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FRAGMENTATION OF TOOLING SURFACES TO ASSES QUALITY IN FREE-FORM MILLING

Jozef BEŇO[1], Peter IŽOL[2], Miroslav TOMÁŠ[3] Ján VARGA[4]
[1-4]Technical University Košice, Faculty of Mechanical Engineering
Mäsiarska ul. 74, 040 01 Košice, Slovakia
[1]jozef.beno@tuke.sk
[2]peter.izol.tuke@tuke.sk
[3]miroslav.tomas@tuke.sk
[4]jan.varga@tuke.sk

Abstract

In this paper, authors perform analysis of the free–form surface milling based on the fragmentation of the design elements which create active surfaces in tool making. Their analysis is based on fragmentation approach which makes the most of combining CAD, modeling and testing objects in tool making as well as selecting of the fragments with parts of free-form surfaces. Examples being introduced in this paper point out that it is volume based fragmentation of free–form surfaces which allows to combine CAD design of tooling parts, their modeling and producing in chosen scale as well as testing different milling strategies. Results also show that it is the Linear strategy of ball end milling which denotes desired compromise between machining time and surface quality when ball end milling fragments with different signed curvature radii.

Key words: tooling surface, design elements, fragmentation types, signed curvature, roughness parameters

1. Introduction

Tools for sheet forming and moulding have significant position in products innovation and reduction of their life cycle for determining product quality and accuracy. They include free–form elements and their active parts are produced by CNC milling which is the largest subject in this technology. State–of–the–art is very wide and can be categorised in six main fields listed hereinafter. The first field is surface design [1], [2] which employs basic features of free–form shape. Composition of the features allows generating complex surface being used in industry including tooling for sheet forming and plastic moulding. The second field is modeling and decomposition of free–form surfaces [3], [4] which applies division of product into fragments with parts of free–from surfaces. Fragments enable programming paths of ball end mill cutters which are based on orientation of any surfaces; such a methodology is applicable in design of moulds. The third field includes milling strategies and directions of tool path [5], [6] which consider machining time and dimension accuracy. Milling strategies assume elimination of the surface inaccuracy by means of topology data [7] and by tool edge contact with workpiece [8]. The fourth subject is programming of tool path and it represents topology and combining of tool motion and so–called CC points in tool path and CL points of cutter position [5]. To check surface inaccuracy, programming considers deformation of the cutter body [9]. Recently, influence of the plane-parallel and radial finishing trajectories on the roughness when milling spherical surfaces have been presented in [10] and [11]. The fifth field is performance of milling cutters as end mill and ball end mill, their performance is given by forces, tool body deformation and machined surface [12]. In moulding of plastics, combination of strategies, cutter diameter and way of milling do affect active surface [13]. Technology to produce sheet forming tools consists of division of active surfaces into fragments [14]. Finally, the last field is quality checking of active surface and critical spots of produced tooling. In fact that field combines following approaches: programming variable data as feed and spindle revolutions [15], surface texture simulation [16] and texture analysis in two directions [17]. To check true machined surface, 3D measurement of texture being dependent on feed and infeed is used [18]; however, digital analysis of texture due to various forms of contact between ball end mill cutter and workpiece is applied [19]. In analysis of quality of free–form surfaces, such approaches as 3D metrology [5], roughness figures [15], [16], surface texture and Abbot's curves [18], texture variation in two directions [10] etc., are employed. Performance of end mill cutters is expressed in terms of tool edge wear [12], [13] and cutting forces [9], [15].

State–of–the art includes design of tooling, manufacturability and preparation of free–form surfaces. Design of tooling is based on product shape and CAD/CAM while its manufacturability determines types of cutter. Cited sources deal few with production of tooling in whole, they include but surface fragments. Manufacturability of free–form surfaces is determined with milling strategies, tool path programs, ways of milling and cutter diameters. Recommendations to use a milling strategy are very common, result of producing such surfaces is not easy predictable. Thus tooling with free–form elements needs finishing of active surfaces. Reduction of surface finishing can enable "preparation" of active surfaces for tooling which include form and relief elements. Figure 1 explains sequence referred to "Preparation of active surfaces", i.e. fields 4, 5 and 6 listed above and that is given as a relationship among tooling, process (deformation, friction, viscosity, etc.) and contact/surface morphology being produced in free–form milling,

