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Intelligent toolpath selection via multi-criteria optimization in complex sculptured surface milling

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Abstract A new approach is presented the first time in the literature to generate multi-criteria optimized toolpaths for the complex sculptured surface machining. This is achieved by developing a mathematical solution that consists of the physical relationship between the mean resultant forces, cycle times and scallop heights. These three critical process outputs in machining are conflicting with each other. In other words, there are tradeoffs between cutting force magnitudes, cycle time and scallop height. This triple bounded problem in machining is solved in this article by using the objective weighting based algorithm. The multi-criteria toolpath optimization method introduced here for sculptured surface machining increases the controllability of the process with the specified criteria. The method also allows determining all pareto optimal solutions and all possible weights of each criteria. Moreover, the method eases to observe and analyze the trade-off between each criterion, facilitate the limitation and minimization of each criterion and determine corresponding toolpath for each solution. This solution produces optimized toolpaths according to preset constraints for mean cutting force, cycle time and scallop height. The method is a generalized solution for determining optimized toolpaths based on given constrains in free-form surface machining. In order to validate the multi-criteria toolpath optimization method, experiments at various conditions are performed on free-form machining and an example is presented in this article.

Keywords Intelligent machining · Milling · Force · Cycle time · Scallop height · Free-form surface · Tool path · Multi-criteria optimization

Introduction

Nowadays, as demands increase for machining of parts with sculptured surfaces in lesser cycle times and costs as well as higher precision and qualities, due to highly competitive markets, high performance machining of the free-form surfaces with CNC codes including intelligently selected toolpaths become vital in industries. Currently, standard toolpaths that are available in commercial CAM programs are used in industry. In existing CAM programs, the standard toolpaths are generated by considering the geometrical aspects only. Unfortunately, mechanics of the machining processes has not been considered in the generation of CNC toolpaths yet. Therefore, from production engineering perspective, these standard toolpaths are away being optimal for milling of sculptured surfaces that are commonly used in automotive, aerospace, optic, electronic, energy biomedical, home appliance and die/mold industries.

For the next generation, intelligent CAM strategies, the author's previous enhanced models of milling mechanics and force based toolpath optimization method for free-form machining are used to simulate cutting forces and to generate force minimized toolpaths. Details of force model for free-form machining can be found in Guzel and Lazoglu (2004) and Erdim et al. (2004). Using this enhanced force model, force minimized toolpaths are generated for free-form machining (Lazoglu and Manav 2009). Here in this article, a more complex problem is handled and solution method is generated. In this article, not only forces but also conflicting constrains, cycle time and scallop heights of parts, are

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considered and a multi-criteria approach is used for toolpath optimization for any given complex free-form surface machining.

Various toolpath generation methods are available in the literature. Ulker et al. (2009) used an artificial immune system approach to reduce machining time in sculptured surface machining. Sheen and You (2006) proposed using pair-wise bridges to merge pockets and islands in toolpath generation Chu et al. (2006) investigated toolpath planning for 5-axis flank milling of ruled surfaces considering CNC linear interpolation. Elber and Cohen introduced a model for gouge-avoiding toolpaths (Chen and Shi 2008). Chen and Shi proposed an algorithm for toolpath generation on the triangular meshes sliced of free-form surfaces. There are also some articles in the literature suggesting different toolpath generation methods, which attempt to keep scallop height constant, are initiated with creating the toolpaths according to iso-parametric method (Elber and Cohen 1987), iso-planar method (Ding et al. 2003) and iso-scallop height method (Sarma and Dutta 1997; Feng and Li 2002). After these studies, Feng and Li generate toolpaths which have constant scallop height by using bi-section method. Yoon (2005) reduced the necessary computational processing power significantly by changing the bi-section method into Newton method. Choi et al. generated toolpaths by using Bézier curves/ surfaces and decreased the adequate CL points to mill the part for CNC Choi et al. (2007). These studies attempted to provide constant scallop height toolpath with shorter toolpaths, which means shorter cycle times indirectly and generally assures less computational power. However, these two dimensional scallop height model needs continuous uniform free-form paths to ensure the constant scallop height and none of these methods give any model about forces and cycle time directly.

In conclusion it can be noted that all these path generation methods available in the literature and in the existing commercial CAM software are based on geometric analysis only and there is a lock of consideration for mechanics of machining processes in CNC toolpath generations. Moreover, since there are different toolpaths available in the literature and in CAM programs to carry out the same process, a practical question arises that which toolpath strategy is the best choice for a specific free-form surface. Each toolpath strategy offers different cutting time, various cutting force magnitude and diverse surface quality.

