Abstract

High-precision manufacturing of thin-walled components in a monolithic form is vital for products having complex functional requirements typically employed in aerospace, automobile, die/mold making, and power generation industries. End milling is preferred for manufacturing of thin-walled components due to its versatility to generate complex shapes in various materials with high quality and productivity. End milling is an intermittent material removal operation with periodically varying cutting forces causing static deflections of thin-walled components. The static deflections are a primary source for the deviation of manufactured components from the design features resulting in rejection and scrap work. The designer specifies allowable deviations as per the Geometric Dimensioning and Tolerancing (*GD&T*) principles [ASME Y14.5-2009, 2009], [ISO 1101:2017, 2017] to transfer designer intent to the manufacturer. According to *GD&T* principles, the deviation of manufactured components is specified using basic dimensions and geometric parameters such as size, form, and orientation.

This thesis work presents 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 flank and bottom cutting edges are two major contributors to the cutting forces during the end milling operation. A comparative assessment of three different analytical approaches is conducted in the thesis work to highlight the importance of incorporating bottom and flank cutting edges in cutting force models for the end milling operation. The results shows that the bottom edge has a marked effect on the normal force component for select combinations of cutting widths. Also, the limitations of the classical physics-based cutting force model in dealing with random process variations is addressed by combining it with machine learning techniques. The thesis explored the development of a hybrid cutting force model that amalgamates the strength of both variants for the improved prediction accuracy.

Another important element of the framework is the estimation of distorted coordinates representing machined surface for planar and curved components. It is accomplished by integrating a cutting force model with the Finite Element (FE) based workpiece deflection model and cantilever beam based tool deflection model. The rigidity of the thin-walled component diminishes considerably with the progress of machining due to material removal. Also, the static deflections of thin-walled component alters *RDOC* and thereby cutting forces. The thesis work developed realistic cutting force and deflection estimation models accounting for the variation in *RDOC* and rigidity of the component with the progress of machining. The estimated deflected coordinates are transformed subsequently into the geometric tolerance parameters (flatness and cylindricity) using Particle Swarm Optimization (PSO) technique. It has been observed that the static deflections of a cutting tool and thin-walled component influence the geometric tolerances considerably. The inevitable aspects associated with the end milling of thin-walled components such as workpiece rigidity and concave-convex side machining of curved sections are investigated subsequently. It was observed that the geometric tolerance during machining of thin-walled curved components is relatively smaller due to structural configuration imparting adequate stiffness to resist cutting forces. The outcomes of the study are substantiated by conducting a set of computational simulations and end milling experiments over a wide range of cutting conditions.

It was observed that the geometric tolerances can be controlled by manipulating the thickness of a component in an unmachined state. The thesis work devices a novel Rigidity

Regulation Approach (RRA) to obtain the semi-finished geometry at the end of roughing operation. The finish cutting sequence is performed subsequently on the geometry for achieving optimal geometric tolerances. The effectiveness of the proposed methodology in optimizing geometric tolerances during end milling of thin-walled components is assessed by comparison of results with an alternative approach available in commercial CAD/CAM software commonly employed by manufacturers. The outcomes are further substantiated by conducting computational studies and machining experiments on various component geometries under different cutting conditions.

The present thesis aids process planners in selection of appropriate cutting conditions by developing a computational framework that estimates geometric tolerance parameters during end milling of thin-walled planar as well as curved components. The thesis also investigates some of the inevitable aspects of thin-walled machining such as workpiece geometry and curvature, thinning of component, end effects, etc. An offline strategy deriving semi-finished geometry for the component is proposed such that geometric tolerances are controlled without compromising productivity. The present thesis work provides meaningful information to CAD/CAM software users and process planners in selecting appropriate machining conditions for producing *first time right* thin-walled components.

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