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Introduction

1.1 MILLING OF THIN-WALLED COMPONENTS

Milling is an intermittent material removal process involving a rotary cutting tool having single or multiple cutting teeth producing chips with varying thickness upon interaction with the workpiece. The advancements in the domain of CNC machine tools, cutting tools, CAD/CAM technologies, high-speed machining, etc., over last few years resulted in the increased importance of the milling process in aerospace, automobile, and die-mold industries. The milling operation involving flat and/or ball end mills is preferred owing to its versatility to generate simple to complex shapes in a variety of materials with high quality and productivity. The end milling operation involves cutter-workpiece interactions through helical flutes located at the periphery of an end mill and generation of machined surface parallel to the axis of rotation as shown in Figure 1.1.

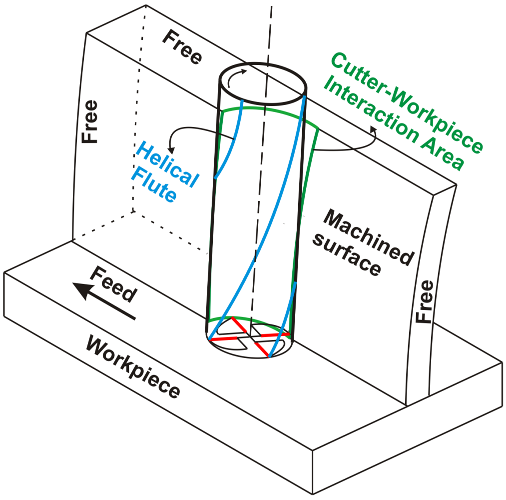

Figure 1.1 : Deflection of Thin-walled Component during End Milling

High precision manufacturing of thin-walled components such as avionics trays and racks, jet engine impellers, turbine blades, monolithic spar-ribs, etc. is essential in aeronautical and automobile industries to meet complex functional and aesthetic requirements. End milling is one of the preferred operation for the fabrication of thin-walled components as it eliminates the need for multi-part manufacturing, large setup times on different machines and assembling of components into the finished product. Thin-walled components are inherently flexible and prone to severe deflections under periodically varying cutting forces of the milling operation as depicted in Figure 1.1. The component rigidity reduces further due to removal of work material which result into increased static deflections with the progress of operation. The static deflections of component alter the relative position between tool and workpiece leaving the uncut material on the machined surface that transforms into the error. The error on machined components must be restricted to the tolerance levels assigned by the designer to ensure functional requirements and reduce rejections or rework.

1.2 TOLERANCES

The tolerance is an admissible deviation of a feature to allow for the inherent variations and inaccuracies of manufacturing operations. The allocation of an appropriate tolerance to the feature is a compromise among functional aspects and manufacturing costs. It is perceived that the lower tolerances impart superior functional accuracy and higher tolerances results into lower manufacturing costs. The designers have been employing Geometric Dimensioning and Tolerancing (*GD&T*) principles [ASME Y14.5-2009, 2009], [ISO 1101:2017, 2017] in recent years to quantify the deviation of manufactured components from the desired level. *GD&T* is a symbol-based terminology employed to communicate the designer intent unambiguously to the manufacturing personnel. *GD&T* is a successor of the Coordinate Dimensioning and Tolerancing *(CD&T)* system overcoming certain limitations [Cogorno, 2006]. Some of the important advantages of *GD&T* are illustrated in Figure 1.2 and summarized as follows;

- The *GD&T* employs cylindrical tolerance zone instead of rectangular tolerance zone as depicted in Figure 1.2. The cylindrical tolerance zone constructs an evenly spaced boundary from the desired position or center in contrast to rectangular tolerance zone. The cylindrical tolerance zone circumscribes the rectangular tolerance zone offering more space for the allowable deviation.