In this study, a new methodology is introduced to determine the optimum toolpaths for free-form surfaces. Unlike only geometric computational analysis of commercial CAM systems, the newly developed optimization process includes the mechanics of milling process for the toolpath generations. The toolpath optimization algorithm presented is a force-scallop height-cycle time-minimal approach. In other words, the objective of the optimization process is to find the toolpath for minimizing the average cutting forces, scallop heights and cycle time with the user defined preset allowable maximum values or objective weightings.

Proposed multi-criteria toolpath optimization method

The multi-criteria toolpath optimization increases the controllability of the cutting operation with the specified criteria, determine all pareto optimal solutions and all possible weights of each criteria, ease to observe and analyze the trade-off between each criteria, facilitate the limitation and minimization of each criteria and determine corresponding toolpath for each solution. Since the problem has three objectives, the problem is redefined as passing over all the cutter location points determined on the 2D uniform grid of the part surface with the specified criteria such as limitation or minimization of the mean cutting forces, mean scallop height and total cycle time.

As the first step for solution of the problem, cutter location (CL) and cutter contact (CC) points are determined using developed algorithm. The next step is the prediction of the slot cutting forces and scallop heights for each connection from CL points to its neighbors. Force map and scallop map are constructed which represents all possible movement with a specific reference force and scallop height value. 3D scallop model is validated by comparing predicted scallop distribution on the surface with the CAM output of Siemens UGS NX7.5 for the same surface. The last step is implementation of the multi-criteria optimization algorithm with the specified criteria including threshold or minimization of the objectives (force, scallop height, cycle time). The solution steps for the multi-criteria toolpath optimization are demonstrated in the Fig. 1.

Since the evolved scallop can not always be represented in two dimensions, the case is different for numerous path segments. In Fig. 2, a free-form cut surface is illustrated where all CL points are visited via plunging operation. Therefore, none of the edges between CL points are cut. In that sense,

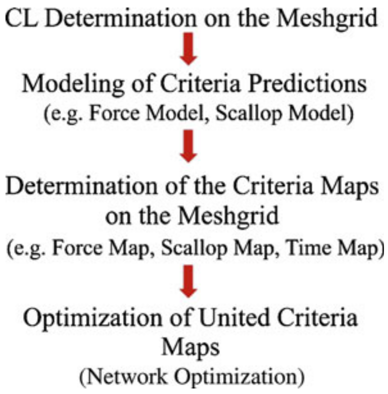

Fig. 1 Solution steps for the multi-criteria toolpath optimization

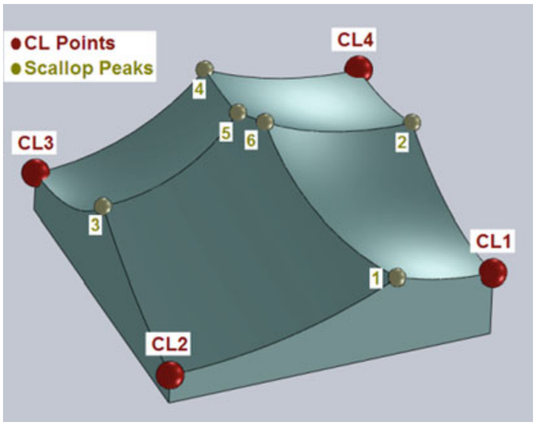

Fig. 2 A free-form cut surface via plunging operation on CL points

the scallop heights on the edges between CL points on this cut surface can be used as reference value for the scallop elimination quantity during the cutting of edges on the toolpath. In Fig. 2, a piece of a part surface enclosed by four CL points is shown. It is assumed that, each CL is visited in different path segments and the edges of this section are not cut.

There are six scallops in this section of the part surface where scallops 1–4 evolved from the intersection of two sphere surfaces and could be represented with the 2D model. However, scallops 5 and 6 evolved from the intersection of three sphere surfaces. Three sphere surfaces could possibly intersect in zero, one or two points.

These surfaces intersect in two points, if the step over—tool radius ratio is smaller than $\sqrt{2}/2$ as in most cases. A single intersection point should be determined which lies on the bottom hemisphere surfaces. Furthermore, there are four possible selections of three spheres for the intersection from the group of four spheres and therefore four possible intersection points lying on the bottom hemisphere surfaces. Every time only two of them evolve since the other two stay in the volume of the fourth sphere.

