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Sy Quy NGUYEN

PREDICTION AND COMPENSATION OF GEOMETRICAL ERRORS IN MILLING PROCESS OF THIN COMPONENTS USING A FLEXIBLE CONFIGURATION SETUP

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PRÉDICTION ET LA COMPENSATION DES ERREURS GÉOMÉTRIQUES LORS DU FRAISAGE DE PIÈCES MINCES AVEC ASSEMBLAGE D'USINAGE FLEXIBLE

Sy Quy NGUYEN

RÉSUMÉ

Cette étude présente un modèle numérique permettant de prédire les déformations durant le procédé de fraisage de plaques minces supportées à l'aide d'un système de montage flexible. Un banc d'essai a été développé afin de monter les plaques en ses quatre coins pour reproduire les conditions de montage réellement disponibles par les systèmes de montage flexibles retrouvés en industrie. Le modèle proposé a recours au calcul par éléments finis afin d'estimer les erreurs d'usinage sous l'action des forces axiales en cours d'usinage. Le processus de calcul des déformations en cours d'usinage est simplifié en une répétition d'analyses statiques de déformation en différentes positions de l'outil tout au long de sa trajectoire empruntée. À chaque étape du processus iteratif, une nouvelle géométrie est produite, un maillage est adapté, et le calcul de la déformation est obtenu en ajustant la force selon un modèle préalablement défini.

À partir du modèle de déformation de la plaque prédit, un algorithme de compensation des trajectoires, basé sur une approche "miroir" est utilisé afin de corriger le parcours d'outil planifié pour obtenir un résultat comparable aux exigences prescrites.

Des essais expérimentaux sont également proposés pour valider l'approche. Les résultats montrent une adéquation raisonnable entre la prédiction calculée et la déformation réelle obtenue lors de l'usinage.

Mots-clés : pièces fines, usinage flexible, prédiction des erreurs, compensation des erreurs.

PREDICTION AND COMPENSATION OF GEOMETRICAL ERRORS IN MILLING PROCESS OF THIN COMPONENTS USING A FLEXIBLE CONFIGURATION SETUP

Sy Quy NGUYEN

ABSTRACT

In this study, a prediction model based on finite element analysis is developed to predict cutting errors during the machining process of thin plates using a flexible setup configuration. The model is based on analysis of the material deformation of thin plates under the action of axial cutting forces using a specifically designed test bed to reproduce commonly used flexible setup in industry. The cutting process is simplified as a static analysis of the material deformation under the effect of the applied cutting forces. In the analysis, different positions of the cutting tool during the machining process are studied to determine the workpiece's geometrical profiles during milling. Several analyses are carried out for different positions of the cutting tool. The cutting force is also modeled to predict the cutting force for specific cutting conditions. This cutting force model is utilized as input to the finite element analysis of the material deformation of the workpiece during the machining process. The experimental system is also designed to conduct tests with different cutting conditions on the three-axis Huron K2X10 CNC milling machine to verify the predicted results obtained from the analysis model. The geometrical errors of the machined plates after machining are determined by using the Mitutoyo Bright Strato Coordinate Measurement Machine (CMM) to measure their geometrical profiles before and after machining processes. Finally, the mirror technique is utilized to compensate cutting deviations based on the predicted results of the workpiece's displacements. Adding the value from the prediction model to the designed cutting depth creates the updated tool path. The results show good agreement in the prediction of the thin plate deformation during the machining as compared to the experimental tests.

Keywords: thin plates, flexible machining, errors prediction, errors compensation.

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LIST OF SYMBOLS AND UNITS OF MEASUREMENTS

y_t^i	y coordinate of the tool's center	mm
y_I^0	The initial position of the tool's center	mm
f	The feed rate of the cutting tool	(mm/sec)
t_i	Time step	Second
$\overline{F}_z$	Average cutting force	N
N	The numbers of flutes of the cutting tool	–
a	The cutting depth	mm
K_{ac}, K_{ae}	The cutting coefficients	–
$h(\emptyset)$	The chip thickness	mm
c	The feed rate	mm/rev.
$\emptyset$	The instantaneous angle of immersion	rad
U1	Forward/back movements	mm/sec
U2	Up/down movements	mm/sec
U3	Left/right movements	mm/sec
U4	Pitch movements	rad/sec
U5	Yaw movements	rad/sec
U6	Roll movements	rad/sec
$(D_i)_0$	Thickness of plate at certain position before machining	mm
$(z_R)_0$	z – coordinates of the reference point on top surface	mm
$(z_C^D)_0$	z – coordinates of the certain position on the bottom surface	mm
$(D_i)_m$	The thickness of plate at a certain position after machining	mm
$(z_i^T)_m$	z – coordinates of that loaction on top-surface from CMM results	mm

$(z_i^D)_m$	z – coordinates of that location on bottom-surface from CMM results	mm
(d_c^i)	The actual depth of cut at this location	mm
ε_m^i	The measured geometrical error at a certain position	mm
d_c	The nominal depth of cut as designed	mm
$\mathrm{d_c}$	The compensated depth of cut	mm
d_n	The designed depth of cut	mm
Δd^i	The cutting error at the location	mm

INTRODUCTION

In the aerospace industry, numerous large parts with complex curvatures and several thin wall/web pockets are required to ensure stiffness and low weight for aircraft structures. Costly processes and dedicated setups are usually required to machine such thin plate components. Therefore, investigating new machining methods involving flexible setups for such parts is an interesting avenue for cost savings, but a big challenge as well, due to a lack of support and part flexibility.

In fact, a flexible setup is a tooling system with numbers of adjustable positioning support pins, which can easily adapt to different workpiece geometries (Figure 0.1). Such systems are becoming widely used in the manufacturing industry in the recent years.

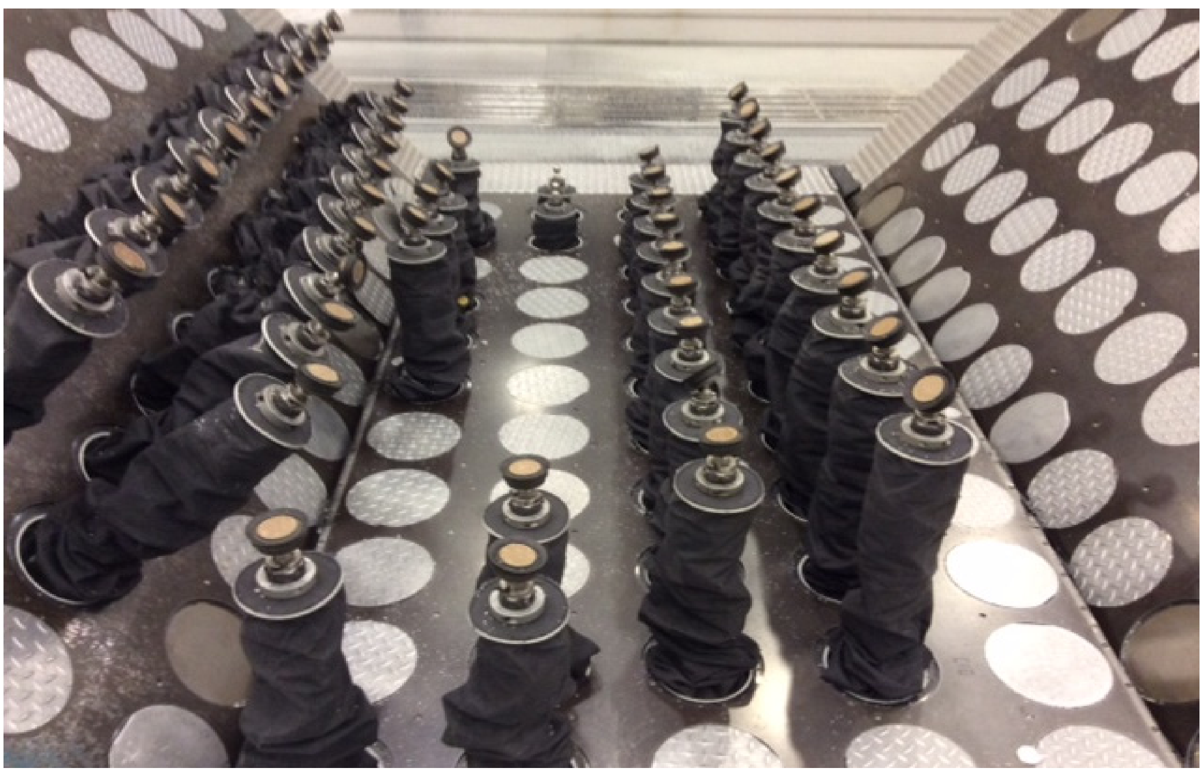

Figure 0. 1. Fixture with support pins on bottom face of the workpiece in the industry

Although they are efficient and capable of productivity increase for specific applications like the milling of prismatic parts with complex surfaces, the trimming or drilling of some composite and metallic parts with compatible thicknesses, they are not yet suitable to the milling of thin parts without using a back plating system. Typically, even though the positioning supports are adjustable, the part deviations are still too big in small areas between the support pins under the effect of the cutting forces.

In this study, we aim to propose a model capable to predict thin plate deformations during a slotting operation under cutting forces and accordingly compensate the tool path to eliminate the geometrical error. This study is part of a research program having as a global objective the development of software capable to properly compensate cutting tool paths for the pocket machining of thin parts using the commercially available flexible setup technologies.

To do so, a small scale test bed system, reproducing the flexible systems concept, is proposed for the machining experiments required for the model development and validation. The model proposed in this research is based on an “iterative” approach considering the cutting process as a static analysis of the material deformation under the acting cutting forces. In fact, different deformation profiles of the plate, related to discrete milling positions are calculated, and utilized to further compensate the toolpath. The deformation and compensation calculation thus requires a cutting force model as input to the finite element analysis. The cutting force model is also developed and presented in this work.

The report is divided into five chapters to present our research work in details. It starts with a literature review which presents recent works regarding the fixture design for the machining of thin/compliant components, and the modeling and compensation of cutting errors occurred during machining processes. The following chapter presents our work on the modelling of the cutting process for thin plates using a flexible setup configuration by applying finite element analysis. The deformation modeling and experimental verification of the results for different cutting conditions is then presented in chapter 3. The correlations and differences of the results obtained using the model as compared to the experiments ones are then discussed in chapter 4. The chapter 5 describes the application of the mirror technique to compensate the cutting errors during the milling operation of thin plates using the flexible setup. The document then ends with the conclusions and recommendations.

CHAPTER 1

LITERATURE REVIEW

1.1 Fixture design for the machining of thin compliant workpieces

In aerospace engineering, one of the most important requirements regards low weight. Since thin plates are not considered as the primary structure of an aircraft, pockets are proposed in their design to reduce the weight of the structure without affecting the stiffness. Thin plates are usually machined using back-plate setup for full support. However, because of the high cost of the tooling system produced specifically for each part model having different and complex surfaces, flexible systems for such parts have been the subject of different researches in the last years. The fixture setups are required to meet the conditions such as positive location, repeatability, rigidity, interference, and positioning fundamentals.

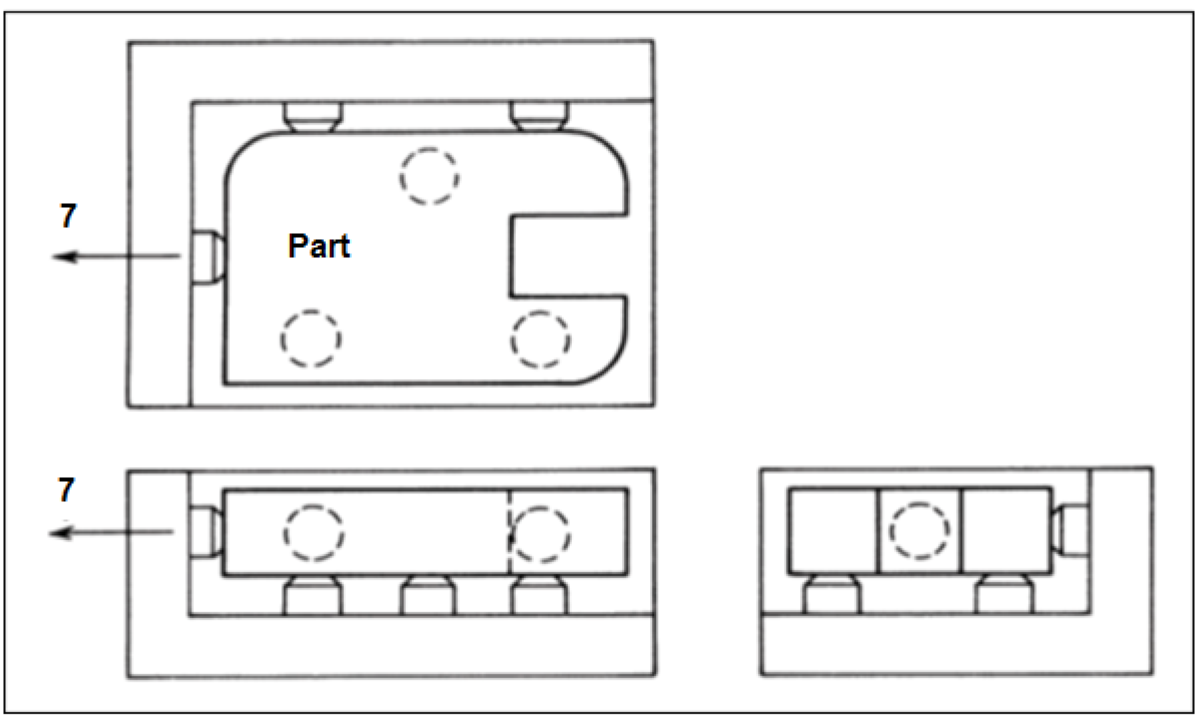

Figure 1.1. 3 – 2 – 1 principle (Foster, 1982)

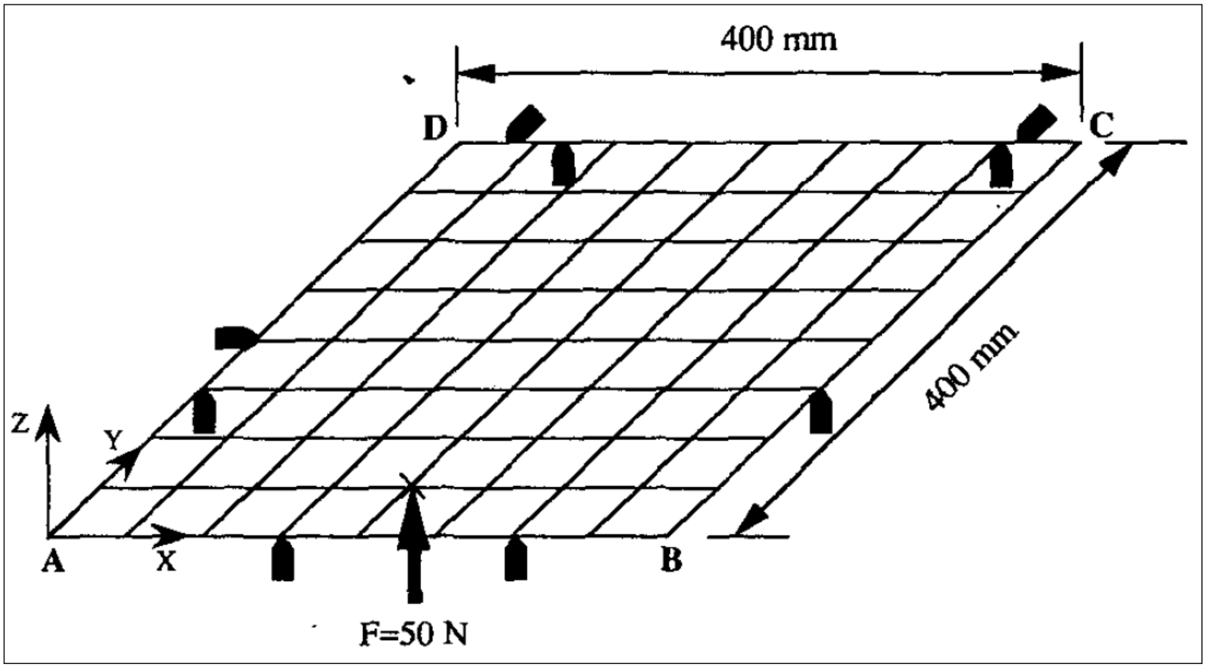

Figure 1.2. An example of system with N-2-1 principle, N = 6 (Cai et al., 1996)

With respect to reduce the cost of the fixture system in machining of thin plates, researchers have been attempted to investigate and develop new design methods for simplifying the system. The most common and earliest method for locating square or rectangular parts investigated is the method of "3-2-1" principle presented by Foster (1982). With using six pins distributed as 3-2-1 on the primary, secondary and tertiary datum surfaces, respectively as well as using a clamp, the system can locate the machining part as 6 freedoms on the fixture system.