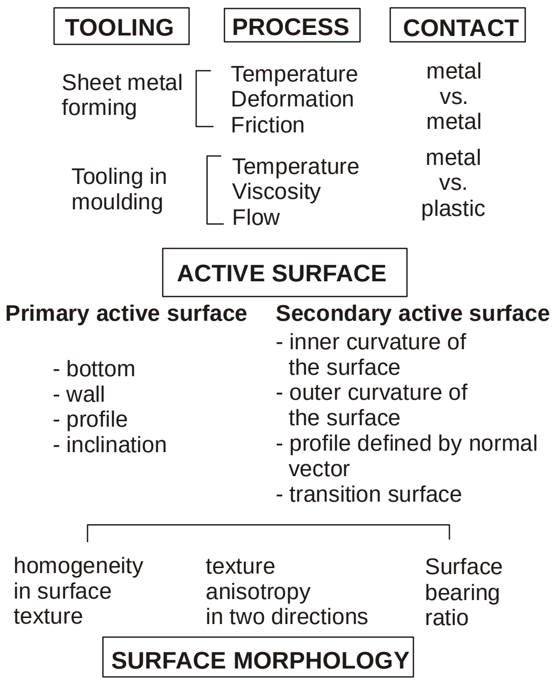


Fig. 1: A chain of the effects producing surface morphology when tool making

Tooling for sheet forming and moulding make form product through their active parts. There are few figures about how any active surface and its morphology affect on process of material shaping into product. State–of–the–art suggests, there is possible to create a morphology of active surfaces of tooling in such a way as they bear two marks. The first is morphology supporting process of shaping (sheet forming, moulding), the second mark is that CNC milling has to provide active surface requiring minimum of finishing or grinding. In order to reduce the need of finishing, process of free–from surface milling is proposed to study in terms of small fragments taken from real product and they are subsequently modelled in the different type of scale.

2. Meaning of the Tooling Fragmentation

In contrast to the traditional milling operations, free–form milling produces 3D surfaces by means of programming and milling strategies. Thus, any surface can assume different features being expressed through measured quantity as its texture, tolerance and surface layer properties, as well. Because of programming, cutting conditions as feed per tooth f_z [mm], depth of cut a_p [mm], side step a_e [mm] do vary, therefore, there is no possibility to express final quality of product in whole but in its fragment. Figure 2 shows an example of tooling part produce by different combination of design elements.

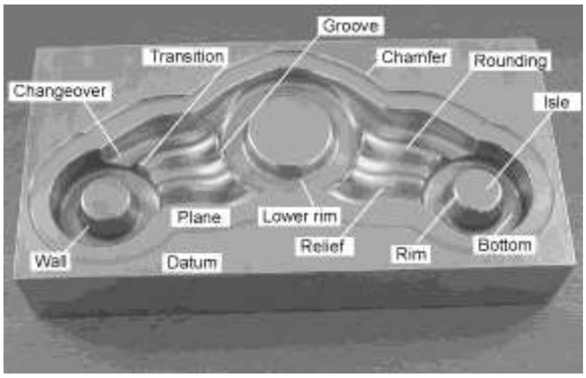


Fig. 2: Some design elements in tool making of the lower die: design attributes and elements with definite dimensions

Basically, such a design element can bear its typical attributes and that are mainly such notations as changeover, transition, relief, rim and rounding. All the five attributes allow wide variety of the shapes for not expressing any dimension or a distance and that are chamfer, groove, wall, isle, etc., the design elements consisting of definite dimension. Finally, such common elements as plane and datum also allow to use not only different milling strategies but they also are supposed to make a link among others design elements as e.g., plane – rim – wall, or as wall – bottom – relief, etc.

Manufacturing of the tooling shape in fig. 2, though, consists of different milling strategies which are expressed through programming instructions; therefore, checking of the final shape gives lack of measurability. In order to secure proper checking of the machined surface quality, there is only way of securing such measurability, the measurable fragments. Fragments are supposed to bear all the significant attributes in the free–form surface whereas they must be capable of identifying and measuring the active surface of tooling being expressed in fig. 1. In order to achieve such a surface checking, the fragmentation is introduced to analyse the fragments of the whole relief surfaces.

3. Methods, Materials and Results

Basic idea of free–form surface fragmentation is that a pattern is taken from the tooling entity, which can be further studied as a fragment of the surface or as a sample being produced in laboratory. This approach offers study of wide scale of effects as formulation of the surface parts as e.g., radii, their transition, datum in fig. 2 which replaces the parts of planes as bottoms, walls, etc. Because of wide varieties in fragmentation, three ways of expressing fragment shape are introduced below.

3.1 CAD Based Fragmentation

CAD based fragmentation of the free–form surface seems to be the feasible tool to investigate end ball milling process. Figure 3 shows process of fragmenting: a part of free form surface is transferred into virtual volume (mainly 100^3 mm^3) wherein such analyses as modelling and simulation of machining are used. CAD drawing of tooling part thus allows to take out the representatives of free form surfaces.

