6
Conclusions and Future Recommendations

6.1 INTRODUCTION

The present thesis developed a comprehensive computational framework to estimate static deflection-induced flatness and cylindricity tolerance parameters during the end milling of thin-walled planar and curved components. The framework consists of a cutting force model, tool and workpiece deflection models, and geometric tolerance estimation algorithm. The cutting force model is integrated with the FE-based workpiece deflection model and cantilever beam based tool deflection model to estimate distorted machined coordinates for straight and curved components. PSO technique based flatness and cylindricity tolerance parameters estimation algorithm is developed to extract the relevant geometric tolerance parameters from the distorted coordinates. Subsequently, a strategy has been devised to control geometric tolerances by modifying the semi-finished geometry of the component. The control algorithm regulates the rigidity of thin-walled components to manufacture it within the given tolerance limits. The outcomes of the proposed models are substantiated by conducting experiments for different geometries under various cutting conditions. This chapter summarizes major conclusions derived from the present thesis along with further research work in the relevant research domain.

6.2 MAJOR CONCLUSIONS

The major contributions of the thesis can be broadly divided into four distinct areas of study namely; cutting force model, modeling of geometric tolerances, analysis of geometric tolerances and control of geometric tolerances. The subsequent subsections summarizes main conclusions derived in individual areas.

6.2.1 Cutting Force Model

The thesis analyzed the contribution of bottom and flank cutting edges on the total cutting force during the end milling operation for a range of cutting widths (*RDOC* and *ADOC*). The major conclusions drawn from the study are summarized as follows;

- The cutting force modeling approach considering independent inclusion of the bottom edge effect through a separate set of constants can predict cutting forces accurately over a wide range of cutting widths, i.e., *ADOC* and *RDOC* for end milling operation. The prediction accuracy of the approach employing measured cutting force data directly and combining flank and bottom edges into a single constant is quite lower as it does not capture the process mechanics of flat end milling operation effectively.

- The contribution of the bottom edge to total cutting force is substantial for combinations involving large *RDOC* and small *ADOC*. Therefore, the independent inclusion of the bottom edge is essential to ensure better prediction accuracy over the entire range of cutting widths. The bottom edge forces are closely linked with the value of *RDOC* as it decides the length of the edge involved in the cut. It is also concluded that the bottom edge has a significant effect on the normal component (F_Y) of the cutting force than the tangential component

(F_X). The cutting forces in normal direction contributes significantly towards the generation of distorted machined surface and it is essential to predict it accurately for estimation of geometric tolerances.

- The contribution of the flank edge force is significant in comparison to the bottom edge force at higher *ADOC* values. The insignificant contribution from the bottom cutting edge at higher *ADOC* values results into identical predictions using approaches with and without bottom edge effects.

- The hybrid cutting force model realized in the thesis can predicts the instantaneous cutting forces variation accurately and it has a better generalization ability. The model predicts a higher value of cutting force in the normal direction consistently, which necessitates further investigations for the improvement in a model. The hybrid model can be improved further by replacing the learning approach or varying ANN parameters. The present work uses shallow networks and the application of modern networks such as Recurrent Neural Networks (RNN) or reinforcement learning can be applied for better realization of the relationship for estimating constant.

6.2.2 Modeling of Geometric Tolerances

The thesis developed a computational framework to estimate geometric tolerances during the end milling of thin-walled straight as well as circular components. The major conclusions drawn upon the development of the framework are summarized as follows;

- The computational framework developed in the thesis work can effectively capture the effect of process faults such as static deflections of cutting tool and workpiece on tolerance parameters over a wide range of cutting conditions. The outcomes were substantiated further by conducting milling experiments that showed good agreement with the computational results. It is inferred that the computational framework proposed in this paper can be employed in estimating flatness and cylindricity errors during the end milling of thin-walled straight and circular components.

- The nature of workpiece curvature has a considerable influence on the cylindricity error and associated parameters. Although concave side machining involves larger cutter-workpiece engagement area and higher cutting forces, the increase of cylindricity error is much lower in comparison to the convex side machining. The behaviour can be attributed to the geometric configuration of concave components, which imparts stiffness to resist static deflections resulting in reduced cylindricity error.