Varying objective weighting algorithm

A common solution to the problem is to simplify multiple objectives into a single objective because network optimization algorithms such as Minimum Spanning Tree (MST) or Minimum Cost Travelling Salesman (MCTS) are only effective with single objective. There is only one single-point solution in the sense pareto optimality can be obtained. The decision maker in practice may prefer one pareto optimal point over the others on the situation. It is useful to calculate all possible pareto optimal solutions, and the optimization routine should be repeated by changing objective weighting several times.

Optimizing each objective separately:

$$\begin{aligned}
&\min z_1(x) = \sum_{i=1}^{m} w_{1i} x_i \\
&\min z_2(x) = \sum_{i=1}^{m} w_{2i} x_i \\
&\dots \\
&\min z_p(x) = \sum_{i=1}^{m} w_{pi} x_i
\end{aligned} \tag{1}$$

There are respectively p optimal solutions x^k, each for one single objective; and p optimal cost values for the objectives, one of each solution minimizes a single objective, each of them lies on the pareto frontier. However, each of them conflicts with another, each cost value should be evaluated with a weighting to determine a total cost value, which means that how much the user desire to get close to the optimal cost of each objective. The total cost function could be written as below:

$$\min z(x) = \sum_{k=1}^{p} \lambda_k z_k(x) \quad \text{where } x \in X \tag{2}$$

If each optimal solution in equation is put into the total cost equation:

$$\min z(x) = \sum_{k=1}^{p} \lambda_k \sum_{i=1}^{m} w_{ki} x_i = \sum_{k=1}^{p} \sum_{i=1}^{m} (\lambda_k w_{ki}) x_i \quad \text{where } x \in X \tag{3}$$

Therefore, it is concluded that weighting of single optimal cost of each objective can be maintained by weighting w_{ki}, the cost values of each objective at each edge, with λ_k, the corresponding weighting value for the objective.

Experiments for validation of multi-criteria tool path optimization were performed on a CNC machining center. The tool was a carbide ball-end mill cutter from CoroMill Plura series of Sandvik with 12 mm diameter, 37 mm projection length and 30° helix angle. The workpiece material was aluminum blocks (Al7039) with dimensions of 250 mm × 170 mm × 38 mm. Kistler 3-component dynamometer (Model 9257B) and a charge amplifier have been used to measure cutting forces. The 3-component dynamometer was fixed to the machine table using fixtures, and the aluminum block was attached to the dynamometer as seen in Fig. 3. Surface profile and scallop heights were measured in the CMM (Dia 7.5.5).

Cutting force, cycle time, Scallop height optimization using varying objective weighting approach

In order to implement the multi-criteria toolpath optimization algorithm for free-form surface machining, varying objective

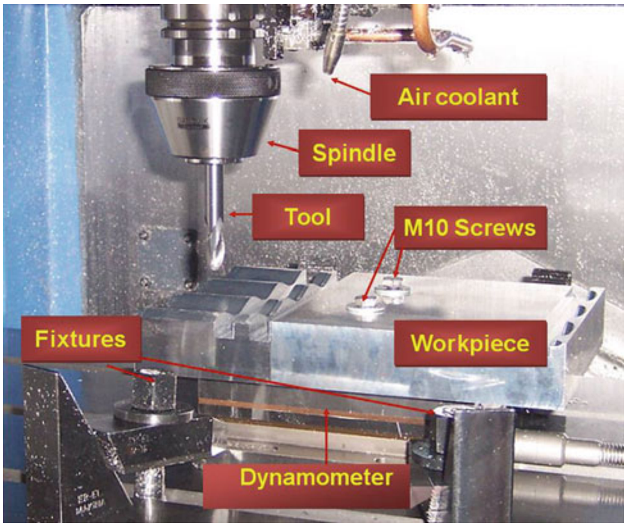

Fig. 3 Workpiece and 3-component dynamometer setup in the CNC for the validations of multi-criteria toolpath optimization

weighting approach is preferred. Mean cutting force, mean scallop height and total cycle time are target objective criteria. In order to investigate the physical relations of the objectives for multi-criteria free-form surface toolpath optimization, a hypothetical force, scallop height and cycle time map is selected and numerous toolpath solutions are optimized using varying objective weighting with 1% sensitivity. The weighting of each objective criterion (mean resultant cutting force, mean scallop height, total cycle time) may be changed from 0 to 100% by using this sensitivity. All non-dominated solutions are plotted to obtain the pareto surface as shown in Fig. 3. The weighting of mean scallop height minimization (W_S) is 0% on square marked boundary curve of pareto surface. In other words, scallop height is not considered into the optimization. The weighting of mean cutting force minimization (W_F) is increased from 0 to 100% throughout the arrow direction of the same curve. Meanwhile, weighting of total cycle time minimization (W_T) is decreasing from 100 to 0%. Similar explanations can be easily made for the curves with diamond-like and circle markers. During the examination of the Fig. 4, it can be realized that the objectives may be conflicting in most regions as expected. The minimization of one objective value, tend to increase other objective values. According to the desired output characteristics, the user can changed the optimization characteristics in this pareto region.

