between two different CNC machines which were used to perform hard milling in AISI H13 steel tempered and annealed to 52 HRC. A curved surface was used in the tests, which requires a higher performance of the machine and the CNC. The parameters used for comparison were processing time and surface finishing.

2. PROPOSED METHOD

Hemispherical parts similar to a cover die of a motorcycle exhaust system were machined at both CNC machines (see Figure 1) with a prismatic workpiece (70 x 70 x 30 mm) in AISI H13 steel quenched and tempered to 52 HRC. Four parts were machined, one on each machine with one replica. Machine A is a high-performance CNC machine with 15 kW power carrying high precision spindles coupled to the servomotors and managed through a Siemens Sinumerik 828D controller, which offers the following set of special software functions: spline A, B, C, COMPON/COMPCURV/COMPCAD compressors, polynomial interpolation, cycle 832, 150 block look ahead, jerk control, soft/brisk acceleration patterns, 1 ms block processing time. According to the manufacturer, these functions allow the CNC to control the machine axes with precision and smoothness of movement at high cutting speeds (high spindle speeds and feeds). Thus, the machine can perform rough and finish machining of hardened steels, cast iron, aluminum alloys and other materials in a shorter time and with high quality surface finish. It has 15 kW power and 8,000 rpm maximum spindle speed.

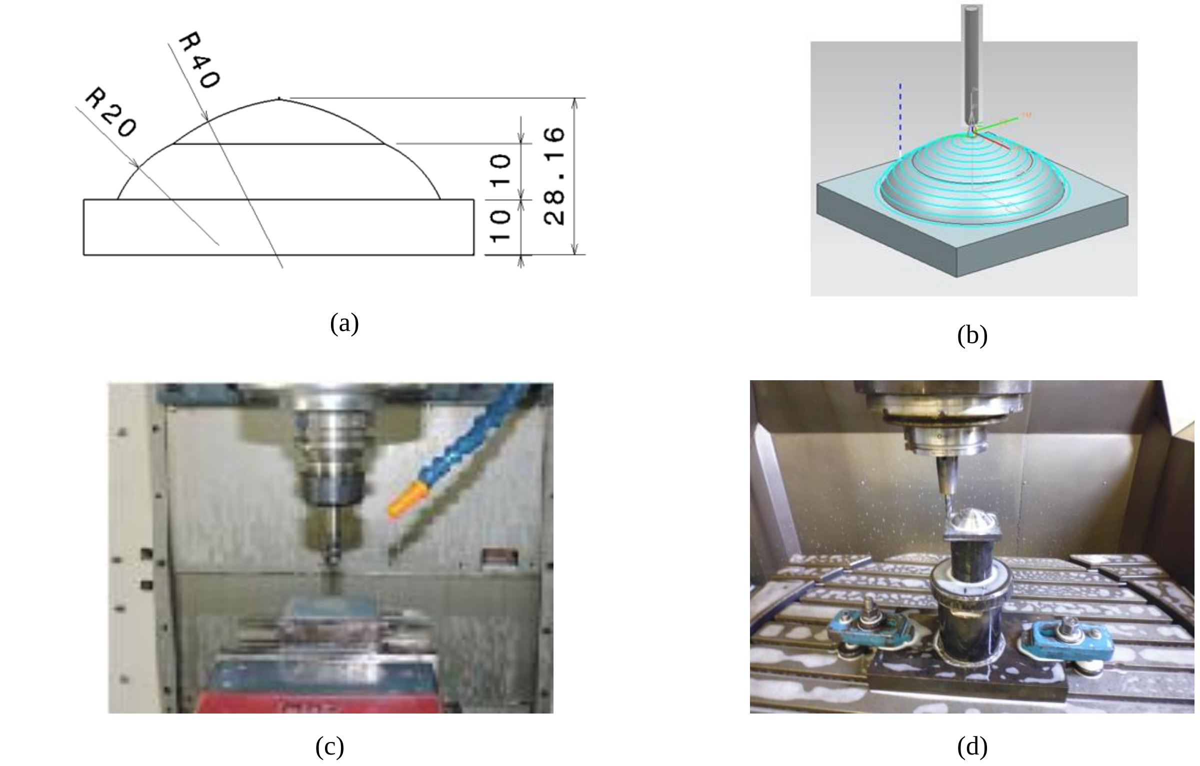

Figure 1. (a) CAD draw of hemispherical surfaces (dimensions in mm), (b) tool path, (c) Part fastened and machined in machine A, (d) Part fastened and machined in machine B.