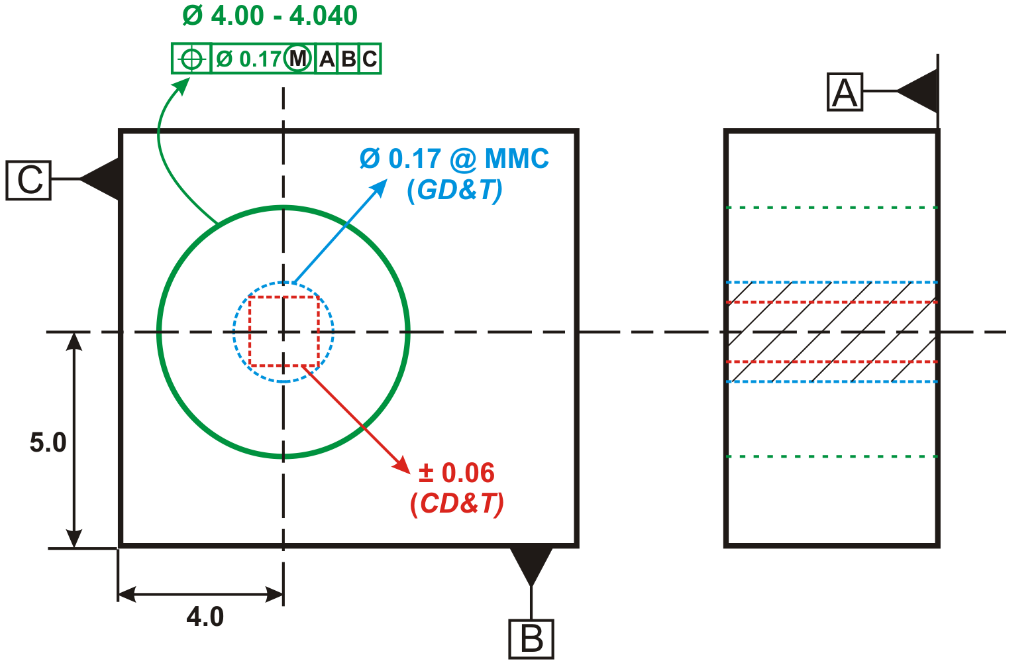

Figure 1.2 : Comparison of *GD&T* and *CD&T*

- *GD&T* specifies the Maximum or Least Material Condition (MMC or LMC) modifier to the size of the feature. It assist manufacturers in controlling the size of a feature within tolerance limits. It ensures that the assembly relationship (clearance or interference) between mating parts is attained even though manufactured at worst desirable tolerances. The modifier also facilitates additional tolerances while migrating form the MMC to LMC.

- The *GD&T* sets the order of precedence for datums as primary (*A*), secondary (*B*) and tertiary (*C*) as shown in Figure 1.2. The datum reference frames consist of three mutually perpendicular planes following 3-2-1 principle of fixturing to locate and orient the part. The *CD&T* does not specify datums and may leads to multiple interpretations for the same drawing during the manufacturing and inspection operations.

It is well-established that the manufacturing and inspection related decisions are dependent on the judgement of personnel involved when part drawings are dimensioned using *CD&T*. It is desirable to specify component drawings using *GD&T* principles to maintain the consistency in decision making from the design stage to manufacturing and inspection. *GD&T* offers multiple advantages to designers and manufacturers such as means for the accurate information exchange, reduction of guesswork to ensure consistent information, adaptability to digital design platforms, ensuring dimensional and tolerance requirements, increased cost-effectiveness, etc. *GD&T* specifies geometric tolerances using size, form, and orientation. For straight or planar elements, the size represents the fundamental dimension (length, width, or depth), while form represents flatness of the feature, and orientation signifies the inclination of a normal to the plane. In case of circular or cylindrical components, the size represents the diameter of a feature while the form is defined using circularity or cylindricity values, and orientation is denoted using axis inclination. The geometric tolerances are essential for manufacturers in ensuring assembly or interchangeability requirements of the component. The geometric tolerances are useful in specifying vital functionalities, e.g., cylindricity is a critical parameter during the piston-cylinder assembly.

1.3 RESEARCH MOTIVATION

The cutting force in milling operation is of fundamental importance as it is a key contributor to the majority of process related faults. The reliable estimation of cutting force is an essential requirement while estimating process faults such as tool and workpiece deflections, tool failure, chatter, inadequate fixturing etc. The total cutting force during end milling operation is expressed as the summation of components contributed by the flank and bottom edges. The literature presents different approaches and models for the prediction of flank and bottom edge cutting forces. However, the prediction accuracy of these variants is not identical over a range of cutting conditions. It is necessary to examine the applicability of these variants over a range of cutting widths that would help in the selection of an appropriate model while estimating process faults.

