Saeed, Int J Adv Technol 2018,9:4
DOI: 10.4172/0976-4860.1000217

International Journal of Advancements in Technology

ISSN: 0976-4860

Review Article Open Access

Influence of offset Magnitude e_c and Angular Location λ_c Different Parameters along with their Calibration Methods and Improvements: A review

Junaid Saeed*

Department of Mechanical Engineering, Guangdong Ocean University, China

Abstract

The purpose of this paper is to elaborate different methods and techniques used by various researchers as a scientist or engineers for the decrement of the effect of geometric parameters (offset magnitude e_c and angular location vector λ_c) on different machining parameters (cutting forces, high tool wear and etc.), cutting tools geometry, work piece material and etc. As three axis or five axis milling machine is used in different areas such as in mechanical, civil, aeronautical engineering fields and etc. for the machining of parts where we can't make compromises in terms of dimensional accuracy such as for jet parts, automobile parts and etc. where highly qualified surface finished products were required. So it is very important to study all the aspects which create problems in the way of destination and do trial through different technical techniques along with the best decision in terms of selecting different cutting parameters (axial and radial depth of cut, feed rate and etc.), creation of mathematical models for cutting forces and etc. Presence of eccentricity or run out characteristics in between spindle and tool or tool and work piece creates uncompromising situations so it should be considered.

Keywords: Magnitude; Angular Location; Calibration

Introduction

Market demands such as the higher production rate by reducing lead time, low production and tooling cost, the work piece having good and fine surface finish quality with high precision and accuracy in all dimensions, process stability of the machine and etc. presents many challenges. But there are many critical parameters which bring off interruption in the fulfillment of the above tasks and eccentricity is one of them. It can be defined as detour or divergence from the oblique path means in machining system when the cutting tool is fixed for the cutting operations then there become two axis, one is term as the main axis or main rotation axis of the machine and second is term as geometric axis of the work piece. If the main rotation axis and geometric axis are in-line or coincide with each other than the system is having zero eccentricity or no eccentricity which is unable to achieve and if the both axis does not coincide with each other than it means that the system is exhibiting eccentricity or run out. Many researchers phrase the word eccentricity as run out in many research papers because both indicates disturbance from their path. The milling cutter eccentricity consists of two detracting parameters, eccentric offset magnitude e_c or displacement and angular location λ_c as shown in Figure 1.

Important thing to note was that how we come to know that this milling cutter contains eccentricity and how the eccentricity is induced in it. It was found that if the cutter contains eccentricity than it may affect the cutting forces in two manners: a) the current cutting edge's cutting force value would be different from the adjacent one. The offset magnitude λ_c affects the cutting forces by surrounding with the chip thickness, the angle when the tooth start cutting the material and the angle when the teeth finish its cutting. b) Other one was that the angle between the current cutting edge and adjacent cutting edge would be less than 180°. The angular location λ_c affects the cutting force by encompassing with rotation angle. There are two types of run out, static run out and dynamic run out. Static run out arrives from manufacturing issues or geometric imperfection, spindle error, thermal deformation, clamping deviation due to chip or dirt, coolant or oil layer present inside the taper when fixed, or insert settings. Dynamic cutter run out arrives from uneven cutting forces or cutting force variation, unbalancing of spindle, tool holder and milling cutter, irregular evolution of tool wear and etc.

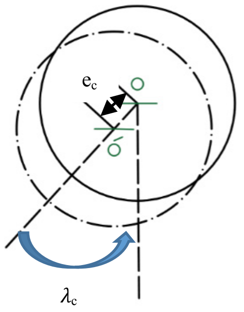

Figure 1: Offset magnitude e_c and location angle λ_c for the cutter eccentricity.