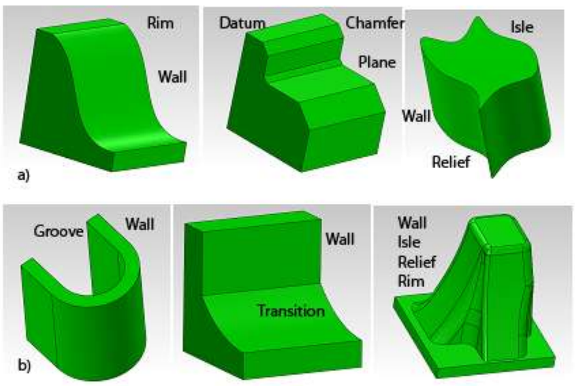


Fig. 3: CAD based fragmentation: attributes of the free form surface in tool making (a) Fragments based on measurability (b) Fragments based on combining of dimension

It means in fact that samples allows to identify feasible milling strategy as well as to make out modelled surface finish. Figure 4 indicates such a way of free form surface fragmenting making the most of applying calculation of the scallop height, the surface error, however, roughness models are based on sequence of milling operations in LINEAR Milling Strategy. In modelling of cusp height, roughing applies ball–end–mill cutter of diameter D=16 mm; semi finishing is modelled with D=10 mm and finishing results from D=6 mm.

3.2 Object Based Fragmentation

While CAD based fragmentation allows to identify wide variety of milling strategies and their effect on surface finish, results always need verifying. In principle, object based fragmentation represents the art of selecting an object which is included in the design of tooling and subsequently such an object is modelled in terms of different milling strategies.

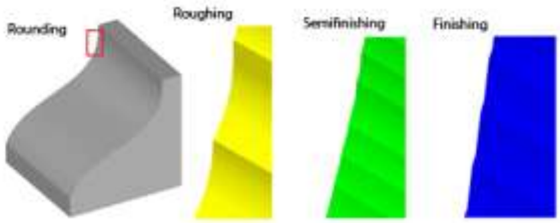


Fig. 4: CAD based fragmentation and sequence of producing resultant surface finish a case of the LINEAR strategy

Simple parabolic surface $y=30–0.048x^2$ was used to verify this approach whereas three kinds of milling strategy as SPIRAL, CONSTANT Z LEVEL and LINEAR were used to produce resultant surface finish. Commercial sintered carbide ball end milling cutter D=8 mm was used to machine AlCu4Mg alloy (feed per tooth f_z=0.03 mm, revolutions n=4900 1/min, side step a_e=0,5 mm, coolant: emulsion, machine tool EMCOMILL 155 with control unit Heidenhein TNC 426). Figure 5 illustrates an example of comparing CAD model with real machined object.

Fig. 5: An example of object based fragmentation: (a) CAD representation of the object defined by parabolic equation; (b) applying of the Spiral Milling Strategy to produce resultant surface finish

Table 1 shows data as the parameters of surface roughness (ISO 4287) which distinguish suitability of Constant Z level as the strategy reducing subsequent grinding and polishing, an isle/wall/transition parts according to the notation shown in fig. 2.

Table 1: Results of measuring surface texture parameters when ball end milling (Mitutoyo SJ 301)

Strategy	Linear	Spiral	Z level
Ra [μm]	2,19	0,58	1,69
Rz [μm]	9,78	9,78	9,78
Rt [μm]	11,71	11,71	11,71
Rv [μm]	5,74	5,74	5,74
Rp [μm]	3,96	3,96	3,96

3.3 Volume Based fragmentation

Two main dimensions create the idea of the Volume Based Fragmentation. The first dimension is 100^3 mm^3, a volume of a part of the product, either a part of tooling in fact as e.g., any die, or an entity as e.g., tooling in injection moulding. A volumetric segment, which is supposed to be of 10^3 mm^3, represent a fragment to measure machined surface roughness, such a dimension allows to replace a part of relief surface by a circle. In order to measure any surface roughness parameter in uniform way, two circumstances must be considered, the measurability and signed curvature radius, the former means explicit positioning of the sample. The latter must be considered in evaluation of the results for true relief surface bears the changes of their radii and that is signed curvature of radii, a fact must be considered in the measured data evaluation In Figure 6, such two circumstances are shown whereas measurability results from positioning of the fragment/sample at prismatic part known as Vee block.