For large and thin parts, the material deformation of the sheet metal in the normal direction of their major surface is the main issue for their machining. Therefore, the key solution in designing the fixture for large sheet metal plates is avoiding their deformation during manufacturing process. Requirement in restricting body motions is not enough for the fixture system in machining of sheet metal. Based from the "3-2-1" principle, Cai et al. (1996) developed a new design of fixture for the sheet metal manufacturing with the principle of N-2-1(N>3). A "N-2-1" locating principle for deformable sheet metal parts was proposed and compared with the widely accepted ' '3-2-1" principle for rigid bodies in order to minimize the total deformation of the deformable sheet metal. By adding a numbers of supports to the primary datum of the large thin workpieces, the sheet metal deformation that could not be neglected, even under self-weight of the workpiece in the normal direction of its surface, was reduced. In order to identify "N", the numbers of supports, as a value to minimize the workpiece deflections, the finite element method was utilized for deformation analysis and the nonlinear programming technique was employed to determine the optimal fixture layout.

However, for the flexible parts, having complex geometries, all support pins have to adapt with the part configurations. Thus, the fixed pins are incompatible for those workpieces. To solve that problem, Walczyk and Longtin (1999) developed a simple and inexpensive design fixture model for compliant parts. The authors used a computer-controlled, reconfigurable fixturing device (RFD) concept in their design. The system was designed with supporting pins that can be moved along the vertical direction controlled by a flat and rigid platen to adapt with the workpiece geometries. When the support pins reach the required position related to the CAD model of the workpiece, a clamping device locks them. The authors developed two kind of clamping devices as electromagnetic-assisted toggle mechanisms and pneumatic clamping.

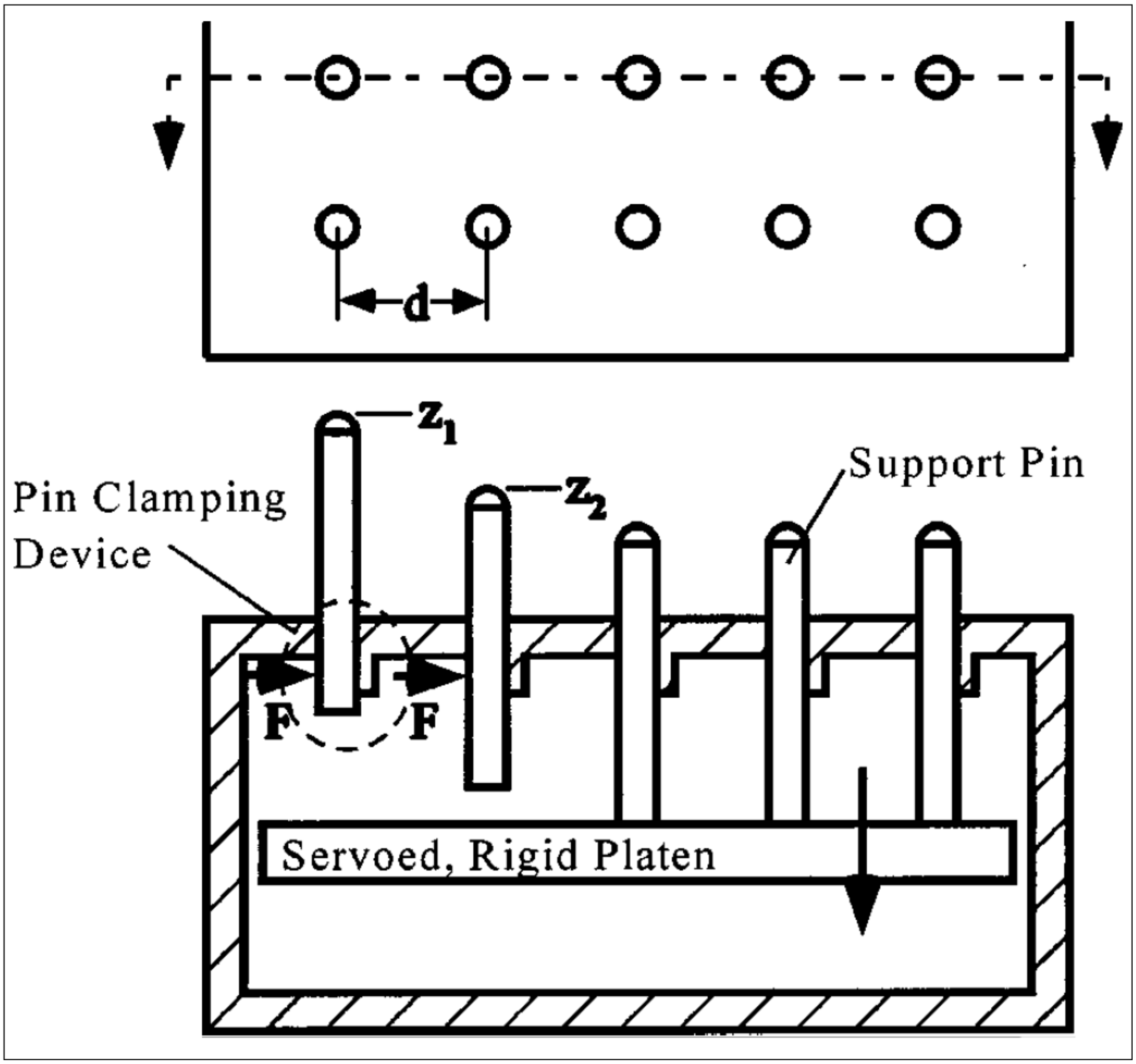

Figure 1.3. RFD concept diagram shown in pin setting mode (Walczyk and Longtin, 1999)

Similarly to Walczyk and Longtin (1999), Aoyama and Kakinuma (2005) also developed a flexible fixture system based on a matrix of support pins to avoid the material deformation of the compliant workpieces during machining. The main idea of the research is the design of the axial adjustment mechanism of the support pins. A low temperature melting alloy is utilized to adjust and fix the support pins to the workpiece's configurations. The support pins are elevated until contacting with the workpiece by a buoyancy force of the melted alloy. The melted alloy then is frozen by a cooling system to fix the support pins at the contacting positions.

In eliminating single-purpose hardware and reducing the human intervention required for assembly station set-up fixture systems, Asada and By (1985) introduced a general-purpose fixturing system activating automatically by a computer-integrated system that includes a robot manipulator. The authors replaced conventional single-purpose fixtures by a group of relocatable fixture elements that can be reconfigured for building different fixtures.

Liao (2003) provided a method based on genetic algorithm to automatically select the optimal number of locators and clamps. The author developed a fixture method that selects the positions of the locators for the locating scheme and determines the number and positions of the clamps for the clamping scheme to minimize workpiece deformation due to the gravity effect, the clamping force and the external operation loads. Two separate locating pools of 3-2-1 and pad-pin-slot were considered for the two different locating schemes. By applying finite element analysis to model the workpiece deformation, the gravity effect and the resulting variation due to part dimensional variation were simultaneously minimized.

In the various research works regarding optimal fixture design for drilling through deformable plate workpieces, Wardak et al. (2001) and Wardak et al. (2001) provided a mathematical model that captures the shape and dimensions of the drilled surfaces. By applying FE analysis and techniques that handle material removal strategies, the model was specifically developed for the rigid drilling process. The method is able to propose optimal fixturing parameters such as the position of locators, the position of clamps, and the magnitude of the clamping forces, by minimizing a user's selected objective function.

A method in the design of fixture configuration, recognizing the importance of the workpiece deformations and stresses, was presented in the study of Prabhaharan et al. (2007). Optimal fixture layout which minimizes the workpiece deformation is one of their design criteria. In fact, the design of the fixture layout is based on the types and number of fixturing elements, material of fixturing elements, and the position of fixturing elements. Their finite element approach described is however computationally intensive (particularly for nonlinear dynamic situations) and requires a considerable care in modeling the boundary conditions. This study gives an idea in milling thin components by optimization of the machining fixture layout using FEM and evolutionary techniques. By analyzing the influences of fixture layout to the dimensional and form accuracy of the workpiece during the machining process and applying finite element analysis for the modeling of workpiece deformation, the dimensional and form errors were minimized.

The paper of Liao and Hu (2001) presented a model developed for predicting the machined surface quality of a fixture-workpiece system. An integrated finite element analysis (FEA) model of the entire fixture–workpiece system is proposed to investigate the influence of clamping preload and machining force on the surface quality of the machined workpiece with taking into account the external loads, fixture compliances, workpiece and its locators/clamps surface-based contact interaction, as well as the dynamic stiffness of the fixture–workpiece system. The results focused on the prediction of machined surface quality by considering the effect of the whole fixture–workpiece system and influences of the clamping preloads and machining forces on the machined errors. However, even though the comparison between the simulation results and experimental data showed reasonable agreement, the difference stills quite significant. This discrepancy may be explained by the fixture–workpiece contact effect that was ignored for the dynamic analysis as well as uncertainties inherent to the FEA, such as the assumptions of the modeling process and boundary conditions.

Youcef-Toumi et al. (1988), Fields et al. (1989), and Youcef-Toumi and Buitrago (1989) in their studies, presented an automated manufacturing system for drilling sheet metal parts with association of robot manipulator.

It could be concluded that all previous methods were designed using adjustable support pins at the backplate of the workpiece and none of them is specifically adapted to thin plates. The pins in these cases provide support in order to avoid the deformation of parts during machining; as well, the special mechanisms for the adjustable pins are designed to match the fixture structure.

1.2 Machining errors and their prediction

In machining of thin components, geometrical errors generally appear because of the cutting deviations (machining deflections) of the process. Machining deflections often occur in the milling process due to the low-rigidity of these components that are thin-walled (floored). There are three major errors issue from the cutting processes; geometric, thermal and cutting-force induced errors (Ramesh et al., 2000, Ramesh et al., 2000). The geometric error is also due to the inaccuracy of the machine tool and the components in the system-assembly.

In support to other researches focusing on prevention and compensation of the cutting deflections occurring during the machining of thin components, many scientists have attempted in their research works to predict the cutting errors due to the deflections of cutting tool system and thin walls during machining (Figure 1.4). Kline et al. (1982) developed a mathematical model for the prediction of the surface error profile with combining cutter deflection and workpiece deflection under effect of cutting forces. The authors developed three models of the cutting force system, the deflection of the cutter, and the deflection of the workpiece. The chip load of the cutting tool was applied to compute the cutting forces in different elements. The cutter was considered as a cantilever beam deflected under the action of the cutting forces in the X and Y direction at each cutting forces' center. A thin walled workpiece was examined with three edges clamped while the rest of edge was free to deflect. The finite element method was applied to predict the workpiece deflection under effect of Y cutting force located at the center of the force distribution in the Y direction. In this research, the authors considered the combination of the cutting forces as well as the cutter and workpiece deflections into their modeling of cutting error prediction. However, their works suffer from the fact that the effect of the cutter and workpiece deflections were not taken into account in their cutting forces calculation.

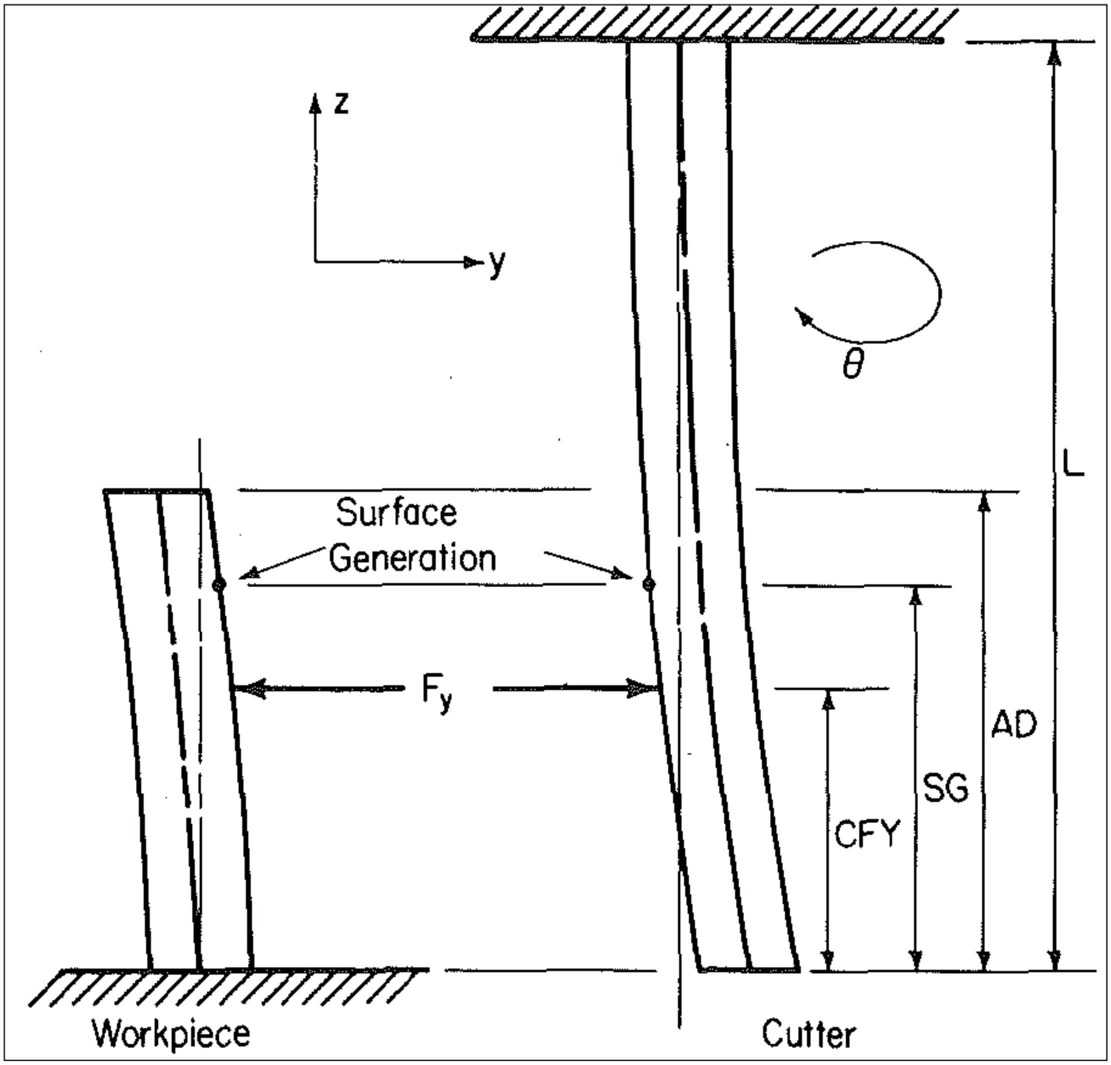

Figure 1.4. Cutter and workpiece deflections (Kline et al., 1982)

Ratchev et al. (2004) developed a flexible force model for the end milling process of low-rigidity parts with taking into account the changes of the immersion angles of the engaged teeth during milling process considered as the deflection of the workpiece (Figure 1.5). The model referred to finite element analysis to predict the part deflection in each computational step. As with the part deflection, the cutting is considered as an oblique cutting in each step while the forces are computed using the "oblique – orthogonal" transformation. An iterative process was developed to compute the cutting forces during machining. Considering the workpiece deflection into account in the cutting model, the method proposed a computational approach of cutting forces and cutting error predictions.