Machine B is a high speed cutting (HSC) 5-axis CNC machine with 16 kW power and 12,000 rpm maximum spindle speed, Heidenhain TNC 640 control with up to 0.5 ms block processing time, 99 look-ahead blocks, built in a monobloc structure. In both processes the hard-milling route was used, where the part is machined in only one setup. Table 1 shows important parameters of the two machines used.

The tools used in the roughing stage were a 12 mm diameter solid carbide end mill, TiAlN CVD coated, micro grain, with four cutting edges, indicated by the manufacturers for material roughing with high hardness (up to 62 HRC). Due to availability reasons, the tools used in the roughing stage were from different manufacturers, but with the same grades and specifications. Thus, the parts processed on machine A were roughed with tools from one particular manufacturer, and the parts processed on machine B were roughed with tools from another manufacturer.

The tools used in the pre-finishing and finishing stages were solid carbide ball nose end mills, TiAlN CVD coated, micro grain, with four cutting edges, 8 mm and 6 mm in diameter, respectively. The tools for the finishing stage were assembled with an L/D ratio equal to 3.5 in both cases. Down milling cut was used.

In the roughing stage, a follow periphery strategy was used (Tunc and Stoddart, 2017; Moodleah and Makhanov, 2015). In pre-finishing and finishing stages, a contour strategy was used from top to bottom (Altintas et al., 2016). The Siemens NX 10 CAM system was used to generate tool paths. Tables 2, 3 and 4 show the main parameters used in the roughing and finishing stages in each machine. Due to the larger maximum spindle speed available in machine B, this maximum speed was used, so the value of feed per tooth was chosen so that the final roughness is appropriate. The cutting time simulated by the CAM software was used to perform this adjustment.

Average arithmetic roughness measurements were made using a Mitutoyo SJ 310 roughness tester with a diamond probe with a 5 µm radius tip, and the part was inclined to perform measurements as shown in Figure 2. Three measurements were taken, and the mean and standard deviation values were obtained in the direction transversal to the tool feed direction in each finished part. The cut-off value used was 0.8 mm, by following the ISO 4288 standard (ISO, 1998).

With regard to the assessment of cutting tool wear, a Hexagon optical measuring system was used, and the magnification value is at the bottom of each image.

Figure 2. Roughness measurement of the machined surface of the workpiece using a Mitutoyo SJ 310 roughness tester.

Table 1. Main operation parameters of machines A and B.

	Machine A	Machine B
Drive power (kW)	15	16
Maximum rotation (rpm)	7,500	12,000
Rapid traverse (m/min) X,Y,Z	30	40
CNC	Sinumerik 828D	Heidenhain TNC 640
Tool holder type	ISO BT 40	SK 40
Tool clamping	Collet chuck	Thermal shrinkage
Cutting fluid	Synthetic oil 5%	Synthetic oil 5%
Number of axes	4	5

Table 2. Machining parameters settled for roughing and finishing with machines A and B.

	∅ cutting tool (mm)	Cutting motion	Cutting speed (m/min)	Feed rate (mm/min)	rpm	Feed per tooth (mm)	a_p (mm)	a_e (mm)
Roughing at both machines	12	down milling	85	361	2256	0.04	0.75	5.0
Finishing with machine A	6	down milling	130	1931	6897	0.07	0.15	0.1
Finishing with machine B	6	down milling	226	2160	12000	0.045	0.15	0.1

3. RESULTS AND DISCUSSION

Since a higher cutting speed could be used in machine B, feed per tooth values were adjusted in order to perform machining in a shorter time when compared with machine A. The reduction in processing time reached about 17% in the finishing stages. As expected, due to machine accelerations and decelerations, which CAM systems usually do not take into account for processing time estimation (Coelho et al., 2010; Tikhon et al., 2004), the actual processing times were higher than the times estimated by the CAM system. They were 12% higher in machine A and 11% higher in machine B (Figure 3).

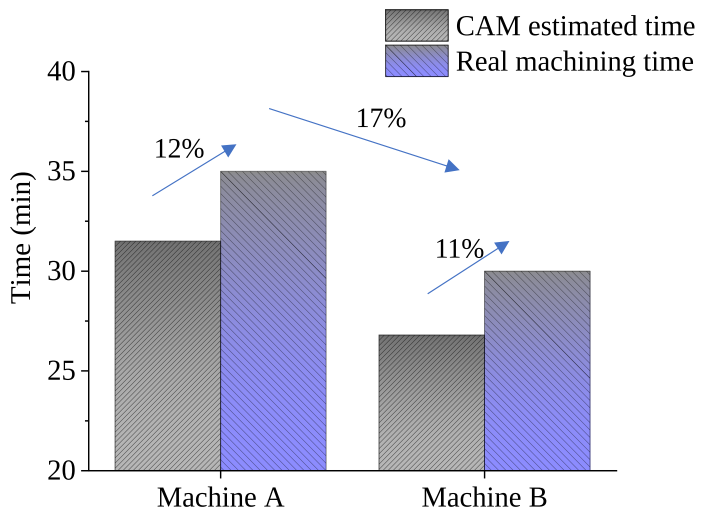

Figure 3. Estimated and real processing times for pre-finishing and finishing of parts achieved in each machine.

