Prediction of Geometrical Errors of Thin Floor Components in Milling Using a Flexible Fixturing Setup

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Abstract: Thin-floor components are commonly used in aerospace industry such as spars, and bulkheads. Their superlative ratio of strength to weight makes them highly demanded by manufacturers. One of the inevitable problems in machining such products is the deformation which is induced by cutting forces and causes surface form errors. This issue becomes more important when a flexible fixturing system is involved to support the workpiece. In order to assure the machining accuracy in milling with such setup, a prediction model for surface dimensional errors is required to avoid costly compensation operations and reach high productivity. In this paper, a structured simulation for the milling process suitable for part geometrical errors induced by axial cutting forces is proposed while the workpiece is fixed to (on) a flexible fixturing setup. The process is designed in an FE model as an implicit/static analysis of material removal and deformation under the influence of applied axial cutting forces. A cutting force model is used to measure the average cutting forces in different positions of the cutter. An Abaqus (Version 6.13-1) Python API is proposed to conduct numerous iterative procedures while creating the model including parametric study, creating repetitive geometry, and managing multiple steps and forces. The advantage of the proposed model is the prediction of the workpiece non-linear behavior during machining due to its constant changing geometry. The approach may help to develop an off-line error compensation model by manipulating and adjusting the depth of cut value through the trajectory in an iterative process.

Keywords: Thin-floor components, FEA, Error prediction, End milling, Flexible fixturing setup

1 INTRODUCTION

Thin-walled components in industries such as aerospace and automotive are required to have a structural homogeneity and a highly desirable ratio of strength to weight, to ensure the stiffness and low weight quality of the parts. For instance, parts such as ribs, stringers, webs and skins in aircraft structures are considered thin-walled components. Fixturing and machining such parts, especially with complex geometry, have been a challenge in the field to overcome. Complex workpieces fixturing for machining is commonly difficult, time-consuming and requires dedicated fixtures having surfaces complying to their counterpart for a full support. For a production environment involving various part families having complex surfaces, this means many fixture designs and manufacturing as well as large floor space requirement for their storage. In the recent years, flexible setup fixtures were proposed to overcome these issues [2,3]. These systems include several adjustable posts which adapt to part geometry, through programming (Figure 1-1). This results in lower setup time and cost reduction, thanks to fixture design/manufacture/storage elimination. These setups reveal full potential for polishing, drilling or milling operations, especially in the case of sufficiently rigid parts. For thin parts, milling operations remain a challenge due to their flexibility. Thus, to take full advantage of these fixturing setups, especially for milling thin parts, an off-line prediction model is required which takes the part deflection under the cutting forces into account. This paper aims to propose such a numerical model to predict the part deformation during milling operations using a flexible setup.

Numerical modelling for milling thin wall parts have been the subject of research works in the last decade. Izamshah et al. [6,7] developed a prediction model using finite element analysis (FEA) for milling processes of thin-walled structures. Their model considered an elastic-plastic deformation of the material. Ma et al. [11] also implemented a numerical model considering the elastic-plastic deformation as well as the influence of bending spring back of thin walls. Denkeka et al. [4] considered the thermo mechanical loads in their numerical model for roughing and finishing operations of thin wall components. Their model is able to reduce the waviness error of the walls during machining. Ji et al. [8] proposed a numerical model based on the Johnson-Cook law for the plastic behavior of the material to

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predict the deviation error when milling thin walls. Moreover, they studied the influence of the feed rate on machining deformation in their paper. Kang and Wang [9] studied two different iterative algorithms, the FIAL (Flexible iterative algorithm) and DIAL (Double iterative algorithm) models, to simulate the chip removal of the cutting process. Their work focuses on decreasing the simulation time of surface deflection in flank milling of thin-walled parts. They found that the FIAL model properly determines the cutting forces for flexible walls while the DIAL model is best suited to predict the maximum surface error for rigid parts. Kang et al. [10] applied a systematic simulation model using FEA (Abaqus 6.13-1) for surface form error prediction in flank milling of thin walls, considering the cutting tool and workpiece deflections. Regarding active compensation during machining, Diez et al. [5] developed a strategy using piezoelectric actuators to compare the measured cutting forces with the nominal ones in order to compensate the deviations during milling. Proper motion of the tool is generated during the operation without having to modify the tool-path.

