IMPROVING OBTAINABLE ACCURACY AND SURFACE QUALITY OF MILLED FREEFORM SURFACES

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Abstract. The process of machining of various freeform, or geometrically complex, surfaces, including dies, moulds, blades, etc. is not only a complicated, but also time-consuming process nowadays. Freeform surfaces machined on modern equipment apply ball-end and chamfered-end milling using either constant tool pitch for rectilinear and angled surface profiles or varying tool pitch for non-uniform surfaces. Various strategies and technologies of ball-end and chamfered-end milling at either a constant tool pitch for even and oblique surfaces or a variable tool pitch for freeform surfaces is required to improve the surface quality, viz. surface roughness, size tolerance and form shape before final machining steps. A classification of parts containing freeform surfaces is offered in the paper, which is followed by the table containing recommended set of machining stages with reference to obtainable surface accuracy and quality. The given recommendations can be used in further researches of ball-end milling and applied in practice during machining freeform surfaces.

Key words. text, text, text, text, text, text, text, text.

1. Introduction

The process of machining of freeform surfaces, e.g. moulds, dies, blades, is one of the most time-consuming and complicated cutting processes. Parts containing such kind of surfaces are applied in aerospace [1,2], automotive [1,2], die mould [1,2,3], biomedical [1,2] and other branches of industry. To produce freeform surfaces, 3 to 5 NC milling machines are used [1,2,3,4,5]. The tools used to produce freeform surfaces are ball-end and chamfered-end mills [1,2,4,5]. The tool path generation is chiefly based on tool path computation, so, in general, tool path consecutiveness is not optimum. The sequence is, the CAM preparation for complex surfaces requires up to 50-fold time of that of the whole manufacturing process. One of the most important factors in producing freeform surfaces is cutting force, which influences the surface topology, which, in turn, results in surface quality and roughness. The tools produced for machining such surfaces are ball-end mills. It is known [4,5,6,7] that the shape of the initial surface and that of the final one are different in configuration, so big amount of bulk material is subject to removal during machining. The final surface with specified surface and form accuracy and surface roughness can only be obtained by polishing [8,9]. Hence, many factors must be taken into consideration. There exist many techniques describing freeform surfaces, including advanced mathematical methods [10,11,12,13] yet no work containing their classification has been proposed so far, although such classification is very necessary when elaborating machining strategy. Many works describing freeform surface machining gave special emphasis on speed [14,15], tool geometry [5,6,16,17,18], surface geometry [3,4,8,19,20,21] machining strategy [22,23,24], tool deflection [4,5,7,23,24], tool wear [14,17,24], surface roughness [14]. There is no denying, however, that decomposition of technological process of machining freeform surfaces into certain stages is a necessary step in writing a workable NC program which, in its turn, influences the total time of process design.

Parts with freeform surfaces contain various integrated sections of surfaces with various geometrical shapes. Each section has its own geometrical parameters, which, in turn, influence shape and size errors. Shape error is the deviation between the actual and the nominal surfaces. Size error is the deviation between the actual and the nominal size.

2. Technical specification of freeform surfaces

A characteristic feature of virtually all freeform parts used in engineering production (including parts of dies and molds) is rigid specification of the machined surface accuracy and roughness, viz.:

dimension tolerance is IT5 to IT11;

hole coaxiality tolerance is half of the size tolerance of the smaller (smallest) hole;

circularity tolerance is 0.3 to 0.5 of the hole size tolerance;

cylindricity tolerance is 0.3 to 0.5 of the hole size tolerance;

positional tolerance is 0.015 to 0.280 mm;

hole axes parallelism tolerance is 0.02 ... 0.05 mm at the length of 100 mm;

perpendicularity tolerance of the end surfaces with reference to the hole axes is 0.01 ... 0.05 mm at the length of 100 mm;

other form, location and interrelation tolerance specifications, viz. axis misalignment tolerance of the hole axes, perpendicularity tolerance of the hole axes, straightness tolerance, flatness tolerance, parallelism tolerance of the surfaces with reference to the hole axes, etc.;

surface roughness is Ra 0.63 for IT 8 to IT11; Ra 0.4 to Ra 0.25 for IT6; Ra 0.03 to Ra 0.05 for IT5.

A wide variety of parts containing freeform surfaces used in machine building requires systematization. Based on various sources, the systematization of dies, moulds, metal models, etc. of freeform parts is performed (see Table 1).

Table 1. Font styles for a reference to a journal article.