The free-form surface sample to be analyzed in this article is illustrated in Fig. 5 where the surface is formed with dimensions 40 mm × 40 mm × 6 mm via the multivariable function explicitly shown in Eq. (4).

$$f(x, y) = 2.5\cos(x)\sin(x)\exp\left(\sqrt{x^2 + y^2}/64\right) + (4xy)/\left(x^2 + y^2\right) \qquad (4)$$

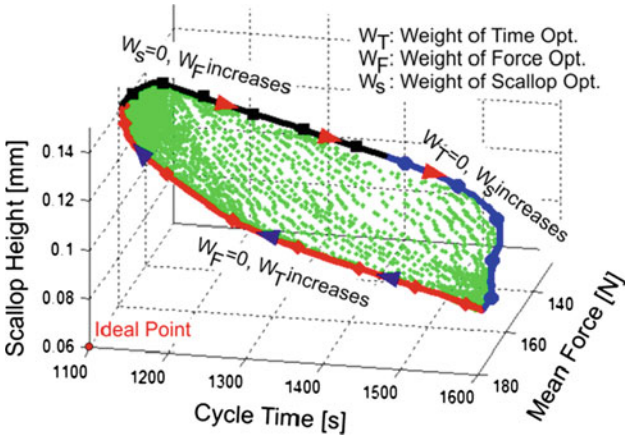

Fig. 4 Illustration of pareto surface and effects of weights for scallop height, cycle time and mean cutting force

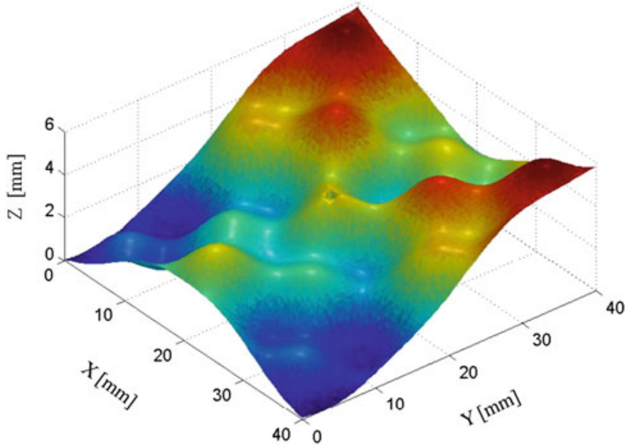

Fig. 5 Illustration of a free-form cut surface for scallop height

The cutter location (CL) points are determined using the collision detection based algorithm. The force, scallop and cycle time maps are obtained using the force and scallop height models as explained before. Cycle time map is easily obtained by calculating cycle times for each edge by division of the distance traveled between the relevant CL points to the constant feedrate of 48 mm/min.

The case of the plunged CL points with all uncut edges represents the whole scallop map. Selection of the machined edges in the CAM operation would decrease the amount of remained scallops in the optimization and a mean scallop height were predicted from the remaining scallops. In Fig. 6a, the calculated scallop points are plotted on the scallop map representative surface to visually validate the pattern of the predicted scallops. The errors were calculated from the distance between the plunged surface exported from CAM program in STL format with 0.001 mm edge tolerance and the scallop points calculated with scallop models in 2D and 3D as discussed above. In Fig. 6b, the error histogram of the scallops is shown. The errors are low and reasonable.