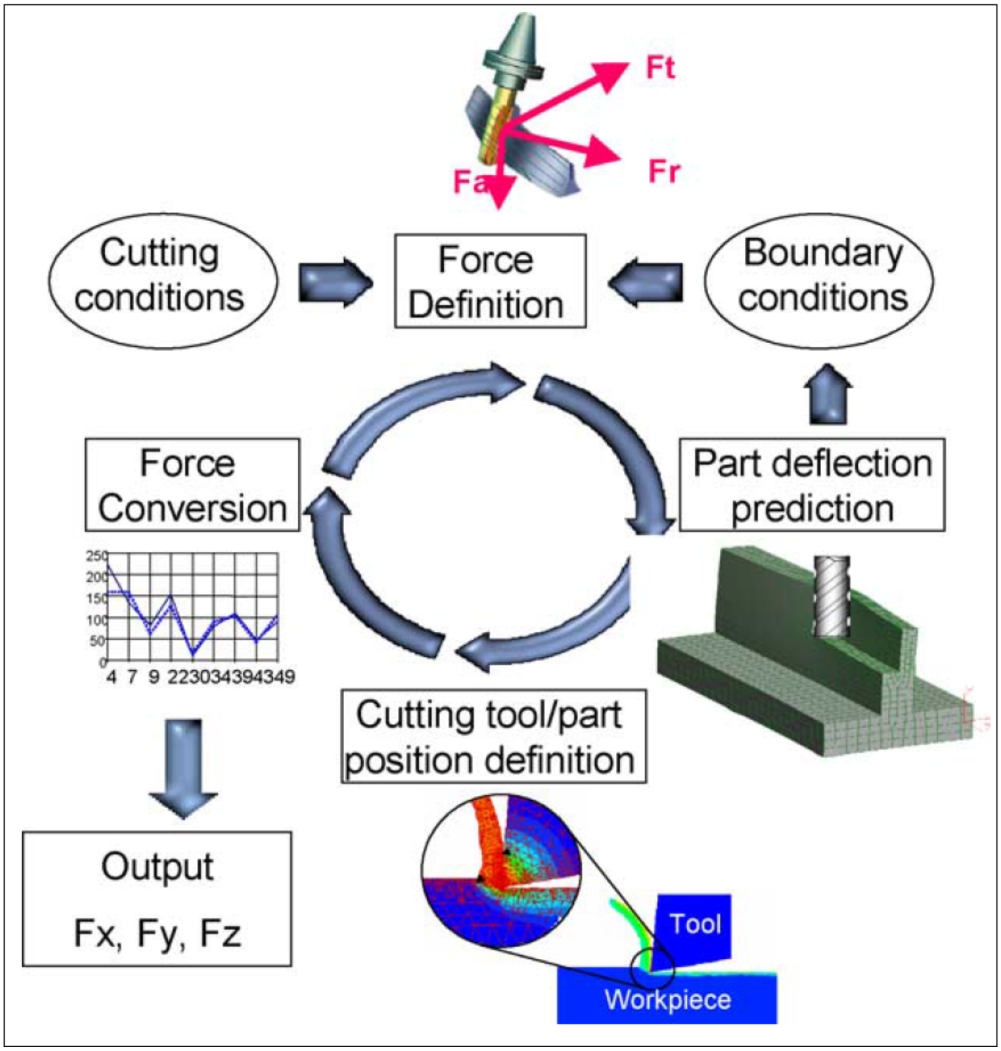

Figure 1.5. Iterative flexible force prediction model
(Ratchev et al., 2004)

Another research of Ratchev et al. (2003) reported a new methodology in the prediction of surface error during machining of flexible thin-walled parts using genetically modified neural networks for force prediction, and FEA for the modeling of part deflection. The voxel-based model of material removal process was applied to their proposed method shown in Figure 1.6. In the voxel method, by linking the FE nodal data to volumetric elements, it allows to directly simulate the material removal process as a Boolean subtraction of the tool volume from the deflected part model. The cutting process now can be simulated by the removal of all the voxels intersecting with the tool volumes by applying a modified "marching cubes" algorithm (Choi, 1998).

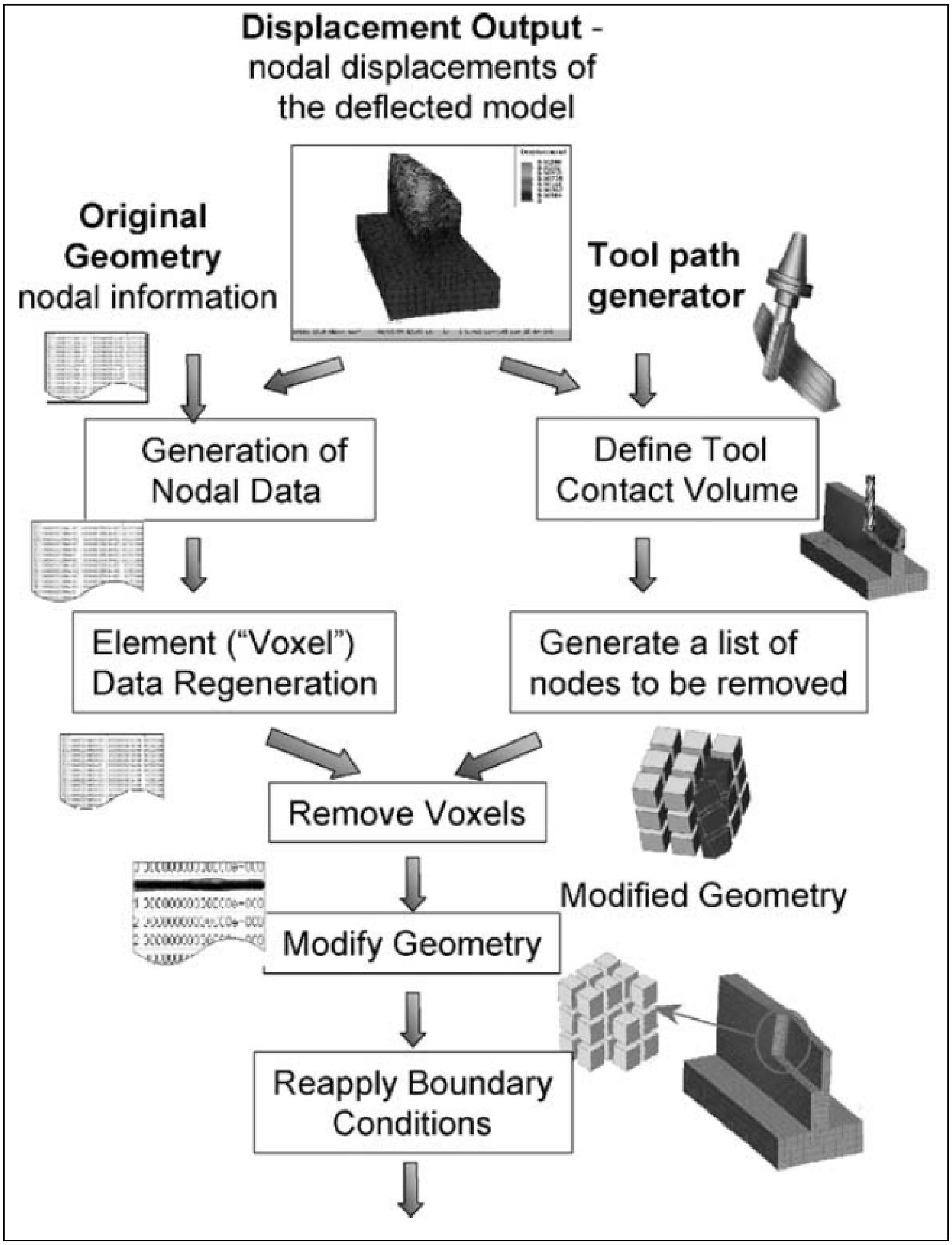

Figure 1.6. Voxel-based modelling for error prediction and compensation (Ratchev et al., 2003).

Tsai and Liao (1999) also developed a force-prediction model to predict geometrical errors in the peripheral milling of thin walled workpieces with considering the cutting tool as a pre-twisted "Timoshenko" beam element and the workpiece with 3D isoparametric 12-node element. The authors applied the modified Newton-Raphson method to solve iteratively the cutting force distribution and the cutting system deflections including the effect of the workpiece and tool's deflection.

Feng and Menq (1996) presented a flexible system model for the prediction of cutting forces and the resulting machining errors in the ball end milling process of thin walled workpieces. The model took into account the instantaneous and regenerative feedback of cutting system deflections to establish the chip geometry in the cutting force calculation algorithm with considering the effect of chip geometry on the deflection of the cutting system and the surface produced by the passage of previous teeth. An iterative algorithm has been presented to describe the method of establishing the deflection-dependent chip geometry, which balances the cutting forces and the associated cutting system deflections.

Sutherland and DeVor (1986) developed a model for the prediction of the cutting forces and the surface errors in end milling. The method incorporates the inherent end milling system flexibilities into the existing end milling force and surface error models. An iterative procedure was used to balance the forces and deflections generated during the cutting process. A new chip load algorithm was also presented and merged with the existing milling model.

Gu et al. (1997) presented their study regarding the prediction of surface flatness in face milling, including the effects of machining conditions, elastic deformation of the cutter-spindle and workpiece-fixture assemblies, static spindle axis tilt and axially inclined tool path.

Golden and Melkote (2008) introduced a method for the prediction of final peak-to-valley (PTV) surface profile variation for face turning of rings of non-uniform cross section with applying the finite element method to supplement an analytical model. Experiments are conducted to validate both the analytical and finite element approaches.

In most machining compensation research works, the key problem is the determination of workpiece's deflections with the main factor being the material deformation. Many research studies have attempted to apply the finite element method in computing material deformation during machining.

In fact, there are three modeling approaches referred to the material deformation prediction; such as the static model, the quasi-static model and the dynamic model. The static model considers the effect of the workpiece deformation, the cutter distortion, and the influence of removal of material on the workpiece rigidity. The cutting forces are calculated directly with nominal cutting depth. The machining deformation is predicted. The quasi-static model considers the influence of the material removal but does not take the workpiece and cutter deformation into account. Finally, the dynamic model does take the deflections into account in calculation and prediction of final cutting errors.

1.3 Error compensation in machining of thin compliant workpieces

In avoiding the geometrical errors of machined parts following the machining process, many research works have been carried out to reduce the cutting deviations in machining of thin parts. They can be classified as two groups: deflection avoidance and deflection compensation. Researches in the group of deflection avoidance have attempted to improve the rigidity of the machining system. However, this kind of method requires a high cost to develop and manufacture the physical structures of the system. Researches related to deflection compensation regard the development of cutting models to optimize the tool paths in order to compensate the cutting deviations. By computing the machining deflections, a new tool path is optimized until the cutting deviation converges to a reasonable value.

Wang et al. (2002) developed a static/quasi-static error compensation system composed of an interpolation algorithm based on shape functions for error prediction, and a recursive software compensation procedure. Based on the proposed schemes, a practical error compensation system incorporated with an automatic NC code identifying/rewriting system was developed for multi-axis machines.

Figure 1.7 shows the compensation model of the research of Ratchev et al. (2006). The method starts with the analysis and prediction of the forces and part deflection by FEA method. It is predicted using a theoretical flexible force model, taking into account the recursive correlation between cutting forces, part deflection and cutter immersion angle. The cutting error is then obtained based on the part deflection. By comparing the nominal cutting path and the predicted cutting error, a new tool path is then optimized. The cutting trajectory is then automatically modified according to the predicted part deflection.

Ratchev et al. (2004) in their paper, also presented an integrated methodology for the modeling and prediction of surface errors caused by deflection during machining of low-rigidity components. The proposed approach is based on identifying and modeling the key processing characteristics that influence part deflections in order to predict the workpiece deflection through an adaptive flexible theoretical force-FEA deflection model and provide an input for downstream decision making on error compensation.

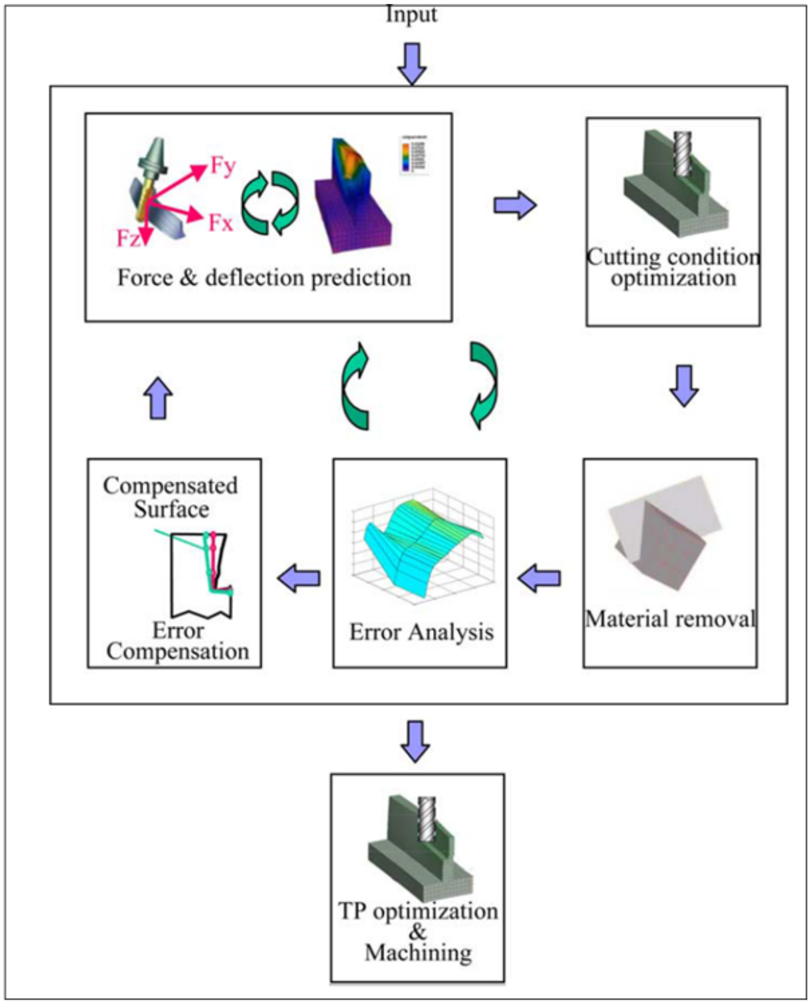

Figure 1.7. An adaptive machining environment methodology overview (Ratchev et al., 2006)

Another research of Ratchev et al. (2005) provided a solution in machining error compensation considering the influence of cutting deflection on cutting forces. The theoretical force model was built taking into account the change of the current cutting point under material deformation. The cutting deflection is then predicted based on the result of theoretical force model by using finite element analysis of Abaqus software. Finally, the tool path optimization model was developed to compensate the cutting deflection calculated by FEA. Experiments were carried out on CNC machine to verify the simulation results. However, due to limitation of the quasi-static model for the optimization process, the compensation was done with single level of compensation. In fact, the cutting deflections in the compensated tool path would be greater than the nominal tool path. The iterative process should be developed in order to re-calculate the new cutting deflections. This research provides an interesting aspect to take into consideration in our thesis; considering the movement of the cutting point into the calculation of the cutting force.