Means there are several sources of instability and these are those sources from which some can be finished through proper cleaning or through technical techniques and some of them can't be finished just decreased. As we know that nothing is hundred percent perfect in this world not the machines, not the tools even not the measuring instruments. All contains error even at a very small level but they have. Due to manufacturing issues, the cutting tools often display variation in the tooth's or in its geometry due to which axis does not coincide and in result chip load on every tooth varies systematically. Variation

***Corresponding author:** Junaid Saeed, Department of Mechanical Engineering, Guangdong Ocean University, China, Tel: +8613025602029; Email: saeedjunaid10@hotmail.com Junaid.saeed@ucp.edu.pk

Received: October 24, 2018; **Accepted:** November 13, 2018; **Published:** November 20, 2018

Citation: Saeed J (2018) Influence of offset Magnitude e_c and Angular Location λ_c Different Parameters along with their Calibration Methods and Improvements: A review. Int J Adv Technol 9: 217. doi:10.4172/0976-4860.1000217

in chip load on every tooth means that the material cut by each tooth during machining operation is not same or non-uniform. Some teeth's will be cutting more material and some of them will be cutting less. And if there is non-uniform cutting then tool edge wear will start which will shorten the tool life and start producing the defective parts with poor surface finish. Due to this there would be increase in cutting force at some tooth's and decrease in cutting force at some tooth's. Uneven or abnormal cutting forces may cause self-excited or forced vibrations, shank and flute breakage of the cutting tool, increase of both thrust and radial force variation on the spindle bearings and on the cutting tool thus decreasing the cutting tool and spindle life along with other elements as well, increase of cutting temperature and many factors as well.

All these affecting reasons and especially not the fulfillment of market demands just because of critical parameter eccentricity or run out create a sense of further research or study this topic in order for the decrement through different mechanical or technical techniques.

Literature Review

Hekman and Liang [1] proposed an on-line approach for the check of cutter run out in end milling due to its adverse effect on the work piece surface quality along with productivity and tool life. The access they used for this study was the time-dependent spectral analysis of cutting force for the estimation of cutter run out geometric characteristics, offset magnitude e_c and angular location λ_c because it will create a cutting force component at the spindle rotational frequency. In the experimental way or mechatronic way, dynamometer was used for the measurement of instantaneous cutting force and was placed between the work piece and machining table along the feed direction for different cutting conditions such as keeping the feed rate constant with the change in the depth of cut or changing the feed rate by keeping the depth of cut constant for different types of milling methods such as up milling or down milling. The cutting force component at the spindle frequency was used to determine the run out offset magnitude and angular location. It showed that sudden change in feed rate cause a spike in magnitude curve and then settled down and run out magnitude increases with the increase in the depth of cut means run out parameters vary in result of the different cutting conditions. The result of their study were that they provide chances for feed-back control of run out through in process monitoring with a priori knowledge of the tool geometry, machining configuration and etc.

Zheng, Li, Wong and Nee [2] presented the new approach in face milling based on predictive machining theory for the theoretical modelling and simulation of cutting forces in the presence of run out. By following the machining theory the aspect of milling cutter was developed as the simultaneous actions of a number of single-point cutting tools. In the model, the effect of cutter run out on the variation in chip load and effect of irregular cutting on the temperature was taken into account for the study. The cutting forces in milling can be envisioned by, according to the tooth geometry, work piece material, type of milling and especially the cutting conditions. The behavior of work piece material was taken as a function of temperature, strain and etc. in the cutting region and a window based simulation system was used for the computation of cutting forces. It reads different parameters which are inputted such as type of milling, material properties and etc. and then manipulate simulation and gives the cutting forces as an output against the cutter rotation. After this different experiments were done on Makino CNC milling and two force component dynamometer was used for the measurement of cutting forces for different cutting conditions with two and four fluted milling cutter. Finally both experimentally and simulated results were compared together with and without the effect of cutter run out and two tooth cutter showed more good relation as compared to four tooth's in case of with effect of cutter run out.