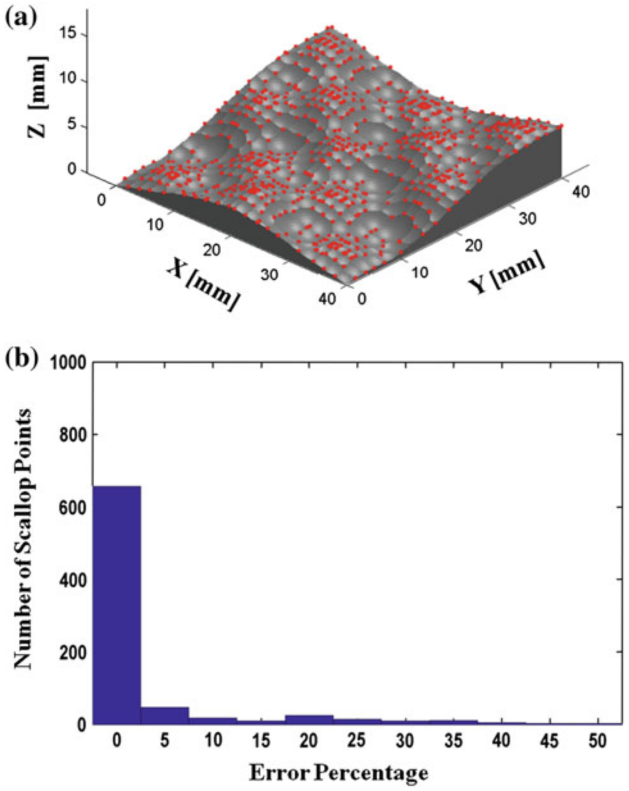

Fig. 6 **a** Illustration of predicted scallop points on the reference surface. **b** Error histogram of predicted scallop heights

Optimization criterion example: mean cutting force < 260 N, mean scallop height $< 100\,\mu$m, minimize cycle time

Varying objective weighting algorithm is used with 1% sensitivity where the weightings of each criteria (mean resultant cutting force, mean scallop height, total cycle time) changed from 0 to 100%. All non-dominated solutions are plotted to obtain the pareto surface as shown in Fig. 7.

All toolpath solutions are represented in pareto surface with their objective values which are stored once the optimization routine is completed. Limited threshold parameters (i.e. Mean Cutting Force < 260 N, Mean Scallop Height $< 100\,\mu$m and Minimized Cycle Time) depicted with two planes in Fig. 6. The allowable region to work is showed in pink points and the cycle time minimized point is big red point on pareto surface. The objective costs of this point is 258 N for mean cutting force, 1,321 s for minimized cycle time and 100 μm for mean scallop height.

The 2-D of optimized toolpath satisfying required criteria is shown in Fig. 7. The circles and x in Figure 7 illustrates start and end points of the toolpath tree branches. When x is reached, tool moves up and travels rapidly to the next start point (Fig. 8).

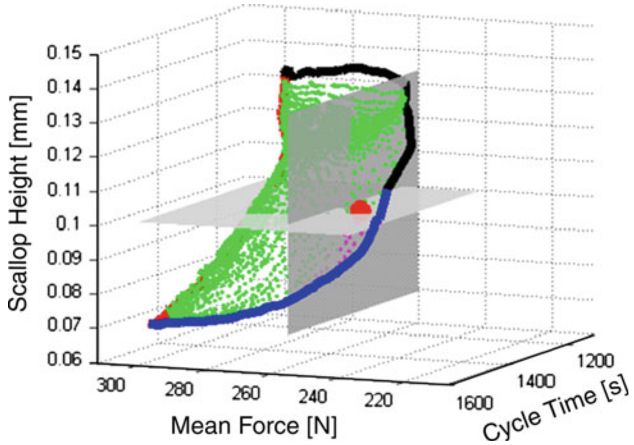

Fig. 7 Pareto surface with objective points of standard and optimized toolpaths

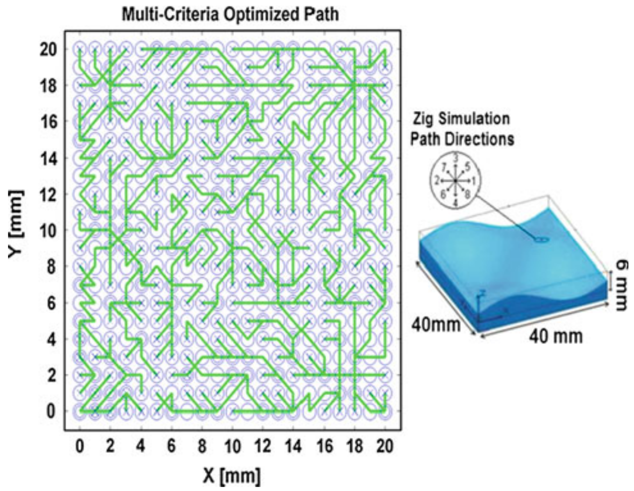

Fig. 8 2D of optimized toolpath for optimization criterion example and zig simulation path directions

The optimized toolpath is verified the selected optimization criteria and represented with red point on the pareto surface as shown in Fig. 7. The selection of force and scallop limitation first, limits the region for minimized cycle time. In that region, predetermined objective weightings of W_F and W_S are 85 and 11%, respectively and in order to satisfy 4% W_T (i.e. minimized cycle time) diagonal edges are needed as shown in Fig. 7.