Chen et al. (2009) also developed a compensation model for thin walled parts machining using a multilayer cutting process. In multilayer cutting, the deformation of each cutting layer affects the nominal cutting depth of the next cutting layer. The authors used the multilayer cutting to improve the cutting quality of the machining thin walled parts. A deformation model was established to predict the cutting depth, which includes the deformation of previous cutting and the nominal cutting depth of current cutting. The error compensation model was finally developed based on the obtained cutting deformation. In the compensation model, the corrected tool path positions are obtained by the so-called mirror error compensation method. This method increases the cutting depth greater/less than nominal cutting depth to compensate the cutting deviations resulted by part deflection. With utilization of the multilayer cutting method, the process reduced the cutting depth at each cutting time, which results in least cutting forces during the machining process. With a low rigidity system related to the machining process of thin walled components, the idea gave a great benefit in strengthening the system's stiffness. However, due to the multilayer process, the total deviation is a combination of each cutting layer. So, the final deviation will be greater. The authors proposed a precise model of the deformation prediction in considering the influence of the deformation of the previous layer to the current cutting layer. In that study, the authors developed two separate processes as the deformation prediction and the deformation compensation. In the deformation prediction process, a method was developed as a dynamic model with considering the influence of material removal and taking workpiece and cutter deformation into account. However, the limitation of the method is that the authors did not consider the influence of compensation into the cutting deformation. Since compensation with new cutting conditions will change the material deformation compared to the value without compensation, the deformation should be re-modeled. As the authors did not consider this aspect in their study, the method could not be seen as a fully optimization method.

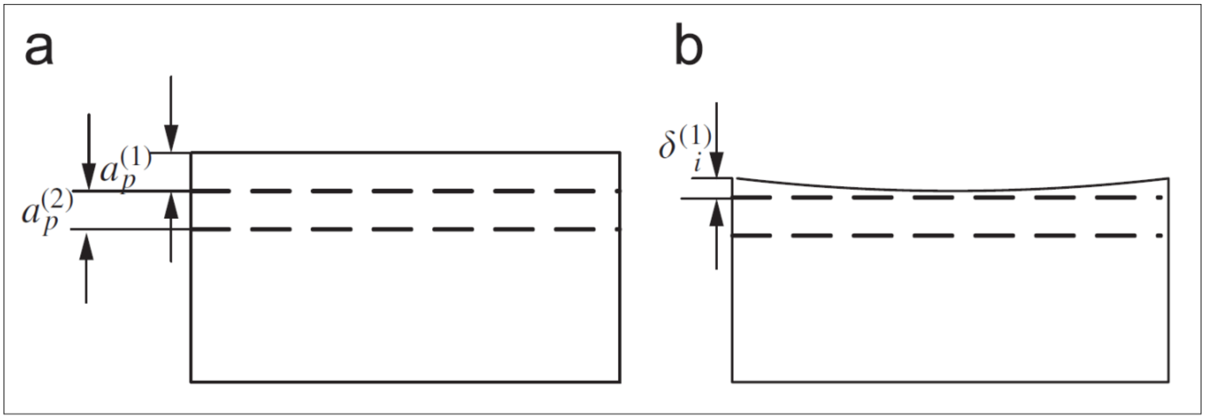

Figure 1.8. Multilayer cutting model (Chen et al., 2009)

Differing from other compensation methods based on part deflection, Dépincé and Hascoët (2006) and Dépincé and Hascoët (2006) developed a compensation model considering the cutter deflection as the main source of deflection. Their researches focus on the tool deflection by force induced. Based on the deflection results from the FEA model created to compute the cutting deflection, the compensation was realized taking into account tool deflection during tool-path generation. The new trajectory of the cutting tool is then proposed to compensate the defects due to tool deflection and allow togenerate the profile equal to the specified profile as shown in Figure 1.9.

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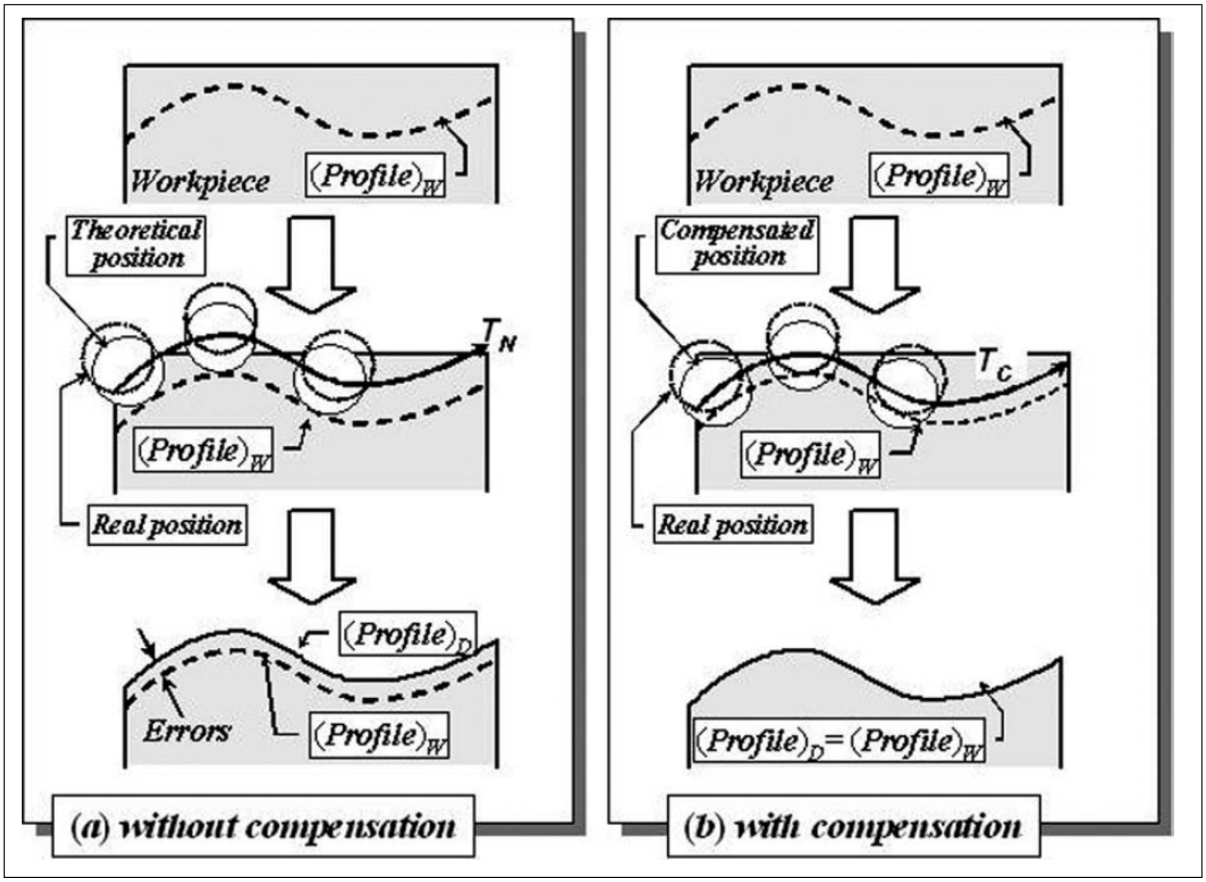


Figure 1.9. Path compensation (Dépincé and Hascoët, 2006)

1.4 Summary of literature review

Recent research works related to fixture design for the milling of thin components proposed different fixture methods using adjustable support pins at the backplate of the workpieces. The pins in these cases provide support in order to avoid the material deformation of plates during the machining process; as well, the special mechanisms for the adjustable pins are designed to match the fixture structure. However, for the machining of large sized thin workpieces, geometrical errors still appear in the un-supporting areas.

In this research work, we propose a test bed system offering partial support to the backface of the workpieces during machining in order to reproduce existing commercial systems. A model using the finite element method is also proposed in order to predict the cutting deviations during the milling process of thin plates using the introducing flexible setup system. Recent research works for the analysis of the machining process of thin walled components are referenced to our proposed model related to the milling process of thin-floored components. The proposed test bed is utilized to mill slots with different machining conditions in order to validate the results of the proposed analysis model.

Finally, the compensation process using a mirror technique is applied to compensate the cutting deviations during machining of thin plates using the proposed system.

CHAPTER 2

MODELING OF CUTTING ERRORS DURING MACHINING OF THIN COMPONENTS USING A FLEXIBLE SETUP CONFIGURATION

2.1 Problem definition

In this research, a method referring to flexible setup configurations for machining thin plates is introduced. The approach considers a partial support to the bottom face of the workpiece to reproduce the existing commercially available flexible setups used in the industry, as shown in Figure 0.1, with using the proposed testbed, the cutting errors appeared in the areas between support pins on the primary surface of the thin workpiece can be examined, and analyzed. The common industrial system (Figure 0.1) could be considered as a combination of multiple testbed models. Given its adjustability, the proposed test bed system is able to adapt to different workpiece configurations, making the setup-configuration flexible. With its simple and low cost structure, the proposed setup with flexible configurations definitely provides an efficient method to develop and validate a model for part deflection prediction and compensation for the milling of thin plates.

Figure 2.1 shows the design of the proposed test bed. The fixture system includes four location pins adjustable in four different positions in the x, y plane. The plate to be machined must be drilled in the four corners to be placed and fixed on the location pins using bolts. The system is designed to make sure the bottom face of the workpiece can be freely deformed in the vertical direction. More details regarding the experimental methodology will be provided in the next chapter.

Since there is no support on the bottom face of the plate during machining with using the flexible setup, the major material deformation of the workpiece is in the vertical direction under the effect of the cutting force in z – direction (F_z). Therefore, the study will mainly focus on this force component for the analysis. Assuming that the deformation of the cutter is negligible as compared to the deformation of the thin part, the cutting deflection will mainly result from the material deformation of the workpiece.

The schematic of the material deformation and the cutting deviations during machining of a thin part using the flexible setup is expressed in Figure 2.2. Because of the cutting force acting on the plate during machining, the thin plate is deformed in the vertical direction. The actual cutting depth at a certain position of the cutting tool (d_c^i) is thus different from the nominal value (d_c^0), representing the programmed depth of cut.

As stated before, this research aims to predict the geometrical cutting errors during the machining of thin plates using a flexible setup configuration, and then compensate the toolpath with appropriate correction factors to make sure the final depth complies to the nominal specifications. The finite element method is proposed in this research to model the cutting process.

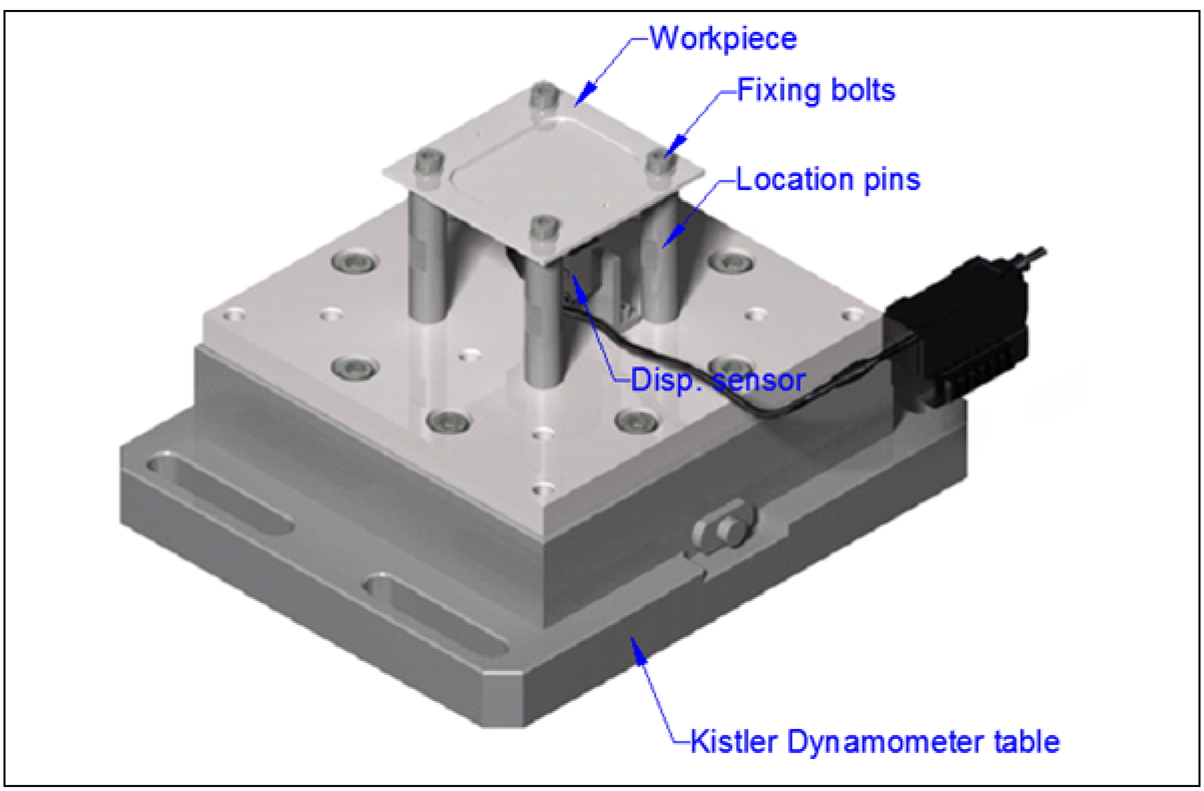


Figure 2.1. Flexible setup design

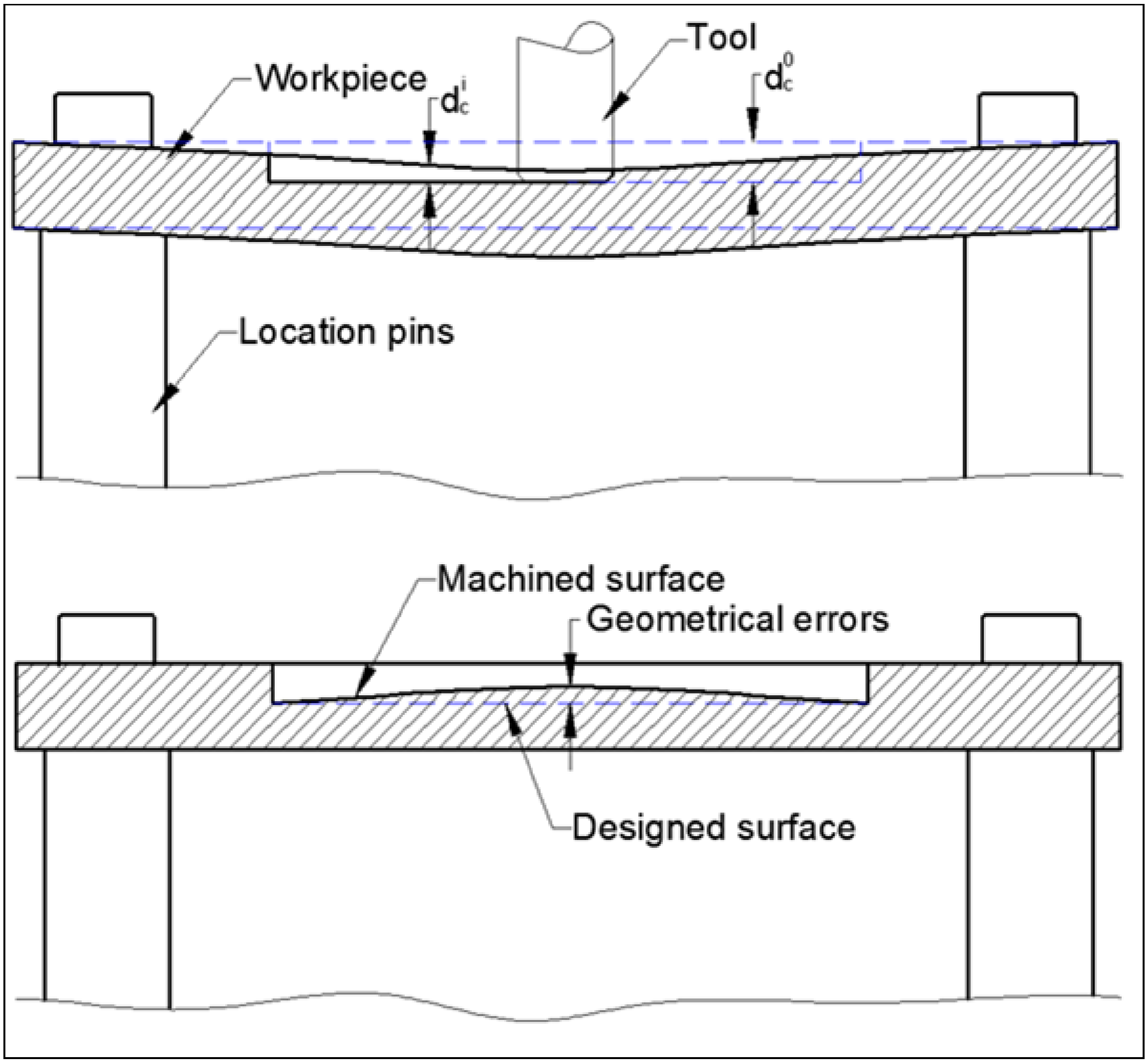


Figure 2.2. Material deformation during machining and geometrical profile after machining

2.2 Methodology

During machining of thin components using the flexible configuration setup, the workpiece is deformed under the effect of the cutting force in the vertical direction. This is the main reason of cutting deviations during machining of thin components using flexible setup. In the present section, a finite element model is developed aiming to compute the material deformation of the workpiece during machining in order to predict the geometrical errors due to cutting deflections.