Even using relatively high values of feed rate in both machines, in order to reduce processing times, the Ra roughness values were below 0.8 µm, which is a value that may contribute to the reduction of manual polishing (Azlan et al., 2017). In machine B the roughness reached 0.5 µm (Figure 4), which was a result of the greater structural rigidity of the HSC machine and its induction heating fixture.

Machine B features a real-time monitoring of the power consumption of the machine spindle as well as temperature. In the finishing stage, even with a high spindle speed, due to the low values of depth of cut, it was verified that the spindle power did not exceed 9% of the total installed power, and spindle temperature was below 38ºC (Figure 5).

The roughing tools used in workpieces processed in Machine B showed severe chipping after approximately 32 minutes (Figure 6) and, because of that, the tool was replaced by another identical tool to machine the remaining volume of the part. The total roughing time was equal to 58 minutes. With regard to the finishing tools, only a small flank wear was observed.

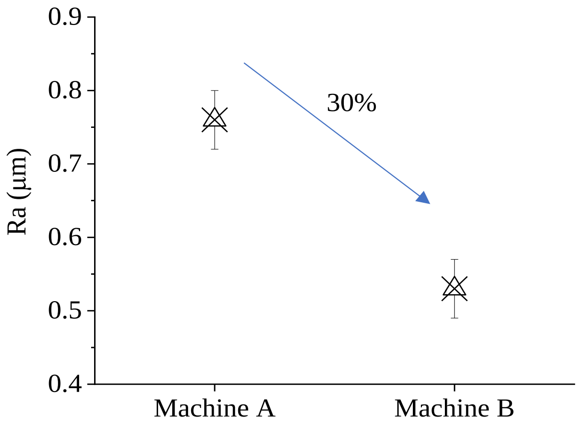

Figure 4. Final average arithmetic roughness values (Ra) in the parts processed in each machine.

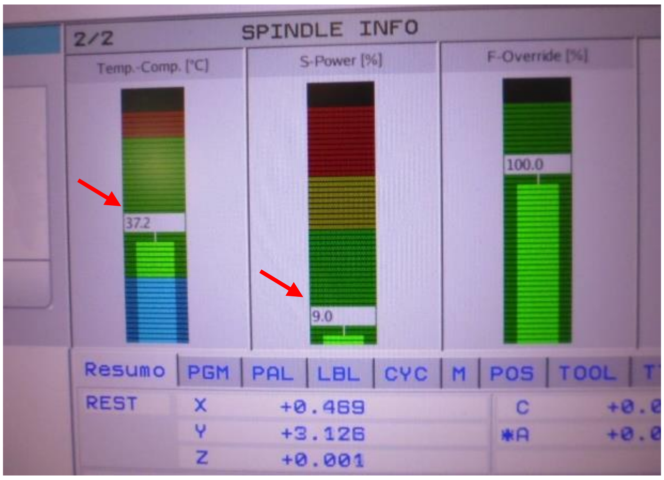

Figure 5. Spindle power and temperature monitoring in the finishing stage for machine B.