These objectives are compared with the experimental cutting forces. Since the force map is formed using slot cutting simulations, it is expected that the forces of the simulated toolpath would remain under the boundary curve of the force map. In that sense, the simulated mean cutting forces needs to be below the objective cost and simulated cutting forces matched quite well with experimental cutting forces in this example as shown cutting force envelops in Fig. 9. The simulated mean cutting forces and total cycle time are 130 N

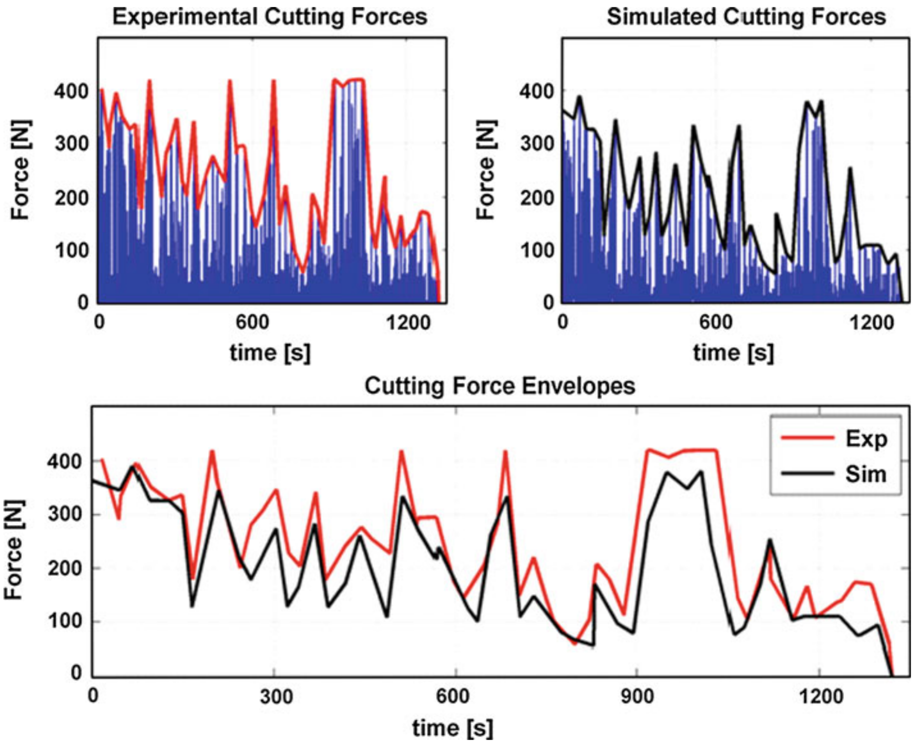

Fig. 9 Comparing simulated and experimentally measured resultant forces for the optimized toolpath

and 1,352 s, respectively. Therefore, the simulated toolpath cutting force is matched quite well with experimental results.

Comparison with standard CAM toolpaths

Mean force, cycle time and mean scallop costs for the cutting directions of 8 standard zig toolpaths are as shown in Fig. 8 (toolpaths from 1 to 4 are non-diagonal, toolpaths from 5 to 8 are diagonal). The experimental cutting operations are performed for these standard zig toolpaths.

Even the objectives are conflicting, pareto optimal solutions exist and dominate standard solutions lying in the objective space. Objective points of standard toolpaths lie above the pareto surface, which assures that standard toolpaths are dominated by optimized solutions. The optimized toolpath provides the operator to guarantee mean scallop height is below 100 µm and the mean cutting force is below that of standard toolpaths.

Conclusions

In this study, a new methodology is introduced to determine the optimal toolpaths for free-form surfaces. The newly developed optimization process includes the mechanics of milling process for the toolpath generations. The presented toolpath optimization algorithm is a force-scallop height-cycle time-minimal approach. In other words, the objective of the optimization process is to find the toolpath for minimizing the average cutting forces, scallop heights and cycle time with the user defined preset maximum values or objective weightings. Further developments on toolpath optimizations can be performed for 5-axis machining.

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