The finite element method is utilized to model the cutting process. The cutting process is simplified to be considered as an iterative process involving a static analysis at a specific position of the cutting tool. Numbers of iterations (computations) are conducted at several times (positions) of the cutting process to compute the deformation of the plate.

The cutting deflection at a specific position of the cutting tool can be estimated by determining the displacements of the workpiece's area under the tool when the tool is at this position. When the computation is finished, the displacements are then collected, and the cutting deflection of the whole plate is determined.

The Figure 2.3 shows the modeling process for each computation at a specific position of the cutting tool. The process starts with collecting initial conditions as the flexible setup design (CAD file), the workpiece geometry (CAD file) and the cutting conditions into analysis.

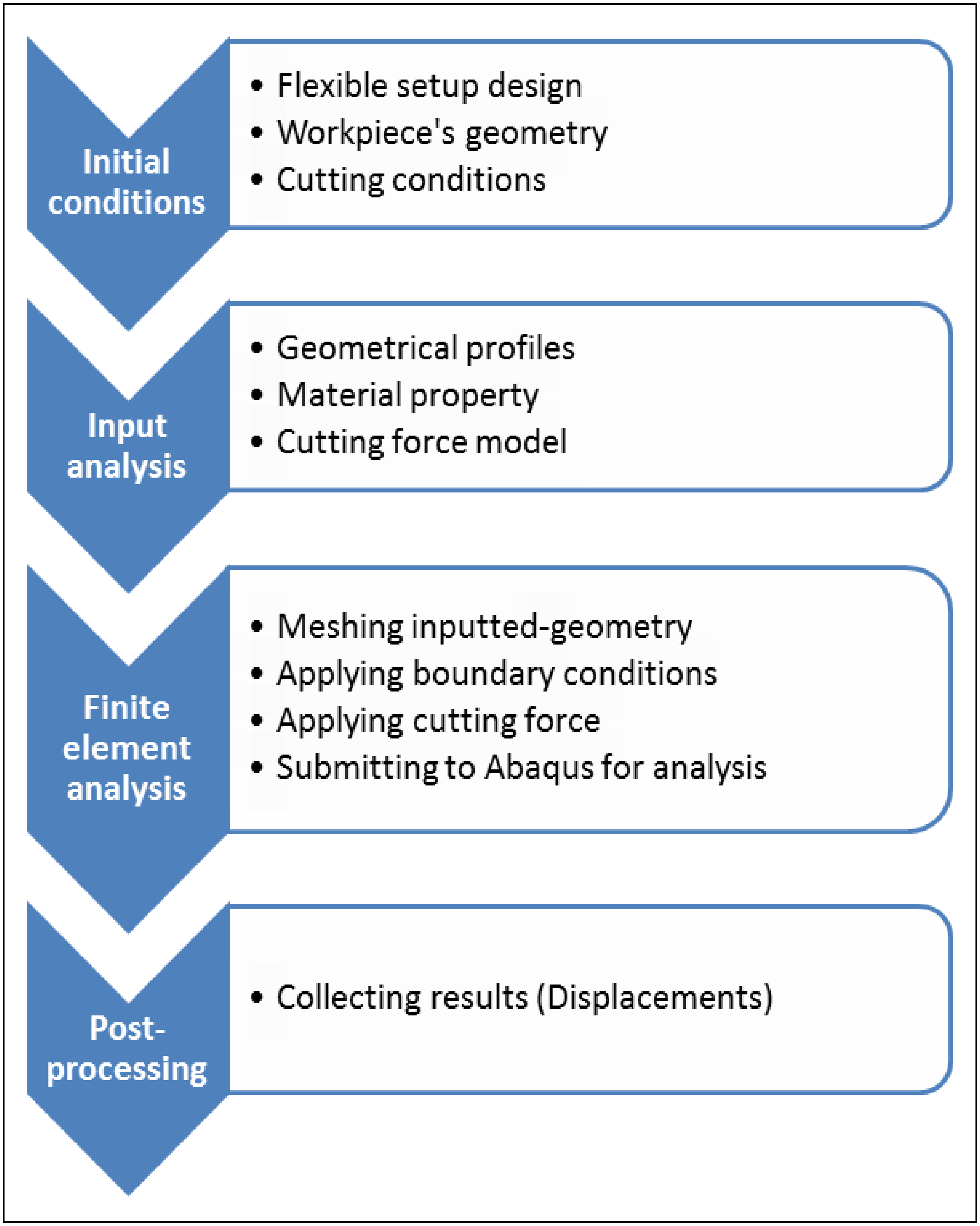


Figure 2.3. Modeling process

As the initial conditions collected, the input analysis is then conducted to determine information to be inputted to the finite element analysis. At this stage, the geometrical profile at a particular computation is defined because a volume of materials is removed from the workpiece during the cutting process; geometries of the workpiece at different times are expressed as different “profiles”. The material property is also identified as the workpiece’s material.

After input of the geometrical profile of the workpiece, the cutting force is then modeled. The cutting force model is built to simulate the cutting force applied to the workpiece during cutting process at all time.

The analysis is continued with the main part of the finite element analysis from all input data obtained from previous stage. The geometrical profile inputted is now partitioned and meshed into nodes and elements. The clamping conditions are translated as the boundary conditions in the finite element analysis. The cutting force modeled is applied with its magnitude and place of application. In this stage, the Abaqus – FEA software is utilized to compute the material deformation of the workpiece under the effect of the cutting force.

Following the finite element analysis for each position of the cutting tool, the displacement results for the complete process are obtained. The behavior of the workpiece during the whole machining process is now collected.

The details regarding each stage of this modeling process are presented in the following section.

2.2.1 Workpiece’s geometry and geometrical profile inputted to analysis

The workpiece geometry used is a thin plate of 120 x 120 x 6.35 (mm) with four holes on the corners and a lead-in pocket as shown in Figure 2.4; the lead-in pocket is prepared as a technical condition for slot milling detailed in the following experimental section. As the tool starts from the lead-in pocket and moves straightly toward the y direction, the geometrical profiles of workpiece is changing during the cutting process.

Figure 2.5 illustrates the changing of geometrical profiles of the workpiece at different times (positions) during the cutting process.

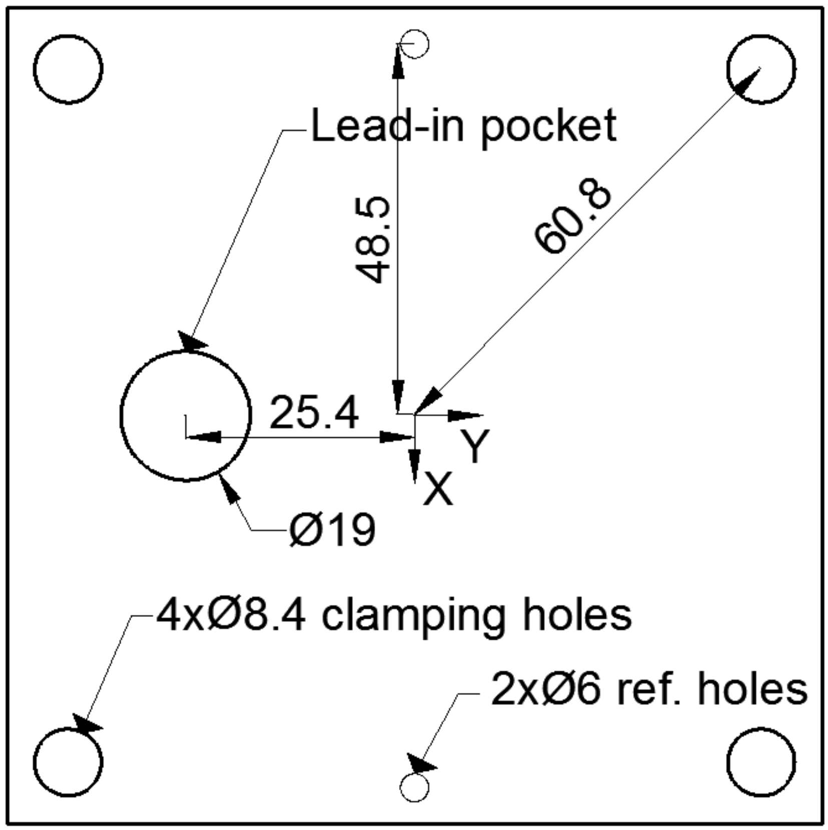
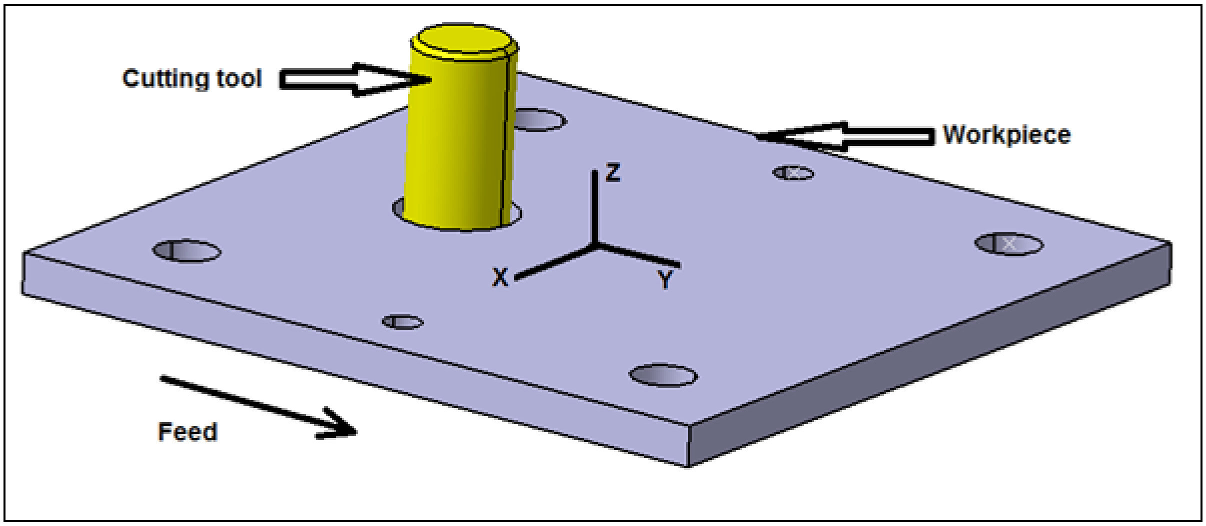
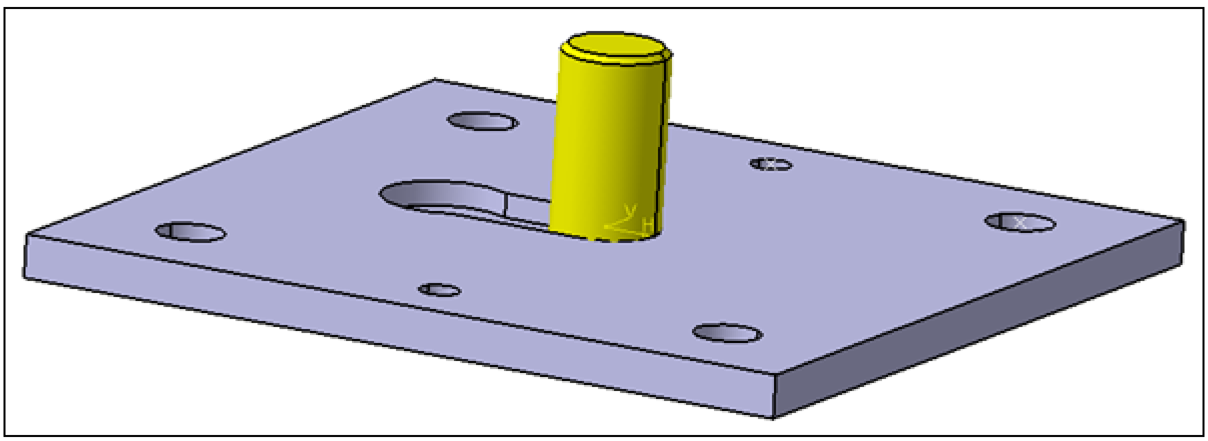


Figure 2.4. Workpiece geometry



(a) Initial shape of the workpiece at the beginning of cutting



(b) The workpiece's geometry and cutting tool at a certain time

Figure 2.5. Workpiece's geometries at different times

In the computation for each position of cutting tool during machining, the geometrical profile of the workpiece is determined by the position of the cutting tool at a certain time. The y coordinate of the tool's center (y_t^i) at the time (t_i) can be calculated as,

$$y_t^i = y_l^0 + f^*t_i \tag{2.1}$$

where y_l^0 is the initial position of the tool's center, it is the center of lead-in pocket, while f is the feed rate of the cutting tool (mm/sec).

With different positions of the tool, the workpiece geometrical profiles are built and lead to different shapes. In fact, a volume of material is removed from the workpiece and a new shape of workpiece is obtained. Sixteen positions of tool have been examined for the analysis of a 42.324 mm total, as shown in Table 2.1

Table 2.1. Positions of tool's center for examination

Number	y – coordinates of tool’s center (mm)	Number	y – coordinates of tool’s center (mm)
1	-16.924	9	2.6099
2	-13.369	10	5.8656
3	-10.413	11	9.1213
4	-7.157	12	12.3771
5	-3.902	13	15.6328
6	-0.616	14	18.8885
7	0	15	22.1443
8	2.6099	16	25.4

2.2.2 Material property

The material of the workpiece used is aluminum 6061 – T6. The mechanical properties of the material are described in the Table 2.2.

Table 2.2. Mechanical properties of Aluminum 6061 – T6

Ultimate Tensile Strength	310 MPa	AA; Typical
Tensile Yield Strength	276 MPa	AA; Typical
Elongation at Break	12 %	AA; Typical; 1/16 in. (1.6 mm) Thickness
Elongation at Break	17 %	AA; Typical; 1/2 in. (12.7 mm) Diameter
Modulus of Elasticity	68.9 GPa	AA; Typical; Average of tension and compression. Compression modulus is about 2% greater than tensile modulus.
Notched Tensile Strength	324 MPa	2.5 cm width x 0.16 cm thick side-notched specimen, K_t = 17.
Ultimate Bearing Strength	607 MPa	Edge distance/pin diameter = 2.0
Bearing Yield Strength	386 MPa	Edge distance/pin diameter = 2.0
Poisson's Ratio	0.33	Estimated from trends in similar Al alloys.
Fatigue Strength	96.5 MPa	AA; 500,000,000 cycles completely reversed stress; RR Moore machine/specimen
Fracture Toughness	29 MPa-m½	K_{IC}; TL orientation.
Machinability	50 %	0-100 Scale of Aluminum Alloys
Shear Modulus	26 GPa	Estimated from similar Al alloys.
Shear Strength	207 MPa	AA; Typica

2.2.3 Cutting forces simulation

In the computation, the vertical deformation of the plate is only considered. Therefore, the effects of the feed force and normal force components are neglected in the analysis of the workpiece's material deformation in the vertical direction.