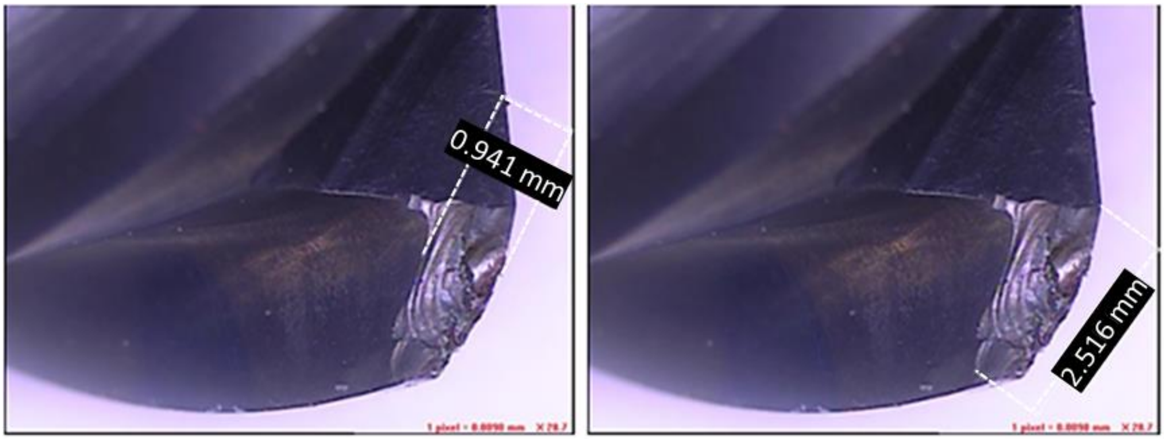

Figure 6. Delamination of cutting tool in the roughing stage (machine B) after 32 minutes, which is the reason why this cutting tool was replaced. 28.7 X magnification.

4. CONCLUSIONS

In this work, hard milling was used to machine a die in AISI H13 steel quenched and tempered to 52 HRC using two machines: a high-performance machine and a high-speed cutting (HSC) machine.

The results show that the manufacturing time can be reduced 17% by using the HSC machine compared to the high-performance machine and with improved surface finishing. Hard milling proved to be feasible in both cases since the tools used in the roughing stage did not show catastrophic failure, whereas in the finishing stage only flank wear was observed in small proportions. Chipping was the predominant wear mechanism in the tools in the roughing stage, whereas abrasion was predominant in the tools in the finishing stages.

In both cases, the average arithmetic roughness values were below 0.8 μm, allowing to substantially reduce the need for manual polishing. Due to roughness values obtained, depending on the application, the manual polishing stage can be significantly reduced.

It is suggested for future work adjusting the values of feed rate and radial depth of cut in order to reach roughness values lower than 0.5 μm.

Also, with the fifth axis in machine B, it can be investigated the variations of the tool rake angle to obtain higher effective cutting speeds, which can lead to a better surface finish. Total hourly costs of each machine can be evaluated to facilitate deciding which equipment to use in each application.

5. ACKNOWLEDGMENTS

The authors are grateful to Moto Honda from Brazil, for allowing the use of HSC machine for the tests. Also, the authors are grateful to FAPEAM, CNPq and CAPES for supporting this work.

6. REFERENCES

Altintas RS, Kahya M, Ünver HÖ (2016) Modelling and optimization of energy consumption for feature based milling. International Journal of Advanced Manufacturing Technology, 86(9-12):3345-3363.

Axinte DA, Dewes RC (2002) Surface integrity of hot work tool steel after high speed milling-experimental data and empirical models. Journal of Materials Processing Technology, 127(3):325-335.

Azlan R, Izamshah R, Kasim MS, Akmal M, Nawi MAHM (2017) Improvement of machining performance using hybrid rotary ultrasonic milling (HRUAM) for hardened D2 tool steel materials. International Journal of Applied Engineering Research, 12(23):13506-13513.

Batista MF, Rodrigues AR, Coelho RT (2017) Modelling and characterisation of roughness of moulds produced by high-speed machining with ball-nose end mill. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 231(6):933-944.

Coelho RT, de Souza AF, Roger AR, Rigatti AMY, de Lima Ribeiro AA (2010) Mechanistic approach to predict real machining time for milling free-form geometries applying high feed rate. The International Journal of Advanced Manufacturing Technology, 46(9-12):1103-1111.

de Lacalle LNL, Lamikiz A, Sánchez JA, Arana JL (2002) Improving the surface finish in high speed milling of stamping dies. Journal of Materials Processing Technology, 123(2):292-302.

de Oliveira AJ, Diniz AE (2009) Tool life and tool wear in the semi-finish milling of inclined surfaces. Journal of Materials Processing Technology, 209(14):5448-5455.

de Souza AF, Berkenbrock E, Diniz AE, Rodrigues AR (2015) Influences of the tool path strategy on the machining force when milling free form geometries with a ball-end cutting tool. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 37(2):675-687.

Dolinšek S, Šuštaršic B, Kopac J (2001) Wear mechanisms of cutting tools in high-speed cutting processes. Wear, 250(1-12):349-356.

Ekinovic S, Begovic E, Silajdžija A (2007) Comparison of machined surface quality obtained by high-speed machining and conventional turning. Machining Science and Technology, 11(4):531-551.