Yun and Chu [3] proposed an upgraded method for the finding of 3D cutting force co-efficient and cutter run out characteristics or parameters regardless of the cutting conditions and milling cutter rotation angle for a given work piece and cutter. The methodology was about the computation of different parameters like uncut chip thickness and synchronization. Cutting forces and run out parameters obtained by uncut chip thickness model and mechanistic cutting force model through simulation was compared with experimentally determined data for different cutting conditions by using the high speed steel (HSS) end mill cutter having four flutes, 10mm in diameter in a vertical machining center and the material of the work piece was aluminum 2014-T6. Moreover this method granted the approach that by using only measurement of cutting force, run out related parameters offset magnitude and angular location can be estimated and by comparing, this method shows better agreement than the method existing before. Based upon their study they concluded that synchronization was an effective method for obtaining the run out parameters and cutting forces.

Wang and Zheng [4] presented the analytical method for the in-process identification of offset geometry through the milling forces with the priority knowledge of cutting force co-efficient. The milling force basically consists of two force components, linear shearing force component and constant plow force component which were having direct relation or proportional to chip thickness with the effect of cutter run out. The Fourier transforms analysis and convolution integration of these force components was done which declared the offset geometry along with the formulas. The proposed method which was used for the identification was validated and tested through numerical simulation results and experimentation. The influence of cutting depths, feed per tooth and the use of two components signal were discussed along with suggestions e.g. for the cutter having N-flutes, the radial depth of cut should be greater than 0.5R and etc. This method required only two cutting tests along with the calculation of two algebraic equations. On testification, it showed good agreement with both numerical simulation and experimentation.

TL Schmitz, Jeremiah C, Eric M and Michael FT [5] explored the act of cutter eccentricity on cutting forces and exterior contour. This study was motivated by the examination that local cutters contained variation in their tooth due to which it can cause failure at the edge and increase the surface roughness of the work piece. They carried out time-domain milling simulation by defining different cutting parameters such as radial and axial depth of cut and etc. and also different experiments were performed for measuring the milling forces by using the air bearing capacitance probe, surface finish was measured by Wyko NT 1000 non-contact interferometric profiler. Than testification was done by comparing simulation results with the experimental results and both showed better agreement. They concluded that there would be decrease in the surface roughness value if the run out is varied for the constant feed per tooth (Figure 2).

Wan, Zhang, Qin and Tan [6] conferred the most advanced and efficient method for the calibration of run out characteristics and instantaneous cutting force co-efficient in end milling for end mills such as bull nose, ball, cylindrical and etc. The total cutting forces they calculated from the mechanistic cutting force model was detached into two components, one was the nominal component which was

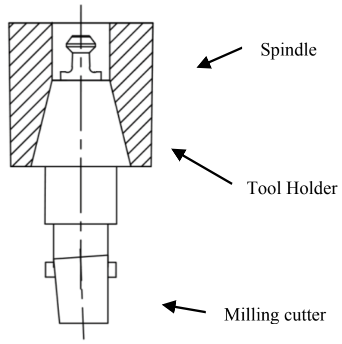

Figure 2: Sample of the milling cutter eccentricity.

independent of the cutter run out and the other was perturbation component which was induced by run out. Cutting force co-efficient was calibrated by using the nominal component whereas run out was spotted from the perturbation component and cutting force co-efficient calibrated through nominal one. Experiments were performed to check the validity of the proposed method and for that twelve tests were carried out for the different machining conditions such as radial and axial depth of cut, RPM and feed per tooth for different types of millings for different types of cutter. Finally they stated that the cutting force model which was calibrated agreed better with the experimental one and its advantage was that the calibration performed for one cutting test can be readily applied for numerous amount of cutting conditions.