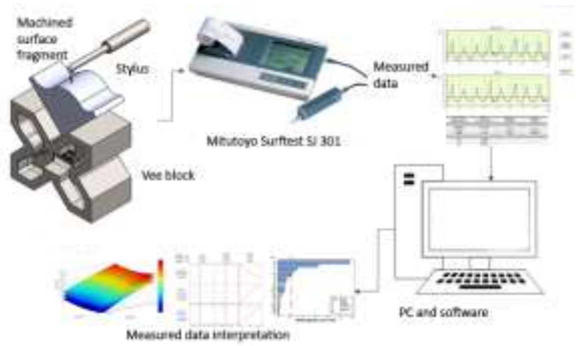


Fig. 6: Measurability of the surface roughness in Volume Based Fragmentation: a chain explains positioning of the fragment/sample of relief surface as well as processing of measured data

Figure 7 gives evidence about how milling strategy LINEAR is being investigated. Positioning of the machined surface in Vee block in fig. 7(a) shows that stylus moves along ridge lines and valley lines of the machined surface, the former means position of stylus in that of figure. If centre of a radius R which defines a part of relief surface is located within a sample, it represents positive signed curvature radius which is taken as k=1/R, a convex case of the signed curvature. Otherwise, the ratio k=–1/R represents the negative signed curvature, a concave case of the measured fragment: in other words said, the centre of the circle radius is located outside machined surface. Such cases of the signed curvature radii are shown in fig. 7(b) and their combination produces final fragment of the machined surface. Now, different milling strategies are applicable to such a fragment.

Experimental measurement were performed to identify effect of signed curvature k and cutting conditions on surface roughness parameters *Ra* and *Rz*. Commercial sintered carbide ball end milling cutter D=8 mm with number of flutes z=2 and helix angle 30 degree was used to machine AlCu4Mg alloy.

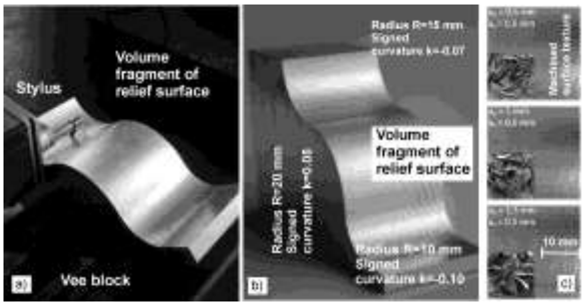


Fig. 7: Measurability of the relief surface fragment: (a) positioning of the fragment at the Vee block and different curvature radii measured in uniform way (b) volume fragment and related radii used in experimental measurements (c) surface texture and its changes as an effect of the depth of cut ap (milling strategy LINEAR, signed curvature k= –1/10 mm= –0.10 mm^{-1}, roughness range *Ra*=1.30–1.60 μm)

The samples included radii and signed curvatures according to the fig. 7(b) while L27 Taguchi design was used in experiments. Identical range of depth of cut ap and side step ae (a_p=0.5 – 1.5 mm, ae = 0.5 – 1.5 mm) were used in L27 Taguchi design while feed rate and spindle revolutions were v_f = 1500 mm/min and n = 5000 1/min; machine tool EMCOMILL 155 with control unit Heidenhein TNC 426. The L27 design was created by MiniTAB software and there is no need to explain its matrix here for returning evaluation instantly including relevance of results. The roughness parameters *Ra* and *Rz* were measured at the ridge/valley lines shown in fig. 7(a) and Taguchi L27 returned following statistical formulae:

$$Ra=0.58+k-1.71a_p+3.63a_e+12k^2+1.09a_p^2-0.50a_e^2+0.97k.a_p-1.69k.a_e-0.40a_p.a_e \quad (1)$$

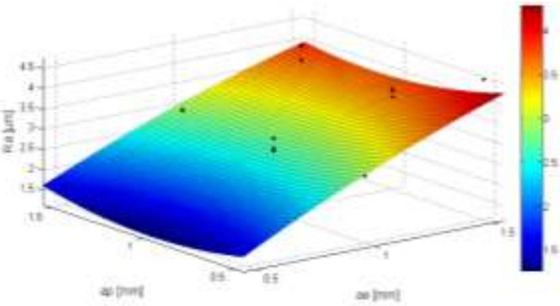
$$Rz=0.33+2.10k-8.23a_p+22.7a_e+102k^2+4.43a_p^2-5.50a_e^2+6.97k.a_p-7.60k.a_e-0.57a_p.a_e \quad (2)$$