Gaitonde VN, Karnik SR, Figueira L, Davim JP (2009) Machinability investigations in hard turning of AISI D2 cold work tool steel with conventional and wiper ceramic inserts. International Journal of Refractory Metals and Hard Materials, 27(4):754-763.

Gaitonde VN, Karnik SR, Maciel CHA, Rubio JCC, Abrão AM (2016) Machinability evaluation in hard milling of AISI D2 steel. Materials Research, 19(2):360-369.

Hassanpour H, Sadeghi MH, Rasti A, Shajari S (2016) Investigation of surface roughness, microhardness and white layer thickness in hard milling of AISI 4340 using minimum quantity lubrication. Journal of Cleaner Production, 120:124-134.

Huo F, Poo AN (2013) Precision contouring control of machine tools. The International Journal of Advanced Manufacturing Technology, 64(1-4):319-333.

ISO (1998) 4288: Geometrical product specification - surface texture: profile method - rules and procedures for the assessment of surface texture”. British Standards Institution.

Lazoglu I, Boz Y, Erdim H (2011) Five-axis milling mechanics for complex free form surfaces. CIRP annals, 60(1):117-120.

Magalhães LC, Ferreira JCE (2019) Assessment of tool path strategies for milling complex surfaces in hardened H13 steel. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 233(3):834-849.

Magalhães LC, Ferreira JCE, Bezerra ALC, Sombra SC (2019) Influence of feed direction on finishing milling cylindrical surfaces in H13 hardened steel. Journal of the Brazilin Society of Mechanical Sciences and Engineering, 41, 171.

Magri ML, Diniz AE, Button ST (2013). Influence of surface topography on the wear of hot forging dies. International Journal of Advanced Manufacturing Technology, 65(1-4):459-471.

Moodleah S, Makhanov SS (2015) 5-axis machining using a curvilinear tool path aligned with the direction of the maximum removal rate. International Journal of Advanced Manufacturing Technology, 80(1-4):65-90.

M'Saoubi R, Axinte D, Soo SL, Nobel C, Attia H, Kappmeyer G, Engin S, Sim WM (2015) High performance cutting of advanced aerospace alloys and composite materials. CIRP Annals, 64(2): 557-580.

Pu Z, Singh A (2013) High speed ball nose end milling of hardened AISI A2 tool steel with PCBN and coated carbide tools. Journal of Manufacturing Processes, 15(4):467-473.

Ramesh R, Jyothirmai S, Lavanya K (2013) Intelligent automation of design and manufacturing in machine tools using an open architecture motion controller. Journal of Manufacturing Systems, 32(1):248-259.

Sundi SA, Izamshah R, Kasim MS and Raffay MR (2018) The effect of surface finish by varying machining strategies of five-axis flank milling for curvy angled convex profile. Journal of Advanced Manufacturing Technology, 12(1):213-222.

Schützer K, Abele E, Stroh C, Gyldenfeldt CV (2007) Using advanced CAM-systems for optimized HSC-machining of complex free form surfaces. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 29(3):313-316.

Tikhon M, Ko TJ, Lee SH, Kim HS (2004) NURBS interpolator for constant material removal rate in open NC machine tools. International Journal of Machine Tools and Manufacture, 44(2-3):237-245.

Toh CK (2004) Surface topography analysis in high speed finish milling inclined hardened steel. Precision Engineering, 28(4):386-398.

Tönshoff HK, Arendt C, Amor Ben R (2000) Cutting of hardened steel. CIRP Annals, 49:547-566.

Tunc LT, Stoddart D (2017) Tool path pattern and feed direction selection in robotic milling for increased chatter-free material removal rate. International Journal of Advanced Manufacturing Technology, 89(9-12):2907-2918.

Urbanski JP, Koshy P, Dewes RC, Aspinwall DK (2000) High speed machining of moulds and dies for net shape manufacture. Materials & Design, 21(4):395-402.

Yao C, Tan L, Yang P, Zhang D (2018) Effects of tool orientation and surface curvature on surface integrity in ball end milling of TC17. International Journal of Advanced Manufacturing Technology, 94(5-8):1699-1710.

Zanoil A, Yazid MZA (2017) Review of development towards minimum quantity lubrication and high-speed machining of aluminum 7075-T6. Journal of Advanced Manufacturing Technology, 12(1):129-142.

Zhenchao Y, Yang X, Yan L, Jin X, Wang Q (2018) The effect of milling parameters on surface integrity in high-speed milling of ultrahigh strength steel. 4th CIRP Conference on Surface Integrity, 83-88.

7. RESPONSIBILITY NOTICE

The authors are the only ones responsible for the printed material included in this paper.