Equipment group	Part	Functional surface accuracy, IT	Functional surface accuracy, IT
Cold sheet-metal dies	Bending and forming dies		
	Die punch	IT8	Ra 0.32…0.63
	Die mould	IT8	Ra 0.32…0.63
	Cupping dies		
	Die punch	IT6…8	Ra 0.32…0.63
	Die mould	IT6…8	Ra 0.32…0.63
	Embossing dies		
	Die punch	IT6…8	Ra 0.32…0.63
	Die mould	IT6…8	Ra 0.32…0.63
Cold forging dies	Cold extrusion dies		
	Die punch	IT8	Ra 0.08…0.16
	Die mould	IT8	Ra 0.08…0.16
	Cold extrusion dies		
	Die punch	IT8	Ra 0.08…0.16
	Die mould	IT8	Ra 0.08…0.16
Hot forging dies	Hammer dies	IT9…14	Ra 0.16…2.5
	Hot forging crank-driven press dies	IT9…14	Ra 0.16…2.5
	Horizontal forging machine stamp dies	IT9…14	Ra 0.16…2.5
Pressure casting dies	Die punch	IT8	Ra 0.08…0.16
	Die mould	IT8	Ra 0.08…0.16
Casting dies	Die punch	IT8	Ra 0.08…0.16
	Die mould	IT8	Ra 0.08…0.16

The qualitative characteristics of dies' working surfaces, viz. accuracy, roughness, waviness, influence the quality of the stamped, extruded, pressed and die-cast parts.

The examination of the data displayed in Table 1 leads to the conclusion that freeform surfaces of dies have accuracy ranging between IT6 and IT14. The comparative study of various sizes reveals that the numerical values of the size tolerances range between 0.01 and 0.5 mm.

The examination of the reference information allows us to split the entire range of tolerances of freeform surfaces into 4 subranges with reference to a respective machining stage: rough machining, semifinish machining, finish machining and polishing (see Table 2).

Table 2. Surface roughness obtained at milling.

Equipment group		Adequate machining accuracy, mm		
Surface asperity class	Adequate surface roughness, Ra	0.05…0.12	0.12…0.3	Over 0.3
11	0.08	Polishing	Polishing	Polishing
10	0.16	Polishing	Polishing	Polishing
9	0.32	Finish machining	Finish machining	Finish machining
8	0.63	Finish machining	Finish machining	Finish machining
7	1.25	Finish machining	Semi-finish machining	Semi-finish machining
6	2.5 (Rz10)	Finish machining	Semi-finish machining	Semi-finish machining
5	5 (Rz20)	Finish machining	Semi-finish machining	Rough machining
4	10 (Rz40)	Finish machining	Semi-finish machining	Rough machining
3	20 (Rz80)	Finish machining	Semi-finish machining	Rough machining

Rough machining strokes at milling of freeform surfaces are mainly used to remove the maximum metal surplus and, thereby, to approximate the workpiece's shape to the specified finished part's shape. Finish machining strokes obtain the specified size accuracy and, generally, shape accuracy. If the specified finished part's shape is not obtained after the rough machining there are added several strokes specified as semifinish machining strokes. Polishing is a process of removing of thin metal layers after finish machining in order to obtain the specified shape accuracy and surface roughness.

3. Factors affecting working inaccuracy

The main performance criteria of the parts with freeform surfaces are the accuracy and the roughness of working surfaces.

To obtain the surface accuracy and roughness specified on a drawing, it is necessary, primarily, to consider the most influencing processing quality factors, and, secondly, to reduce, where possible, their influence in order to reduce processing errors.

The total processing error can be divided into two main components: the error caused by the technological system (TS error) and the error caused by the CNC system (CNC error).

The data examination displays that the TS error exceeds 60% of the total processing error. The TS error can be, in turn, subdivided into the following components:

error caused by geometric inaccuracies, e.g. inaccuracies of the machine-tool;

error caused by elastic deformations, viz. mutual elastic deflections of the tool and the workpiece;

error caused by rapid processes, viz. vibrations, transient processes in the machine drive, cutting area and the CNC system;

error caused by medium-speed processes, viz. tool wear, thermal deformation;

error caused by slow processes, viz. workpiece buckling, aging.

The CNC error, respectively, can also be subdivided into the following components:

programming error, viz. rounding, approximation, precorrection errors in the NC program;

machine setup error, viz. machine zero point setup and off-line tool setup error;

positioning error, viz. operating device coordinate location error;

tool-changing error at multi-tool machining.

4. Conclusions

The given article has observed the classification of parts containing freeform surfaces, presented the classification of operating steps, classification of machining errors. Based on the given tables, the further researches [25,26] allow us to reduce the most influencing errors and, as a result, to improve the freeform surface accuracy and roughness.