Firstly, the cutting coefficients for the milling of aluminum 6061 – T6 , using and end mill Niagara Ø5/8" – 2F – TiCN coated, must be determined by conducting numbers of tests in the same rotational speed of the cutting tool(spindle speed) and different feeds as shown in the Table 2.3.

The method to determine the cutting coefficients is proposed by Altintas and Lee (1996), Budak et al. (1996) and Altintas (2012). The average cutting force is expressed as,

$$\bar{F_z} = \frac{Na}{\pi} K_{ac} f + \frac{Na}{2} K_{ae} \tag{2.2}$$

$$\bar{F_z} = \overline{F_{zc}} f + \overline{F_{ze}} \tag{2.3}$$

where N is the numbers of flutes of the cutting tool, a is the cutting depth, f is the feed rate, and K_{ac}, K_{ae} are the cutting coefficients.

From the experimental results, $\overline{F_{zc}}$ and $\overline{F_{ze}}$ can be integrated from the average cutting forces obtained as shown in Figure 2.6.

From the figure we have,

$$\begin{cases} \bar{F}_{zc} = -617.53 \\ \bar{F}_{ze} = -7.2293 \end{cases} \tag{2.4}$$

Table 2.3. Cutting conditions for the determining cutting coefficients.

Test #	Spindle speed (rpm)	Feed rate (mm per tooth)	Average Cutting Force ($\bar{F_z}$) (N)
1	6111	0.127	-72.0452
2	6111	0.1397	-78.292
3	6111	0.1524	-85.259
4	6111	0.1651	-96.825
5	6111	0.1778	-101.992

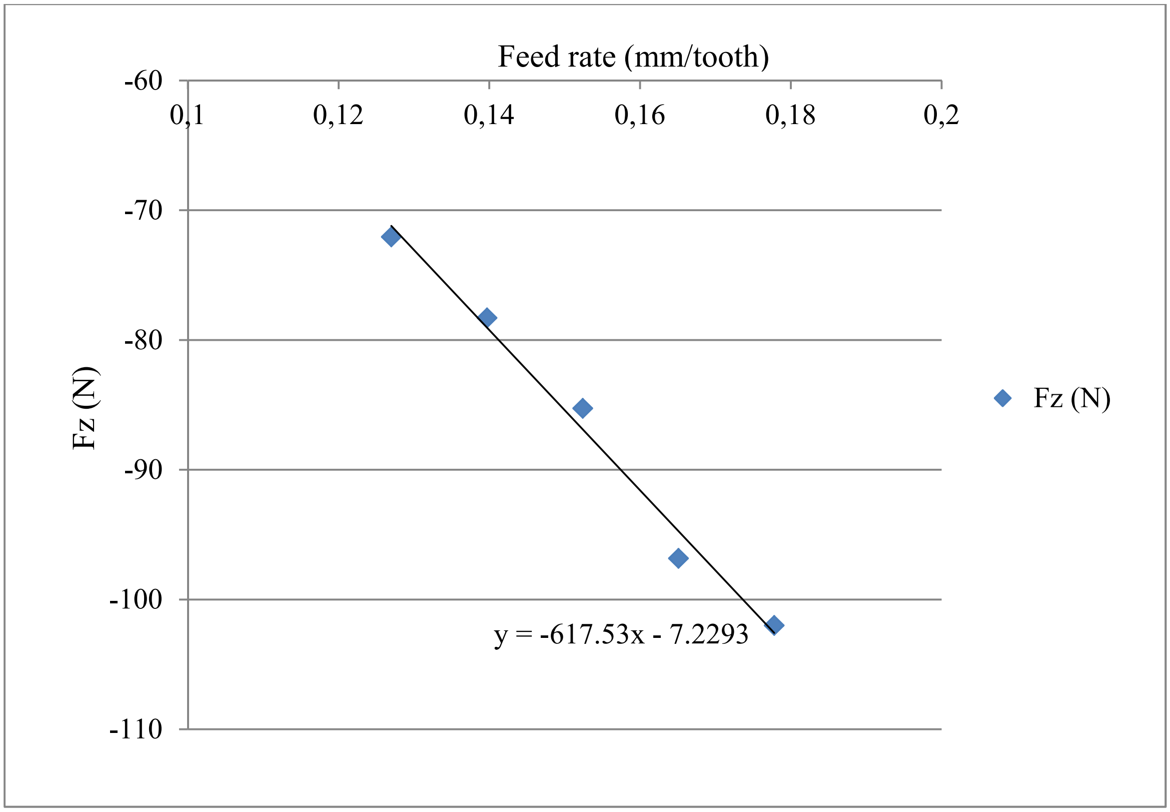


Figure 2.6. Cutting force average

With number of flutes (N) = 2, and depth of cut (a) = 2.0 mm, the cutting constants in z – direction can be calculated as,

$$\begin{cases} K_{ac} = \frac{\pi \bar{F}_{zc}}{Na} \\ K_{ae} = \frac{2\bar{F}_{ze}}{Na} \end{cases} \tag{2.5}$$

$$\begin{cases} K_{ac} = -485.007 \\ K_{ae} = -3.6147 \end{cases} \tag{2.6}$$

The cutting force in z – direction is calculated as (Altintas, 2012),

$$F_z = -F_a = K_{ac} * a * h(\emptyset) + K_{ae} * a \tag{2.7}$$

where a is the depth of cut and $h(\emptyset)$ is the chip thickness. $h(\emptyset)$ can be calculated as,

$$h(\emptyset) = c * \sin(\emptyset) \tag{2.8}$$

where c is the feed rate (mm/rev-tooth) and $\emptyset$ is the instantaneous angle of immersion.

The modeled cutting force (*Fz*) is then calculated for our milling process using equation 2.7.

As an example, Figure 7 shows the comparison between the simulated and the experimental results of the cutting force for the cutting condition related to the first test. The model was carried out to simulate the cutting force as a function of the rotation angle of the cutting tool.

During one rotation of the tool, the cutting force is changing continuously because of the changing of the instantaneous angle of immersion. The cutting force reaches the maximum value when the angle of immersion is 90^O or 270^O.

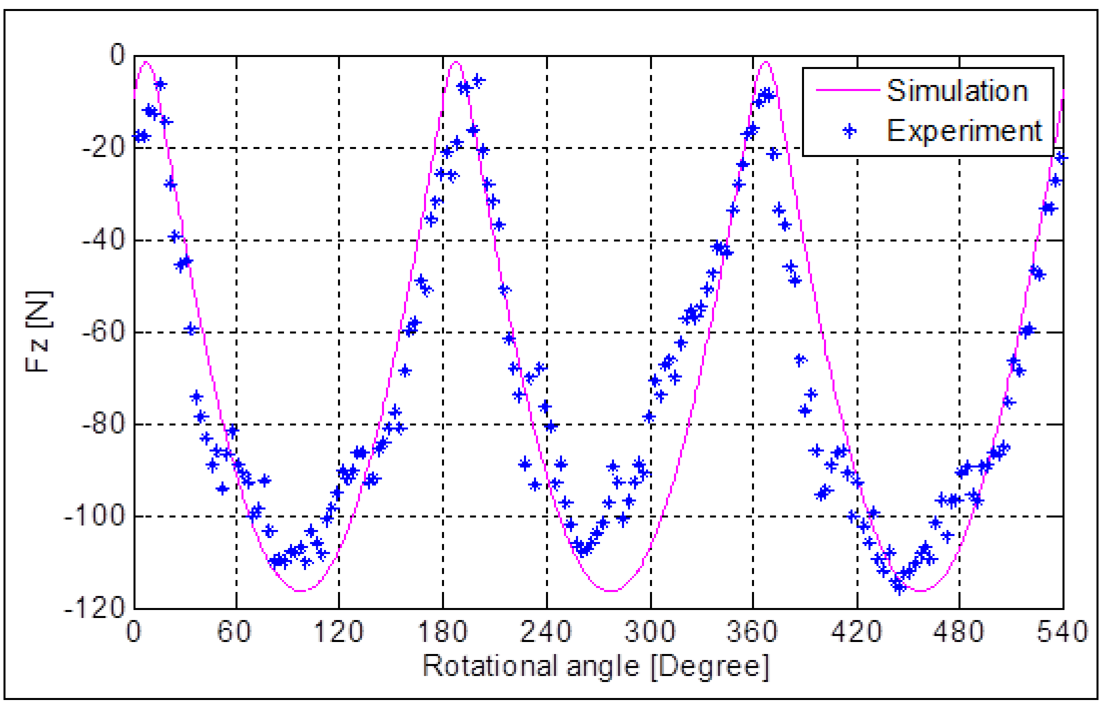


Figure 2.7. Comparison of axial cutting force (6111 RPM, 0.127 mm/tooth)

2.2.4 Meshing

Since the workpiece profile used is complex and transformed during the analysis at each cutting tool position, the meshing types should be different in each area of the geometrical profile. The part is therefore partitioned into different areas, as shown in Figure 2.8.

There are two important partitions for the part; the cutting area and the four holes used to fix the plate to the location pins of the machine table. Thus, those areas should be meshed using tetrahedral elements while the rest of the plate is meshed exclusively with hexahedral elements, as shown in Figure 2.9.

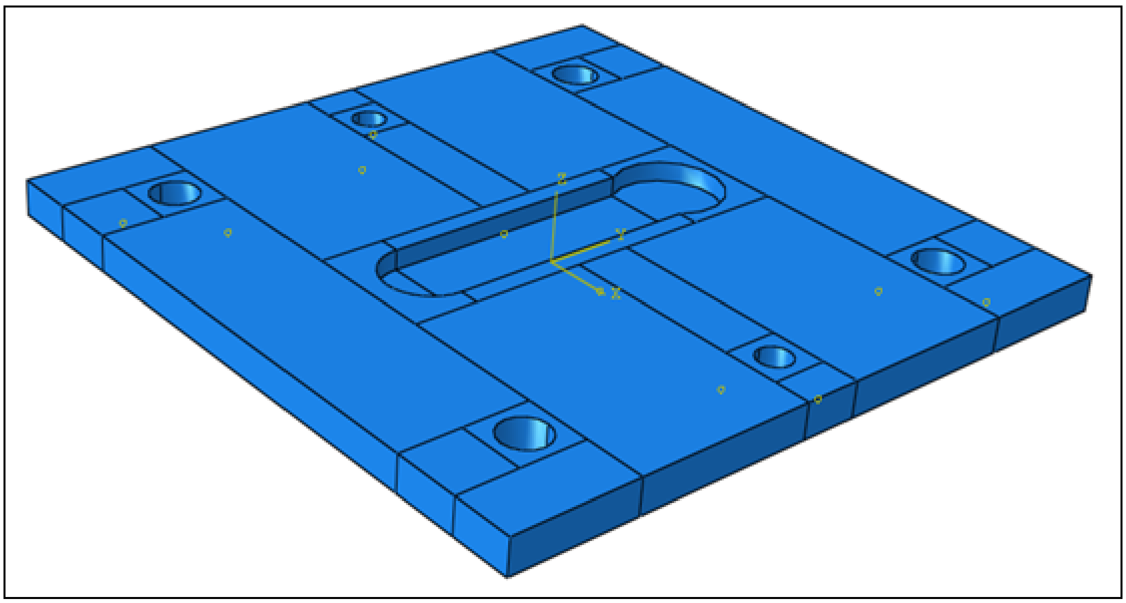


Figure 2.8. Partitioned part

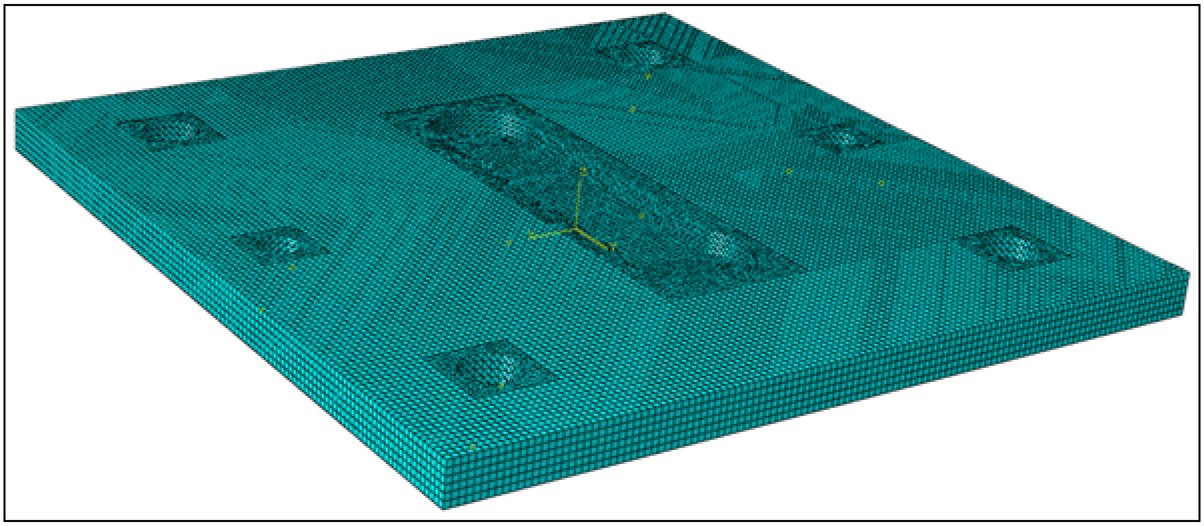


Figure 2.9. Meshed part

2.2.5 Application of cutting forces

As shown in the simulation and experimental results, the cutting force varies during one rotation of the cutting tool. With the cutting tool's spindle speed of 6111 rpm, the variation of the force during one cycle is quite small as a function of time. As we consider the cutting force as static in our calculations, we propose to approximate with the force value as the maximum one during a complete rotation of the cutting tool.

In reality, the cutting force at a certain time acts on the flutes of the tool and the contact area between the flutes and the workpiece. In the computation with a time step greater than the force cycle, it is assumed that the cutting force is equally distributed in the area of contact between the cutting tool and the work piece, as shown in figure 2.10.

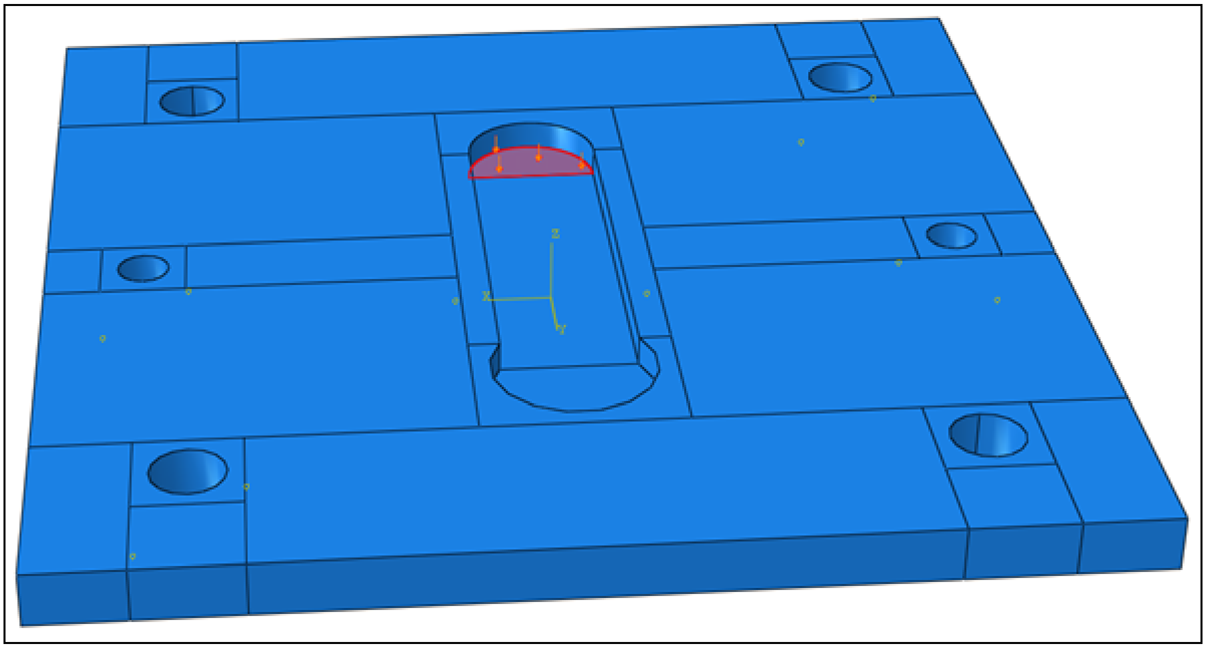


Figure 2.10. Area of the acting cutting force F_z

2.2.6 Boundary conditions

In milling using a flexible setup configuration, the workpiece is clamped to the location pins by using bolts throughout four holes at the corners of the plate. The boundary conditions therefore are set at those holes to prevent any movement as shown in Figure 2.11.

$$U1 = U2 = U3 = UR1 = UR2 = UR3 = 0 \tag{2.9}$$

where U1, U2, U3, U4, U5, U6 are forward/back, up/down, left/right, pitch, yaw, roll movements of the inner surface of the four holes at the corner of the workpiece, respectively.