Wan and Zhang [7] discussed five different methods for the calibration of cutting force co-efficient and cutter run out in peripheral type milling. Some methods are originally developed with optimization idea and some are taken from previous researches for comparison in order to ensure the effectiveness of present method. For that, mathematical expressions through derivations and the procedure were carried out on the measured cutting forces whereas in some methods cutting force co-efficient were assumed as constant values and in some methods it was taken as a function of instantaneous uncut chip thickness. Experimental verification was also done and for that three down milling tests were organized for different cutting conditions by using the carbide flat end mill having three flutes with a helix angle of 300 and 16mm in diameter and all tests were carried out without coolant on the work piece material Al7050. For the validation, both theoretical and experimental results were compared and it was found that the methods in which influence of cutter run out was taken into account, they was having high calibration accuracy. The methods which were carried out through optimization method become more efficient.

Wan, Zhang, Dang and Yang [8] given the new and simplified approach and used the instantaneous cutting forces rather than using average measured forces for the calibration of run out parameters and cutting force co-efficient for cylindrical type end milling. Other researchers just did derivations in XYZ coordinate system for a two fluted ball end mill whereas in this paper mathematical derivations were carried out by developing a mathematical accord between instantaneous cutting forces and instantaneous uncut chip thickness for the general calibration procedure through mechanistic cutting force model in which cutting force co-efficient were taken as the power functions of IUCT (Instantaneous uncut chip thickness) in cylindrical type milling with random numbers of teeth in radial-tangential coordinate system. Moreover, all derivations were based on radial, tangential and axial cutting force components transformed from the forces measured from the Cartesian coordinate system whereas the transformation makes the procedure easy and simple and also after coordinate transformation the cutting forces which are measured can be directly used for the calibration, no need to separate first as others did. Experiments were performed for different cutting conditions but with some limitations like small depth of cut means up to 1-2mm etc. for carbide cutting tool and Al7050 work piece material and etc. Than the experiments and theoretical run out geometric parameters and cutting force co-efficients were compared and good agreement both in shape and magnitude were obtained. Only one cutting test is required for the calibration over a wide range of cutting conditions through this method.

Cifuentes, Garcia, Villasenor and Idoipe [9] did the dynamic analysis for the correction of cutter run out or to diminish its effects in milling due to uneven cutting forces, decrease in tool life, having bad impact on machined surface quality and etc. This process was carried out by the modification of chip thickness by means of the fast correction of the cutter feed rate and the modification of feed rate was done with fast feed drive system (FFDS) which was driven by piezoelectric actuator. For the dynamic analysis of run out, simulation and experiments were done along with testification which shows good relation in between and moreover this paper indicated effectiveness and benefits of the new methods by controlling the run out through the modification method.

Irene, Joan and Hernan [10] conferred the role of eccentricity, feed and helix angle on the exterior contour which was obtained in side milling by using cylindrical tools. For their study, a model was created and numerous numbers of experiments and measurements were done along with simulation for one specific tool which was having eccentricity and grinding errors for different helix angles, for finding out the effects of different parameters on surface topography. The results were like if the feed per tooth increases then more cutting teeth's will leave lines on the surface of the work piece and if eccentricity increases then examination was that, cutting edge marks per revolution was lower or three. If the both grinding errors and eccentricity are high then this may lead to two cutting edge marks per revolution means lower and the presence of roughness heterogeneity bands is remarkable. It was noted that the profile of surface roughness does not alter if the helix angle is not considered and if considered with both high grinding errors and eccentricity than roughness heterogeneity bands were seen. More helix angle, the distance between the heterogeneity bands become less.

Liu, Wu, Li and Tan [11] did case study on the spectral characteristics of milling cutting forces with cutter wear and eccentricity for the end mill having four flutes because the influence of different parameters such cutter wear, cutter eccentricity and chip load on cutting forces was same so in order to differentiate them from each other this study was carried out. Simulation method and amplitude spectra for every possible phase spectrum of cutting force such as under neither wear nor eccentricity, both wear and eccentricity, only eccentricity and etc. for one tooth happened by wear were studied. Then experiments were performed on milling and the relationships between different parameters and amplitude of force were inspected and the experimental results were compared with simulation and amplitude spectra. In comparison, it was found that both showed good agreement with each other. Their study given a boldness of recognizing the cutter eccentricity, wear with force itself.