All the previous cited works strictly focus on part deviations during thin wall machining while very few studies consider the simulation of thin floor machining. One of these works is proposed by Nguyen and Chatelain [13,14]. In this work, a numerical model is proposed to predict thin floor deformations during surface milling under the axial force of the cutting tool. Their work also proposes a compensation model for the tool trajectory using a mirror approach. The proposed research in this paper is an attempt to reduce the computational process of Nguyen's work using the new modeling and analytical approaches.

Figure 1-1: Flexible fixturing setup [12].

2. METHODOLOGY

In this section, an FEA-Python API method is introduced to predict the deformation and consequently the cutting deviation of low-rigidity components during a slot milling operation, using a flexible setup configuration. A simplified testbed is proposed to investigate the cutting deflections. The setup partially supports a rectangular aluminium plaque (120 x 120 x 12.94 mm) in 4 corners with 4 locator pins. The milling trajectory is a simple straight line. The following flowchart (Figure 2-1) illustrates the prediction model procedure.

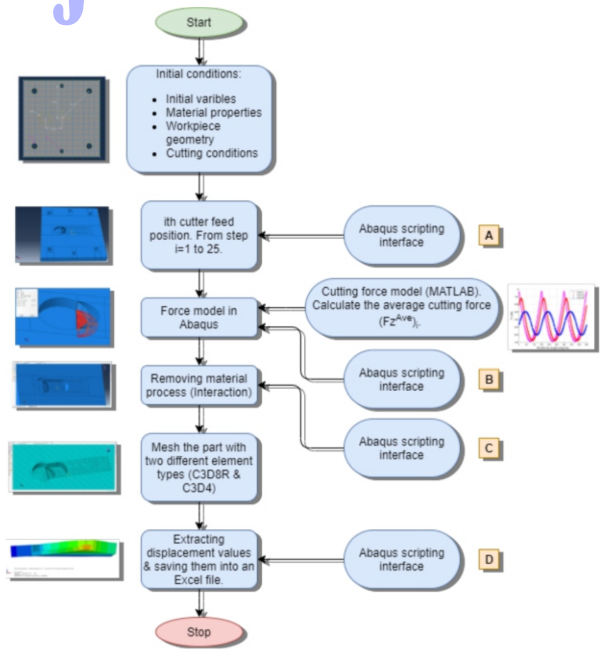

Figure 2-1: Simulation process steps.

The process starts with creating the model in order as shown in Figure 2-1. Several iterative algorithms were developed in form of Python scripts and applied in both preprocessing and postprocessing to facilitate the modeling and extracting results processes. First, the workpiece geometry, boundary & cutting conditions, material properties and steps are defined. Second, the workpiece is partitioned into 25 uncut chip cells (crescent/C shape) in the cutting area with respect to the cutting conditions (Figure 2-2). The first few chip cells -located in the impact area of the tool and workpiece- have been sized with respect to a feedrate value of 0.34 mm/rev. Thus, each cell represents the amount of material which is removed after one rotation of the tool. The rest of them are created with a larger size (3.26 mm/rev) and equidistant from each other towards the end of the trajectory. This has been done to reduce the computational time significantly since the simulation refers to an implicit analysis. Here to avoid the manual iteration in creating the larger chip cells, a Python script is developed to carry out the task (fragment A in the flowchart). Third, a MATLAB script is applied to calculate the average cutting force at each position of the tool (for each step) throughout the trajectory with respect to the tool's geometry and cutting conditions. Later, this value will be fed to Abaqus as the magnitude of the force for each step. A comparison of the proposed cutting force model from the MATLAB script and the one obtained from the experiment was found satisfactory.

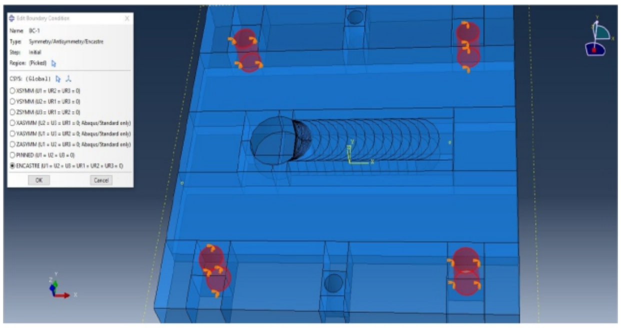

Figure 2-2: Boundary conditions, the four holes are fully fixed.