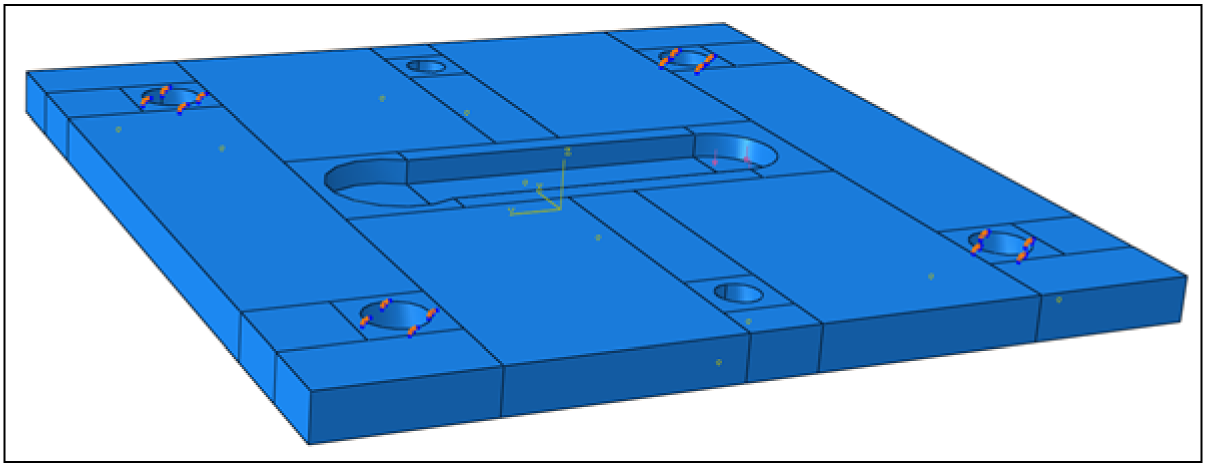


Figure 2.11. Boundary conditions

CHAPTER 3

EXPERIMENTAL METHODOLOGY

As discussed, the removal of support to the bottom face of a workpiece leads to geometrical errors after machining of thin/compliant plates using the proposed flexible setup configuration. In this section, experimental tests under different cutting conditions are carried out to verify the results of the prediction model regarding the cutting deviations during the slot milling of thin plates using the proposed flexible setup.

3.1 Raw material preparations

As already mentioned, the raw material consists of aluminum 6061 – T6 plates of 120 x 120 x 6.35 (mm). Four holes of 8.4 mm diameter on the corners are used to fix the plate while two holes of 6mm diameter are machined to be utilized as references during the inspection process.

A lead-in pocket (blind hole in the middle of the part) was also prepared to avoid the penetration of the tool during the beginning of the machining, as shown in Figure 3.1. The depth of the lead-in pocket equals the depth of cut utilized in the slot milling tests and its diameter of 19 mm, is a little larger than the cutting tool's diameter to avoid interference. The depth of cut of the slot is 4.0 mm.

The preparation process is conducted using a backplate support to prevent any deformation at this stage.

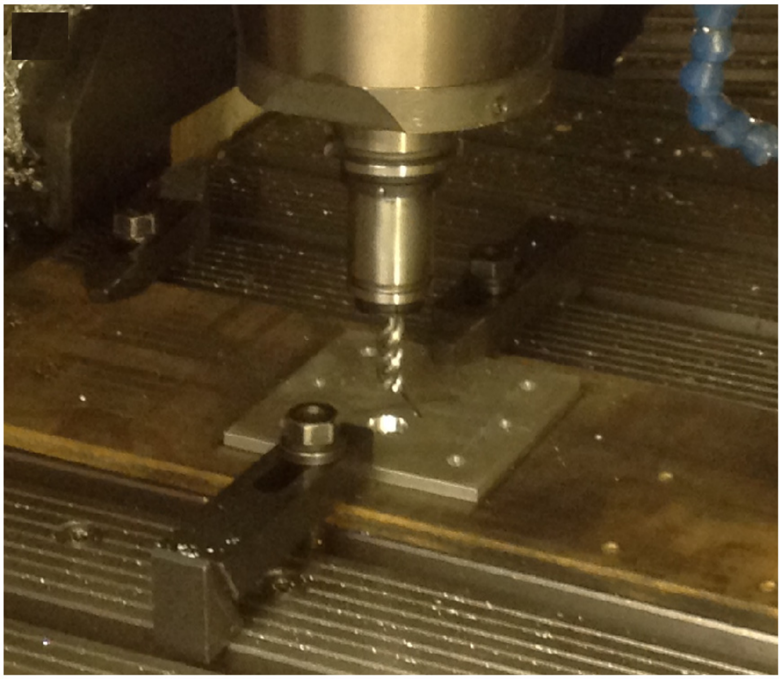


Figure 3.1. Raw material preparation

3.2 Identification of geometrical profiles of workpieces before and after machining

In order to evaluate the cutting deviations in milling of thin plates using the flexible setup, geometrical profiles of workpieces are necessary to be measured. Since the geometry of workpieces used for the experimental tests are not "perfect", a measurement process is conducted to identify their initial profiles before machining, but after preparation. A Mitutoyo Bright Strato Coordinate Measurement Machine (CMM) is utilized to measure the prepared raw materials as well as the machined workpieces in order to define their geometrical profiles before and after the machining tests.

Figure 3.2 shows the setup used for the measurement of a plate on the CMM. The plate is clamped to the machine by its side and the two small holes machined during the preparation process are used as references for the current process of measurement.

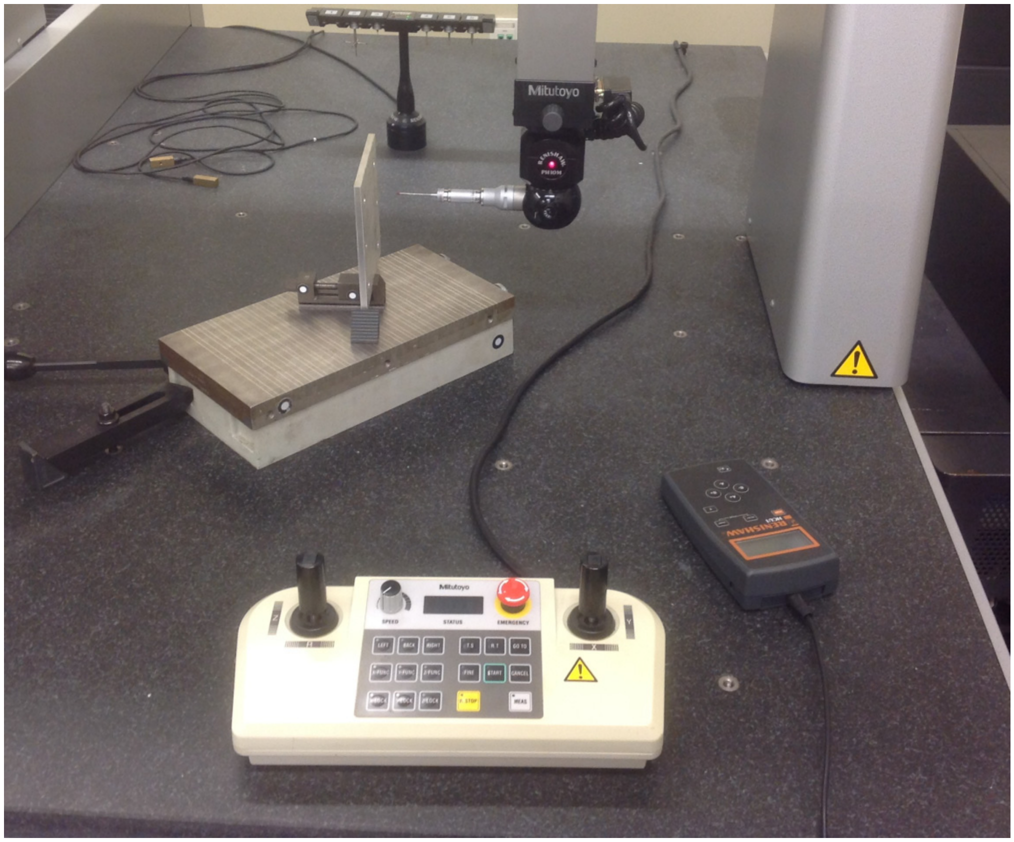


Figure 3.2. CMM measurement of the thin plates

The central point of the line relating the two centers of the reference holes is designated to be the origin point of the local coordinate. Each point on the plate's surfaces is identified as a position (x, y, z coordinate) with respect to the origin and defined reference system. The depth of the plate at a certain position is determined by comparing the z coordinate of two points having the same x, y coordinates on both opposite surfaces. A total of 26 points on each surface are measured along the $y_1 - y_1$ axis, as shown in Figure 3.3

After the machining experiments, the geometrical profiles of the machined plates are then measured again using the same CMM and measurement process plan. The measurement results related to the plate "before" and "after" machining will then be utilized for the analysis to determine the geometrical errors during the slot milling of the plates using the flexible setup, as detailed and discussed in section 4.3.

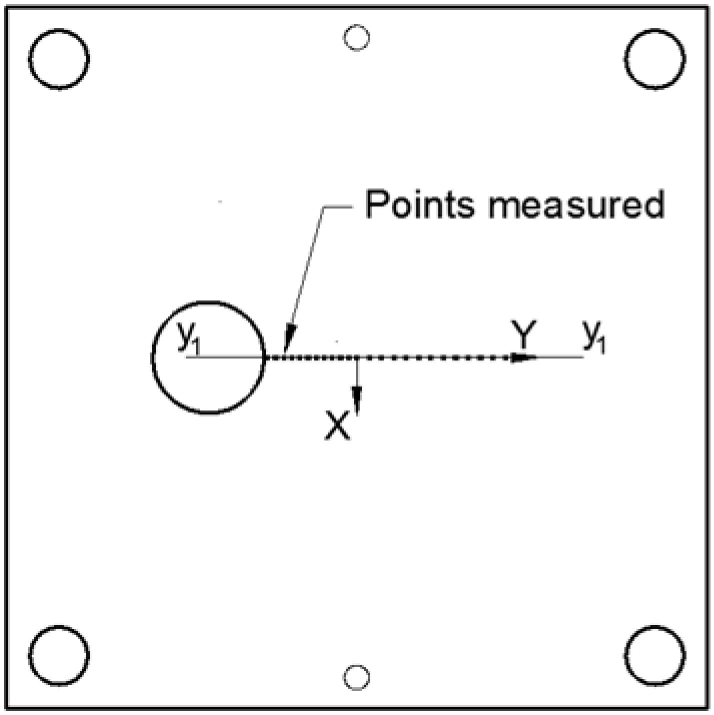


Figure 3.3. Measurement points

Table 3.1. Measurement point locations

No	y - coordinate	No	y - coordinate	No	y - coordinate	No	y - coordinate
1	-15.32065	9	-6.10997	17	7.01696	25	24.696315
2	-14.86211	10	-4.651635	18	9.934615	26	25.237765
3	-13.40385	11	-3.19293	19	12.85142		
4	-11.94471	12	-1.73485	20	14.310235		
5	-10.48623	13	-0.275645	21	15.768725		
6	-9.393225	14	1.182595	22	17.227525		
7	-8.227335	15	2.641405	23	20.14462		
8	-7.56927	16	5.558795	24	23.155175		

3.3 Machining tests using the flexible configuration setup

A three-axis Huron K2X10 CNC milling machine was utilized to conduct the experimental tests (Figure 3.4). The cutting tool used was an end mill Niagara Ø5/8" – 2F – TiCN coated.

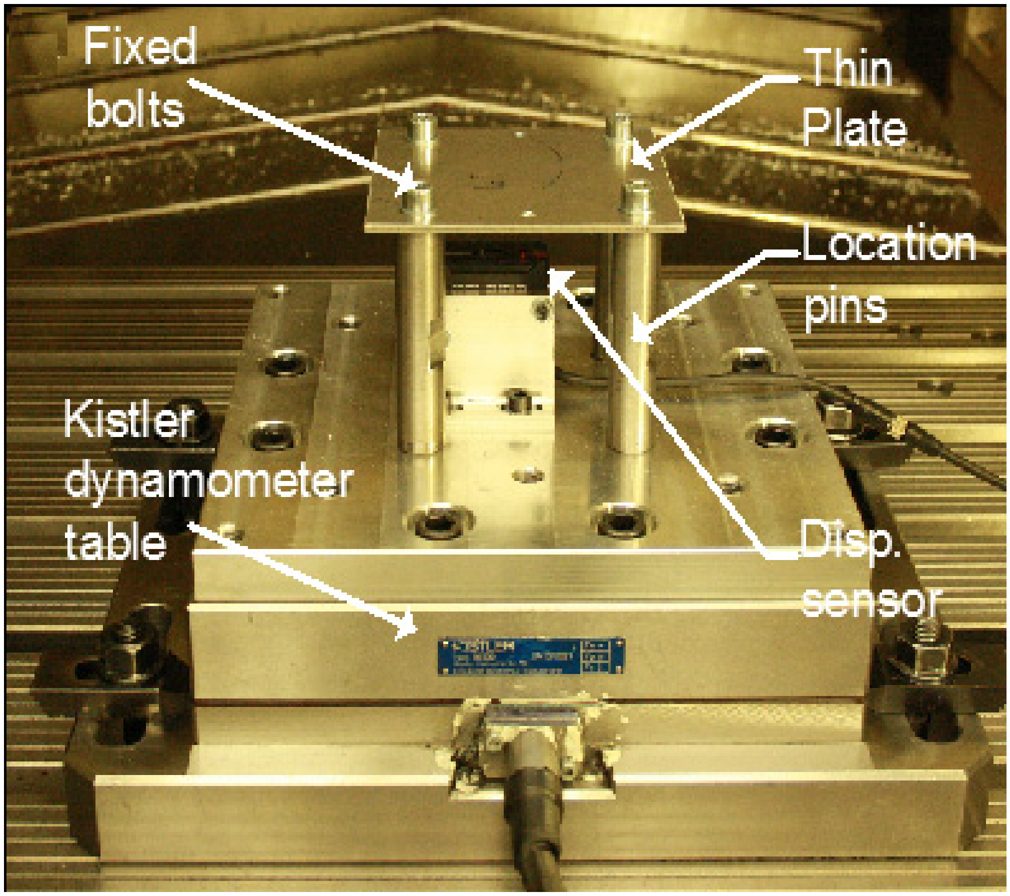


Figure 3.4. Experimental setup

During the machining tests, a 3-D Kistler 9255 type dynamometer table was utilized to record the acting forces on the location pins with a 12kHz frequency, while a Keyence displacement sensor with an IL-1000 sensor amplifier was placed under the workpiece to measure the displacement of the central point of the bottom face of the thin plate during and shortly after the machining tests. Numbers of tests were conducted with different cutting conditions, as shown in Table 3.2.