Qingyuan Cao, Jun Zhao, Yueen Li and Lihong Zhu [12] proposed the experimental and theoretical study that how cutter eccentricity geometric parameters, offset magnitude e_c and angular location λ_c influence the cutting forces by surrounding with different factors such as chip thickness, rotation angle and etc. along with their models in multi-axis CNC milling centers by using the ball-end mill. Simulation was done for different parameters like rotation angle etc. with the act of cutter eccentricity geometric parameters on it and moreover, they verified their model through plentiful experiments in different aspects for different parameters and by using the dynamometer for the measurement of cutting forces observed that e_c affects the value of cutting forces whereas the λ_c cause the delay phenomenon of the cutting forces. Theoretical analysis of cutting forces while taking into account the effect of cutter eccentricity more especially the effect of λ_c agreed better with the measured forces instead of without taking into account (Figure 3).

Uysal, Karaguzel, Budak and Bakkal [13] projected the aspect of cutter eccentricity on tool wear and machined surface quality for different cutting conditions by cultivating an extensive geometric process model which consists of chip geometry and cutting force calculations for orthogonal turn-milling operations. The reason behind their selection for this machine was that it consists of both turning and milling centers and also provides the benefit for lower cutting temperature, higher process efficiency and etc. Experiments were performed for different random inserts and tool wear was measured with Nanofocus μ surf 3D profilometer whereas surface roughness was measured with Mitutoyo portable surface roughness tester. The results were like for the standard inserts if the eccentricity is increased the surface roughness decreases and for the wiper inserts if eccentricity increases surface roughness also increases because it decline the tool-work piece engagement length. In case of tool wear when the eccentricity is at optimum level then engagement length between tool and work piece is maximum and provide uniform loading due to which tool life increases. When eccentricity is at higher level than tool-work piece engagement length decreases which means only the side edges will take part in cutting and non-uniform distribution of cutting load leads to premature wear along with decrease in tool life.

Zhu, Yan, Peng, Duan, Zhou, Song and Guo [14] bestowed the cutting edge element moving (CEEM) method for the forecasting of instantaneous uncut chip thickness (IUCT), to differentiate work piece/cutter engagement length and to pretend the five axis machining cutting force while taking into account the cutter run out for the end mills. This method was introduced because of the increment in the machining parameters due to the change in cutter position and the unavoidable eccentricity between the spindle and end mill. For the solution of this problem they introduced CEEM method and this method was figure out by parametric expression of coordinate transformation matrix and feed vector and then fix to three sub models which were cutter run out, cutter position and cutter position change. After this, the cutter run out characteristics, and cutting force co-efficients were calibrated through different cutting tests and dial gauge method. The methods they presented in order check the effectiveness of projected method were inclined axis cutting tests for bull nose mill and cylindrical face-milling test for ball end mill and etc. and its decomposition method. Analysis was done of the decomposition model related to cutter position and changeable speed, the influence of changing of cutter position to cutting forces were estimated and may be used for the mentor of feed rate outlining. The major contribution was the modelling of cutting force, feed rate models about cutter position, change of cutter position and etc. for five axis end milling for the decrement of cutting parameters.

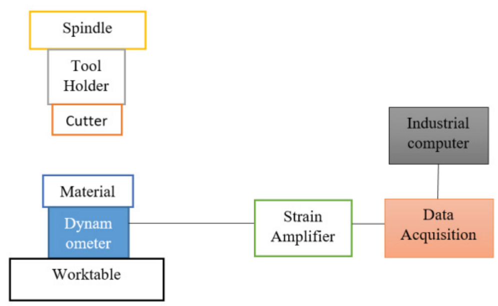

Figure 3: Measurement setup for the cutting forces.