6.2.3 Analysis of Geometric Tolerances

The thesis further analyzed the effect of variation in different structural attributes of the thin-walled planar and circular components on geometric tolerances. The major conclusions drawn from the parametric study are summarized as follows;

- The analysis of geometric tolerances for various geometries over a wide range of cutting conditions highlighted that the unmachined state of the thin-walled component is critical in deciding the magnitude and distortion of distorted coordinates. The process planner can consider the unmachined thickness of the thin-walled component to control the geometric tolerances. The *RDOC* and cutting forces increase at higher unmachined component thickness but imparts adequate rigidity to the component for resisting cutting force induced deflections. An appropriate balance of *RDOC* and static deflections can be employed to derive an optimum end milling strategy that controls geometric tolerances within the limits specified by the designer.

- It was observed that the contribution of tool deflections to geometric tolerance is considerably lower at higher *ADOC*. These observations are in contrast to the general comprehension which expects higher contribution due to increased cutting forces. On the contrary, the tool deflections contribute significantly to the geometric tolerance at lower *ADOC* values. The same can be attributed to the higher rigidity of thin-walled components at these conditions and reduced contribution from workpiece deflections.

- The thinning of the component with the progress of milling operation has a marked effect on static deflections and geometric tolerance. The increased deflections with the progress of machining can result in a wider spread of distorted coordinates and increased geometric tolerance but a small change in the angle of inclination. The information related to the contribution of thinning on geometric tolerance parameters can be useful for process planners in devising an appropriate strategy to obtain components with better accuracy.

6.2.4 Control of Geometric Tolerances

The thesis devised a strategy that controls geometric tolerances during end milling of the thin-walled straight and circular components. The approach considers regulation of component rigidity by integrating physics-based end milling process model and PSO to derive appropriate semi-finishing workpiece geometry. The major conclusions drawn from the study are summarized as follows;

- The Rigidity Regulation Approach (RRA) developed in the thesis effectively regulates the rigidity of the thin-walled component at each cutting instant to control geometric tolerances during end milling operation. The proposed approach is substantiated by conducting end milling experiments that showed good agreement with the computational results.

- The comparative assessment of RRA with constant *RDOC* approach shows considerable improvement in the value of geometric tolerances. The developed approach has great potential to reduce the value of geometric tolerances during end milling of straight and circular components without compromising productivity.

- The developed approach reduces the inconsistency in the magnitude and profile of the deflected coordinates by optimizing all three elements governing tolerance zone while controlling geometric tolerances. The algorithm is independent of workpiece geometry and can be generalized over straight, circular concave and convex geometries.

- The proposed algorithm is able to capture the significance of all three elements governing tolerance zone while controlling geometric tolerances.

6.3 FURTHER SCOPE OF INVESTIGATIONS

The proposed research work can be extended in the multiple directions which may lead to further investigations regarding milling of thin-walled components. The further research work includes following aspects:

- The present thesis investigated the usefulness of different computational models in predicting cutting forces accurately during down milling of $2\frac{1}{2}$-D parts employing a flat-end milling cutter. The work can be extended with minor modifications to up-milling of the similar cavities. It can also be extended to the end milling of free-form 3-D parts, which requires the application of ball end mills. The computational models for ball-end milling require the changes in the process mechanics due to the presence of a hemispherical portion in the cutter.

- The Machine Learning-based model presented in this thesis to predict mechanistic cutting constant can be improved further by replacing the learning approach or varying ANN parameters. The present thesis uses shallow networks which can be replaced with modern networks such as Recurrent Neural Networks (RNN) or Reinforcement Learning for better realization of the relationship.

- The thesis considers the effect of cutting force induced static deflections of tool and workpiece while realizing computational framework for estimation of geometric tolerances. The dynamic component of cutting forces can be further incorporated in the framework to predict machining chatter for thin-walled components. The combined static and dynamic effects in the computational framework would result into a realistic estimation of geometric tolerances in straight and circular components.

- In the present thesis, the computational framework for estimation of geometric tolerances has been substantiated during end milling of straight and circular (constant curvature) thin-walled components. However, the thesis work can be further extended to free-form components with varying workpiece curvature along the tool-path.

- The thesis investigated the effect of structural attributes such as rigidity, curvature, thinning, etc. of the straight and curved thin-walled components on geometric tolerances. The present thesis effectively regulates the rigidity of thin-walled component to control geometric tolerances subsequently. The other attributes can be further studied to develop control strategies for geometric tolerances.

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