The cutting force is responsible for deflections of end mill as well as thin-walled components, and thereby violation of the geometric tolerances on the feature. According to the ASME Y14.5-2009 [2009] standard, the workpiece is said to be geometrically and dimensionally accurate when each feature or dimension of a manufactured component is within the desired tolerance specifications. The suitability of manufactured components in an assembly along with other functional requirements not only depend on the dimensional correctness but also relies on the accuracy of actual geometric surface generated during the operation. The actual geometric surface is defined using the set of coordinates representing machined or mating surfaces. *GD&T* system assigns tolerances to both, the basic dimension and geometric feature of the component. The majority of previous literature focuses on the estimation and control of dimensional error due to static deflections of thin-walled components. A process planner requires a reliable framework that can correlate deflections of thin-walled component with dimensional and geometrical inaccuracies simultaneously. Such computational tool will aid process planners in devising appropriate machining strategies and selection of process settings such that tolerance requirements of the component are satisfied.

The control of geometric tolerance is essential for manufacturers in ensuring assembly or interchangeability of components and imparting other functionality, for example, clearance for lubrication between mating parts. The manufacturer is required to estimate process parameters (e.g. Radial Depth of Cut (*RDOC*), Axial Depth of Cut (*ADOC*), feed rate, etc.) based on tolerance specifications and optimize manufacturing-related goals of productivity and reduced rejections/rework. The manufacturers employs conservative process parameters to ensure conformance with specified tolerances by compromising productivity. A computational framework experiencing pseudo-real end milling operation of thin-walled geometries can aid manufacturers while devising an appropriate strategy to control geometric tolerances within the design limits. Such approaches can provide the meaningful information to the CAD/CAM software users and process planners in selecting appropriate machining conditions without compromising manufacturing productivity for producing thin-walled components *first time right*.

1.4 RESEARCH OBJECTIVES

The primary research objective of the present thesis is to develop a computational framework that estimates and analyzes cutting force induced geometric tolerances during the end milling of thin-walled components. In order to accomplish the same, the objectives of the thesis are stated as follows:

- To develop a cutting force model for analysing material removal action of flank and bottom cutting edges during end milling of thin-walled straight as well as curved geometries.
- To establish an FE-based methodology to estimate distorted machined surface for thin-walled components and transforming the same into geometric tolerances.
- To examine the effect of workpiece geometry on geometric tolerances.
- To devise a methodology that can control geometric tolerances without sacrificing manufacturing productivity during end-milling of thin-walled components.

The scope of the present thesis is restricted to down milling and machined surface distortions caused due to cutting force induced static deflections only while attempting above research objectives.

1.5 RESEARCH APPROACH AND THESIS OUTLINE

The thesis begins with the review of previous literature related to development of models predicting cutting forces, tool-workpiece deflection induced errors and its control (Chapter 2). Mechanistic force model has been reviewed along with extraction of process geometry parameters which forms input to the FE model. A summary of literature related to approaches used for estimating deflections of a cutting tool and thin-walled component with different geometries is presented. The literature related to models for the control and compensation of errors is presented subsequently. Mechanistic force model incorporating independent contributions of the flank and bottom cutting edges along with the procedure to determine cutting constants have been summarized in the Chapter 3. A comparative assessment of three different approaches is presented to highlight the importance of incorporating bottom and flank cutting edges for end milling operation cutting force models. A hybrid methodology to determine the relationship between cutting constant and uncut chip thickness by combining physics-based models and Machine Learning approach is presented subsequently. Chapter 4 summarizes the FE-based methodology to estimate distorted machined surface due to static deflections of cutting tool and thin-walled component. The distorted surface obtained in the form of point-cloud data is further transformed into geometric tolerance parameters using the PSO technique. The chapter also discusses several other aspects related to milling of thin-walled straight and curved components such as variation in radius of curvature, rigidity, machining from concave or convex side, etc. Chapter 5 conceptualizes the methodology to control geometric tolerance parameters by optimizing unmachined thickness of the component as a function of rigidity along the length of cut. The algorithm has been developed to optimize the *RDOC* such that the component is manufactured within the tolerance limits. The thesis ends with conclusions drawn from the present work and suggestion for further work in Chapter 6.

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