Budak and Bakkal [13] given out the analytical model for the evaluation of the role of cutter run out on the cutting forces due to the accompanied of milling operations by the cutter run out of the cutter cutting edges which was basically persuaded by the clamping deviation or clamping error in between different machining elements such as between tool and spindle. This model was necessary to be carried out because of the non-uniform forces automatically applied on all the tooth's of the cutter due to run out and finally it causes the intermittent wear at the edges thus reducing the tool life. Accordingly, the cutting force modelling while considering the run out is very important in order to have the milling operations properly. So in the force model they presented, 3D chip flow in milling is elucidated as the piling up of the orthogonal cutting in the cutting velocities plane and chip flow velocities plane. The purpose for noting down the direction of chip flow was minimizing of cutting forces. The cutting force applied on each edge of the cutter tooth was simulated with the rotation angle of the edge. After this the experimental analysis was carried out by performing different experiments with different conditions in order to check the validity of the method they presented. During the experimentation the measurement of cutting forces was done with the cutter run out and then testification was done between simulated cutting forces and measured forces which show the good agreement.

Materials and Methods

The methods which were followed to explore the effects of cutter eccentricity on different parameters such as on cutting forces, surface finish, tool wear, chip load and etc. are theoretical analysis in terms of spectral characteristics of milling forces with simplified milling force model, process models which consists of chip geometry and cutting force calculation, time-domain simulation method and development of computational programme for the simulation to study the eccentricity effects on surface finish, rotation angle model with the effect of angular location offset vector λ_c, chip thickness model with the effect of offset magnitude e_c and etc. Experimental analysis through performing numerous number of experiments under different cutting conditions on different machines such as orthogonal turn-milling machine, DMU-70V vertical machining center and etc. with the different types of milling such as up milling or down milling in face milling, side milling, peripheral milling, cylindrical milling and etc. Different instruments were used for the measurement of different parameters during experiments such as two force component and three force component dynamometers for measuring cutting forces, roughness stylus profilometer for measuring surface roughness, Nanofocus μsurf 3D profilometer for measuring tool wear and etc. Different types of milling cutters were used having 2 flutes, 3 flutes, 4 flutes, 6 flutes and etc. The materials used for milling cutters were high speed steel, carbon steel, carbide steel and etc. along with work piece materials AISI/P20, hardened steel WNr 1.2344, AISI 1050 steel and etc. At last comparative study was done between theoretical and experimental to check the validity of presented methods. The methods which were pursued for studying the role of cutter run out on different parameters, efficient calibration and determination of cutter run out and cutting force co-efficients were theoretical analysis in terms of implementation of different methods, different theories such as chip flow theory, predictive machining theory and etc. through mechanistic cutting force models proposed by different researchers and for the in-process monitoring of cutter run out analytical formulation methods were used such as Fourier transformation, convolution integration and etc. The dynamic analysis for the fast correction of cutter run out was done with Fast feed drive system (FFDS) driven by piezoelectric actuator. Experimental analysis was carried out by using the same instruments such as dynamometer and etc. by using the same tool material, flutes and geometry according to the requirements on the different types of work piece materials such as Al 7050 and etc.

Discussion

Many researchers performed different types of theoretical analysis and experimental analysis and finally comparison was done in between theoretical and experimental results to check the validity of proposed method. In earlier, when this critical parameter was considered it was very difficult to control this because at that time there was not so much highly accurate machines and techniques but day by day the new and easy techniques were introduced for the minimization of the effect of geometric parameters such as in 1996, on-line or in process monitoring of cutter run out was done through time dependent spectral analysis of cutting forces with the priority knowledge of co-efficients and for comparison more tests were needed whereas in 2003, Wang did the theoretical analysis through convolution integration and Fourier transformation without the priority knowledge of co-efficients and for comparison only two tests were needed. In 2010, Cifuentes did the dynamic analysis of cutter run out and introduced the new Fast Feed drive system through which cutting forces, chip load and etc. parameters can be controlled easily with the variation in the feed rate. Researchers worked on these parameters by studying its role on surface topography, milling forces, tool wear and etc. and proposed the new calibration procedures for the cutter run out by amending different cutting force models. This all was just because of implementation of modern techniques and researchers found the cutting conditions and manufacturing processes through which we can decrease this parameter.