Meaning of the above mentioned formulae is contribution of the end milling factors to the resultant surface roughness. Though determination index is very high (R^2=0.94 and 0.91, respectively), contribution of the factors as a_e and a_e and k is quite different. Results of ANOVA (Analysis of variance) points out that the a_e bears the main effect on the resultant surface roughness which was found out to be about 90–91 %, while the a_p and k brought effects no greater than 2.1–2.5%. In other words said, the signed curvature of workpiece is rendered through the errors in models, thus final effect of a_e and a_p was found out as:

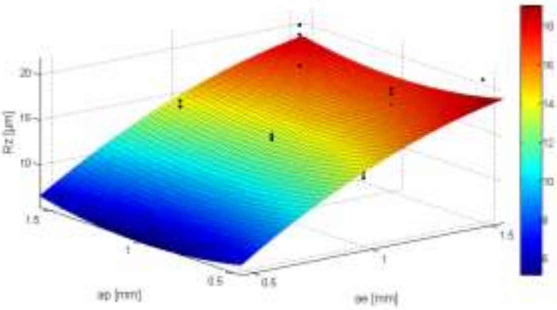
$$Ra=0.62-1.75a_p+3.71a_e+1.02a_p^2-0.50a_e^2-0.40a_p.a_e \quad (3)$$

$$Rz=0.27-8.51a_p+23.00a_e+4.43a_p^2-5.61a_e^2-0.57a_p.a_e \quad (4)$$

and they are shown in figs 8(a) and (b).



(a)



(b)

Fig. 8: Effect of cutting conditions a_p and a_e on surface roughness parameters based on L27 Taguchi design (a) mean arithmetic deviation *Ra*, (b) average maximum height of the profile *Rz*

4. Discussion of Results

CAD based fragmentation is applicable in limited scale for such surfaces as datum or inclined walls. The former, however, implies such a shape of fragment to provide for measurability. Figure 3(a) indicates such a case of fragmentation whereas desired measurability is provided for. An advantage of such a case of fragmentation is that it is capable of displaying machined surface, though this displaying of machined surface does not distinguish elements in set of circumstances mentioned above, for instance, fig. 4 says nothing about how such a texture is produced, or about how such a representation is applicable for different geometry/micro geometry of ball end milling cutter.

Object based fragmentation enables to check suitability of any milling strategy and fig. 5 shows a comparison of CAD modelling and real object. If the best result is desired, the Constant Z level strategy seems to meet this requirement, however, total machining time is a limitation in this approach. Another limitation is measurability: the case of definition of the free–form surface allows to measure roughness parameters in only position. The last case in fragmentation approach is volume based approach shown in figs 6 and 7. It allows to evaluate such a strategy of milling wherein the acceptable results are expected and measurability of roughness parameters is accomplished. Performed laboratory testing proves that it is side step a_e in Linear Strategy which creates resultant roughness *Ra* and *Rz*. The ways of volume based approach can be found in some works which test either milling strategies or they investigate effect of cutting conditions on machined surface parameters. However, such works investigate mainly milling of hardened steed for tool making purpose as [12] which quotes what is Linear strategy and *Ra*= 0.3 – 1.8 µm in initial stage of tool wear when a_e=1 mm and a_p=0.5 mm. In uniformly spaced Linear strategy, the source [15] quotes *Ra*=1.49 µm and *Rz*=5.61 µm when machining aluminium 6061T6. The source [13] introduces a sample which can be referred to Volume–based fragmentation to machine 1.2344 hardened steel and it allows investigation of way of milling (conventional/climb milling) and variable position of roughness measurement. Source [13] also shows that it is radial depth of cut alias a_e which produces the *Ra*= 0.25–1.52 µm.

5. Conclusion and Prospect

In this paper, author introduces their results based on fragmentation of definite free form surface in tool making. Their approach combines set of factors affecting design in tooling and a simple notation of design shapes in tool making is introduced. Three ways of fragmenting of the active surfaces in tool making are proposed. There is limited field of application for CAD based fragmentation, however, it can be used to rapid creating of the fragments. Prospect of such an approach is that it combines models of surface fragments and their relationship to the kinematics of any milling strategy. It is also supposed to provide a base to optimize milling operation in question. The Object Based Approach defines a part of tooling which is produced in any scale to study effect of milling strategy on its resultant surface quality. It can be shown that roughness data are not only results assessing quality of free–form milling, it is too dimension accuracy which implies surface metrology. Advantage of the Volume Based Fragmentation is combining of CAD, experiments and surface metrology, and it provides for verifiable results being tested in laboratory. The variable signed curvature and design of testing pieces presented in this paper are one of the possible solutions which are offered by design of tooling. Because of large set of factors as sort of milling strategy, diameter of end ball milling cutter, cutting conditions, etc., use of experimental design identifies all the relevant influences and in fact, design of experiment allow to optimize this process as such.

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