Fourth, for each chip removal, a distributed load on a semi-circular surface located on a force plane and underneath the relevant chip is defined. The force plane is defined with respect to the nominal depth of cut. This process is repeated for all larger chip cells with another Python script (fragment B in the flowchart). Fourth, the removing material action occurs. By using Abaqus modules, the uncut chip cell geometry is selected in GUI (Graphical User Interface) for each step and is excluded from the relevant step and all the future steps during the analysis. Fifth, the part is meshed with two different element types (linear hexahedron and linear tetrahedron). Sixth, the displacement value in Z-direction (U3) for each node (located on the machined face i.e., force plane) in the last frame of every step is extracted and written in an excel file using a Python script (fragment D in the flowchart). Plotting these values with respect to their X position along the trajectory shows the cutting deviation after machining.

3 RESULTS

A simplified static analysis was utilized to predict the elastic behavior and the deflection of the thin part. The cutting deflection was estimated according to the material deformation in different positions of the tool along the trajectory. This deformation was caused by an applied cutting force model in Z-direction in the prediction model. The force model in Abaqus represents the generated cutting forces caused by removing material (chips) from the workpiece in the experiment. Figure 3-1shows the deviations resulting from the cutting process based on the Abaqus model. The Z axis shows the magnitude of deviation with respect to the tool position along the trajectory.

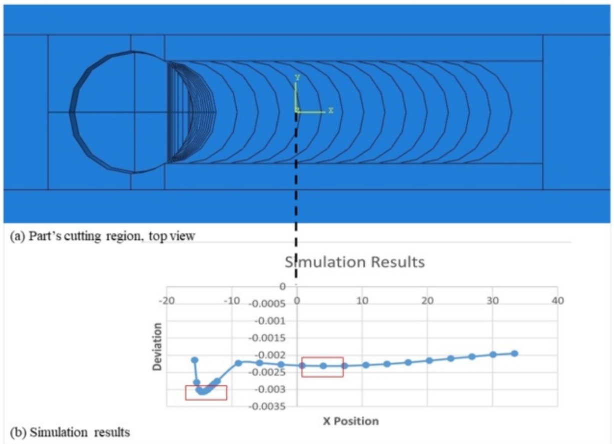

Figure 3-1: Predicted machined profile of the cutting region in Z-direction.

The numerical deviation profile as seen in the Figure 3-1 approximately shows the same valleys (two red rectangular insects) and the form as in the experimental results [1].

Under the action of the cutting force during machining, all displacement values (Z axis) are positive because of the load direction. This means the milling tool cuts more material as it advances through the workpiece (overcut). The maximum deflections happen in two locations according to.Figure 3-1. First is when the impact of the tool-workpiece occurs and next, it is somewhere close to the center of the workpiece ($X \approx 5$ mm), where the part is at its maximum flexibility. The average cutting force (Fz^{Ave}) value reaches to the highest value prior to the radial full-immersion condition in the impact. Once full-immersion happens, the deformation distribution relies only on the positions of the applied loads. The prediction model is compared to the experimental results [1] and shows the same deflection shape including the two valleys as presented in Figure 3-1.

According to the results, the displacement of the nodes is depending on two main factors; first, the position of the load when reading the value and the second is the magnitude of the load.

4 CONCLUSION

This study addressed a systematic semi-automated method for the modeling of the milling process of thin floor structures in both preprocessing and postprocessing, using Python Abaqus API. Implementing this type of API has not been a focus before, especially in milling thin walls. Although, FEM software programs are very powerful in simulation of machining processes, they all lack iterative algorithmic features which are necessary in prediction or compensation models, and they need to develop an in-house code for each particular process. Therefore, to reach the desired surface finish with a very low tolerable surface form error, a reliable method which considers iteration in all layers is essential. The proposed approach facilitated the prediction modeling process in Abaqus 6.13-1 by using several Python scripts in defining the model and reading the displacement results sections.

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