Conclusion

It has been observed that due to the detracting geometric parameters offset magnitude and angular location vector, the machining system and machining parameters goes through severe conditions such as uneven cutting forces applied on all the tooth's just because of different chip load or thickness which causes the premature tool wear from the tooth's and finally tends to decrease the tool life along with the work piece having poor surface finish, inaccuracy and not precise in dimensions. The most important is that market demands can't be fulfilled because eccentricity or run out characteristics are directly proportional to the cutting forces and excessive level of cutting lead the process along with everything to failure. So by keeping all things in mind perfect models should be developed with appropriate cutting conditions and good quality manufactured cutting tools should be used and according to cutting conditions the material of cutting tools is very important to be considered. Moreover during fitting of tool holder or tool in spindle, it should be cleaned properly in order to avoid loss and to decrease the geometric parameters effect because it can't be fully removed from the system.

References

1. Keith A, Hekman, Steven YL, George W (1996) InProcess monitoring of end milling cutter run out. Mechatronics 7: 1-10.
2. Zheng HQ, Li XP, Wong YS, Nee AYC (1999) Theoretical modelling and simulation of cutting forces in face milling with cutter run out. Int J Mach Tool Manu 39: 2003-2018.
3. Yun WS, Cho DW (2000) An improved method for the determination of 3D cutting force coefficients and run out parameters in end milling. Int J Adv Manuf Technol 16: 851-868.
4. Wang JJJ, Zheng CM (2003) Identification of cutter offset in end milling without a prior knowledge of cutting coefficients. Int J Mach Tool Manu 43: 687-697.
5. Schmitz TL, Couey J, Marsh E, Michael FT (2004) Investigating the role of cutter eccentricity on surface finish and milling forces. Proceedings of IMECE.
6. Wan M, Zhang WH, Qin GH, Tan G (2007) Efficient calibration of instantaneous cutting force co-efficient and run out parameters for general end mills. Int J Mach Tool Manu 47: 1767-1776.
7. Win W, Zhong WH (2009) Systematic study on cutting force modelling methods for peripherals milling. Int J Mach Tool Manu 49: 424-432.
8. Min W, Zhang WH, Dang JW, Yun Y (2010) A novel cutting force modelling method for cylindrical end mill. Appl Math Model 34: 823-836.
9. Cifuentesa ED, Garciab HP, Villasenora MG, Idoipec AV (2010) Dynamic correction of run out in milling.
10. Corral IB, JV Calvet, Hernan GR (2011) Influence of feed, eccentricity and helix angle on topography obtained in side milling processes. Int J Mach Tool Manu 51: 889-897.
11. Liu C, Jing-quan W, Guang-hui L, Guang-yu T (2013) Frequency-spectrum characteristics of force in end milling with tool wear and eccentricity. Int J Adv Manuf Technol 67: 925-938.
12. Qingyuan C, Jun Z, Yueen LI, Lihong Zhu (2013) The effects of cutter eccentricity on the cutting force in the ball-end finish milling. Int J Adv Manuf Technol 69: 2843-2849.
13. Emre U, Umut K, Erhan B, Mustafa B (2014) Investigated eccentricity effects in turn-milling operations. 6th CIRP International Conference on High Performance Cutting.
14. Zhu Z, Rong Y, Fangyu P, Xianyin D, Lin Z, et al. (2015) Parametric chip thickness model based cutting forces estimation considering cutter runout of five-axis general end milling. Int J Mach Tool Manu 101: 35-51.