References

1. G. He, W. Ma, G. Yu, A. Lang, Modeling and experimental validation of cutting forces in five-axis ball-end milling based on true tooth trajectory, International Journal of Advanced Manufacturing Technology, **78**, 189-197 (2015).
2. Y. Boz, H. Erdim, I. Lazoglu, Modeling cutting forces for five axis milling of sculptured surfaces (Conference Paper), Advanced Materials Research, **223**, 701-712 (2011).
3. T. Ko, H. Kim, S. Lee, Selection of the Machining Inclination Angle in High-Speed Ball End Milling, The International Journal of Advanced Manufacturing Technology, **17**, 163-170 (2001).
4. M. Kang, K. Kim, D. Lee, et al., Characteristics of Inclined Planes According to the Variations of Cutting Direction in High-Speed Ball-End Milling, The International Journal of Advanced Manufacturing Technology, **17**, 323-329 (2001).
5. W. Ji, X. Liu, L. Wang, et al., Research on modelling of ball-nosed end mill with chamfered cutting edge for 5-axis grinding, The International Journal of Advanced Manufacturing Technology, **87**, Issue 9, 2731–2744 (2016).
6. H. Ghariblu, S.J. Abedi, A new layered manufacturing machine with cutting force analysis in tapered end milling, Journal of Mechanical Science and Technology, **28**, 3087-3093 (2014).
7. N. Zeroudi, M. Fontaine, Prediction of tool deflection and tool path compensation in ball-end milling, Journal of Intelligent Manufacturing, Volume **17**, 3 (2013).
8. J.-K. Seong, Gershon Elber, J.K. Johnstone, Myung-Soo Kim, The Convex Hull of Freeform Surfaces, Computing **72(1)**, 171-183 (2004)
9. D. Berestovskyi, W.N.P. Hung, P. Lomeli, Surface Finish of Ball-End Milled Microchannels (2014)
10. Luca Pagani, On the characterisation of freeform surfaces, (2012)
11. Yi-Jun Yang, Wei Zeng, Xiangxu Meng, Conformal freeform surfaces, Computer-Aided Design **81** (2016)
12. Aysu Berk, Harry Giles, Quadrilateral panelization of freeform surface structures, Automation in Construction **76**, 36-44 (2017)
13. Johannes Stock, Anika Broemel, Johannes Hartung, Dennis Ochse, Herbert Gross, Description and reimplementation of real freeform surfaces, Applied Optics **56(3)**, 391 (2017)
14. H. Onozuka, K. Utsumi, I. Kono, J. Hirai, Y. Numata, T. Obikawa, High speed milling processes with long oblique cutting edges, Journal of Manufacturing Processes, **17**, 95-101 (2015).
15. M K. Dikshit, A. B. Puri, A. Maity, Analysis of cutting force coefficients in high-speed ball end milling at varying rotational speeds, Machining Science and Technology **21(3)**, 416-435 (2017)

16. B. Mikó, J. Beňo, Effect of the working diameter to the surface quality in free-form surface milling (Conference Paper), Key Engineering Materials, **581**, 372-377 (2014).
17. Chung-Liang Tsai, Yunn-Shiuan Liao, Prediction of cutting forces in ball-end milling by means of geometric analysis, Journal of Materials Processing Technology, **205**, 24-33 (2008).
18. N. Guillemot, B. K. Mawussi, C. Lartigue, et al., A first approach to characterize the surface integrity generated by ball-end finishing milling, The International Journal of Advanced Manufacturing Technology, **64**, 269-279 (2013).
19. Q. Cao, D. Xue, J. Zhao, et al., A cutting force model considering influence of radius of curvature for sculptured surface machining, The International Journal of Advanced Manufacturing Technology, **54**, 821-835 (2011).
20. L. Geng, P.L. Liu, & K. Liu, The effect of curvature radius of sculptured surface on finish milling tool path selection, The International Journal of Advanced Manufacturing Technology, 1-9 (2016).
21. S. Wojciechowski. The estimation of cutting forces and specific force coefficients during finishing ball end milling of inclined surfaces, International Journal of Machine Tools and Manufacture, **89** (2014)
22. Y. Quinsat, L. Sabourin, Optimal selection of machining direction for three-axis milling of sculptured parts, The International Journal of Advanced Manufacturing Technology, **33**, 684-692 (2007).
23. Zhongtao Fu, Wenyu Yang, Xuelin Wang, J. Leopold, An analytical force model for ball-end milling based on a predictive machining theory considering cutter runout, International Journal of Advanced Manufacturing Technology, **84**, 9-12, (2015).
24. K. Kasahara,·K. Ohtaka, S. Ito, A. Hirota, Influence of Tool Tilting Angles on Cutting Forces and Tool Deflection in Ball End Milling (3rd Report), Journal of the Japan Society for Precision Engineering, **80**, 209-213 (2014).
25. A. Vyboishchik, Modelling Topology of Freeform Surfaces with Ball-end Milling, Procedia Engineering, **150**, 761-767 (2016)
26. A. Vyboishchik, The Influence of Dynamical Parameters on Surface Quality during Ball-End Milling, Procedia Engineering, **206**, 1029-1033 (2017).