Table 3.2. Cutting conditions

Test	Thickness of plates (mm)	Cutting tool's diameter (mm)	Depth of cut (mm)	Rotational speed of the tool (rpm)	Feed rate (mm per rev)
1	6.35	15.875	4	4584	0.3386
2	6.35	15.875	4	4889	0.3175
3	6.35	15.875	4	5317	0.2919

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Cutting forces

This section presents the results of the developed cutting model which was presented in chapter 2 for different cutting conditions of the conducted experimental tests, as presented in Table 3.2. The cutting forces in the z – direction recorded by Kistle dynamometer table during experimental tests, are also analyzed. Figure 4.1 shows the simulated and experimental results of the cutting force in z – direction (F_z) by the rotational angles of the cutting tool for the three different tests (Table 3.2). This figure expresses the experimental cutting forces as a function of the rotational angle of the cutting tool. These were obtained from the conversion of the forces recorded as a function of time using the dynamometer table. In the figure, the cutting force varies in each tool rotation and reaches its maximum value when the instantaneous angle of immersion is 90^o. This is because the cutting force is a function of $\sin(\emptyset)$; it reaches its maximum value when $\sin(\emptyset) = 1$ and its minimum value when $\sin(\emptyset) = 0$.

These results also confirm the relationship of the cutting force with the feed rate. The comparison of the cutting forces for the three tests show the maximum value of the force during the first test since it was carried out at the greatest feed rate. In contrast, the third test show the minimum value since it was processed using the minimum feed rate.

The simulation results shown in the figure were calculated using the axial force model, equation 1.7, developed in chapter 2. The correlation is strong between the simulated results and the experimental values. As specified in chapter 2, the modeled results are utilized as input to our finite element model to compute the plate deformation. For the static model, the maximum value of the modeled axial cutting force is utilized.

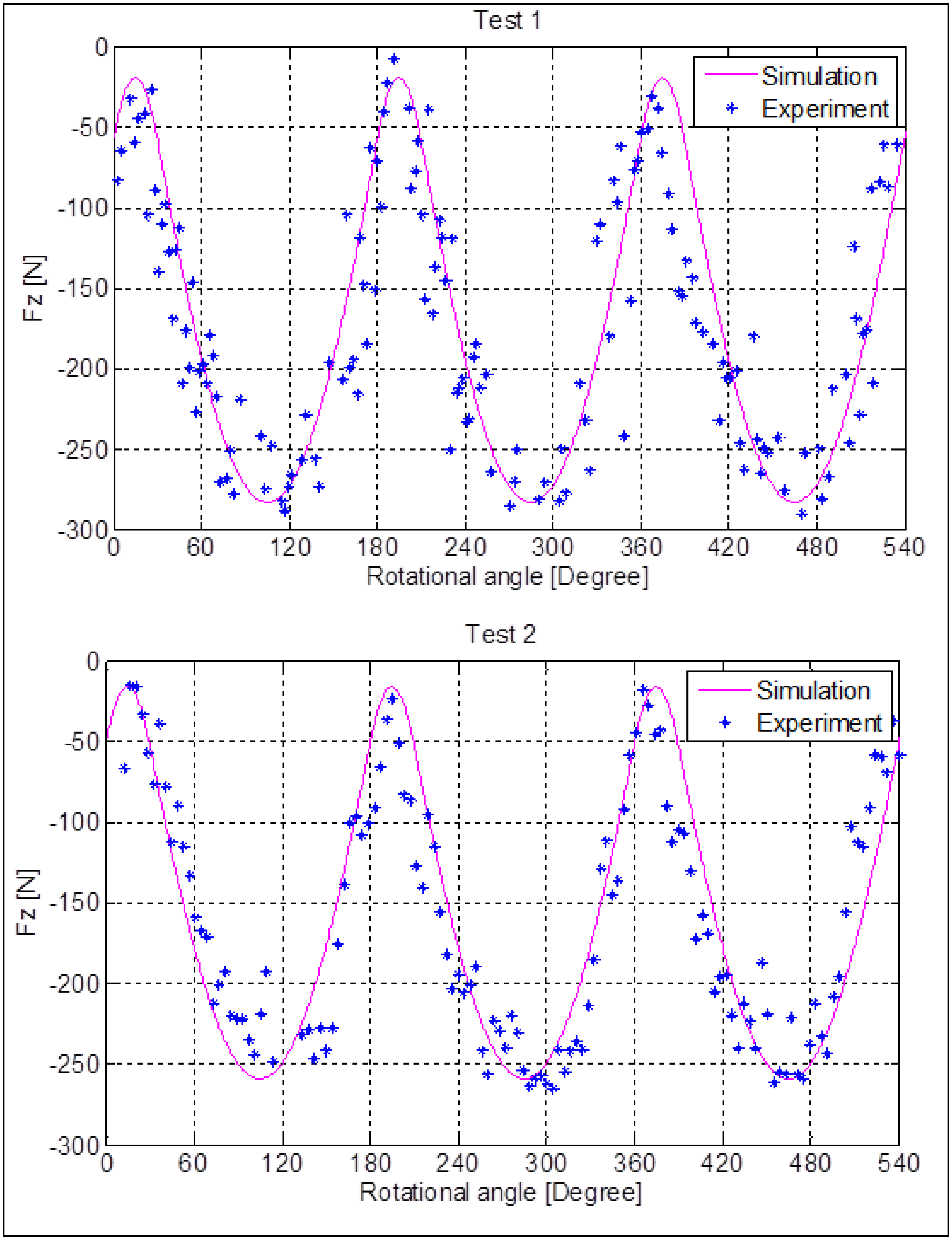
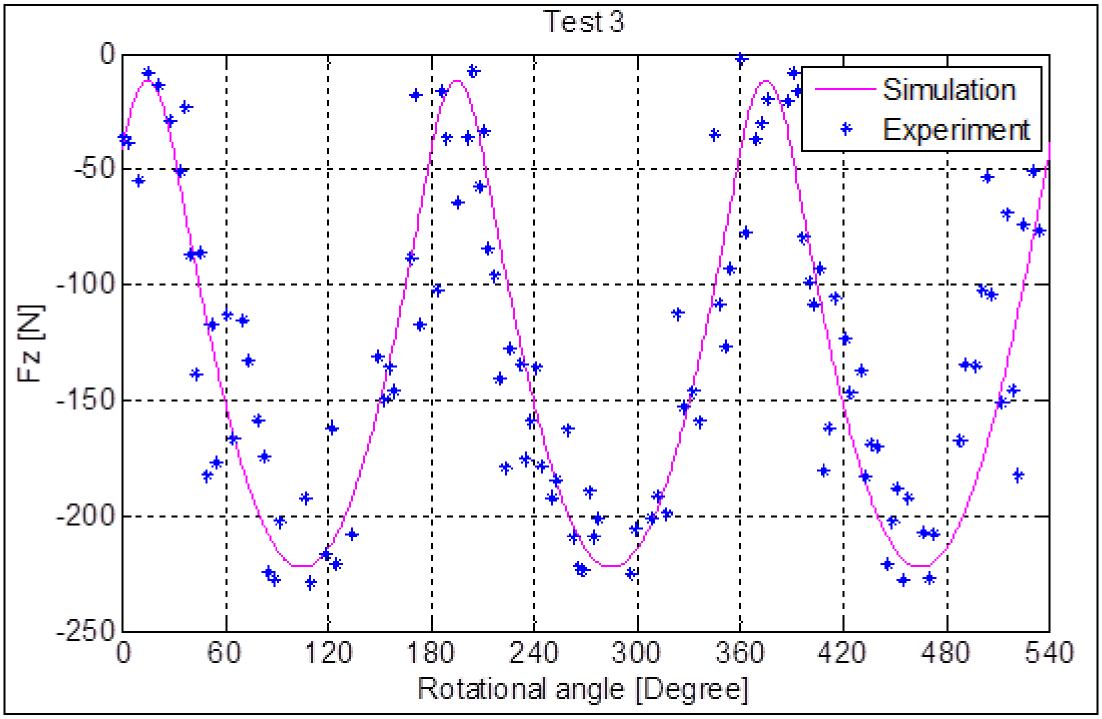


Figure 4.1. Cutting force in z –direction (Test 1 and Test 2)

Figure 4.1. Cutting force in z –direction (Continued - Test 3)



4.2 Central point displacements

Having no support on the bottom face during machining, the workpiece is freely deformed and displaced in the vertical direction. Figure 4.2 shows the displacements of the central point of the plate before, during and shortly after the machining test as recorded by the Keyence displacement sensor**.**

The displacements of the plates represent the material deformation resulting from the cutting forces acting along the cutting path, with different magnitudes, depending on the tool positioning points. The displacement is produced when the cutting tool begins removing the workpiece's material and increases along with the movement of the cutting tool and reaches a maximum value when the tool passes over the central point of the workpiece. Thereafter, when the cutting tool moves to other points of the trajectory, the displacement decreases and starts returning to the original value after the machining process ends. It proves that the deformation of the thin plate during milling is an elastic deformation. In fact, the displacement of the central point increases from the initial value (zero) to the maximum value when the tool is on the central area of the workpiece.

When comparing the values of the central point displacement for the three tests, the maximum value of the first test is the greatest while the third test is the smallest. It is because the central displacement of the workpiece occurs under the effect of the cutting force in the z – direction. The greater cutting force results greater displacements.

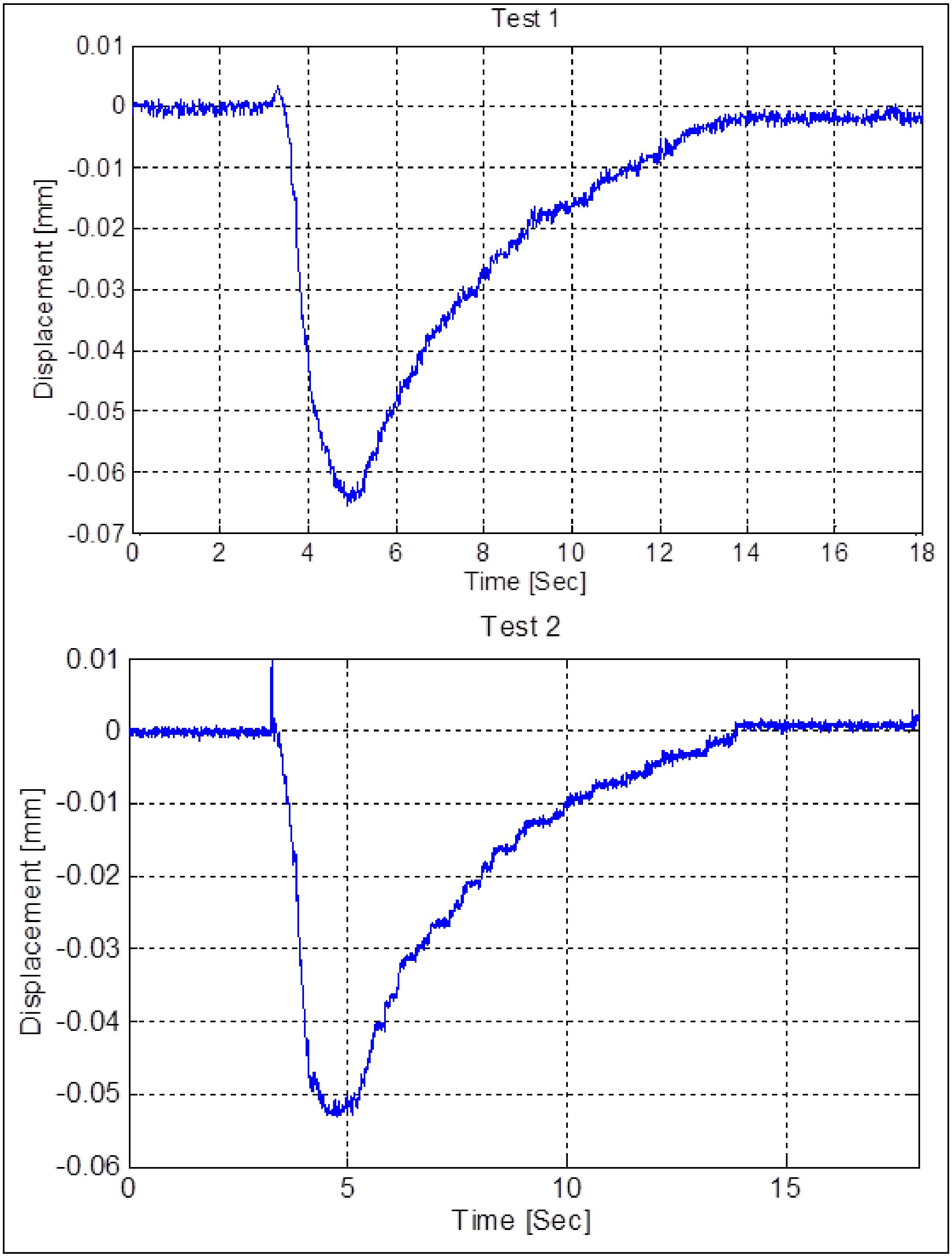
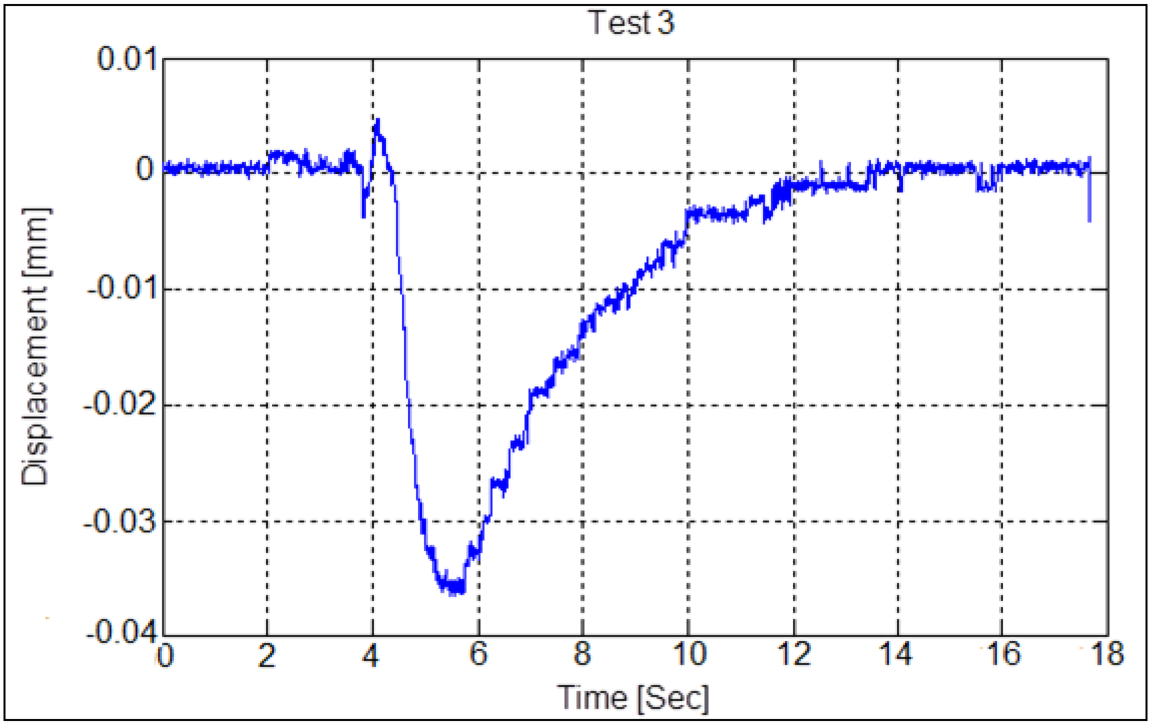


Figure 4.2. Displacement of central points in different tests (Test 1 and Test 2)

Figure 4.2. Displacement of central points in different tests (Continued – Test 3)



4.3 Geometrical errors

In this section, the results of the computed displacements of the workpiece during machining using our finite element model and the measured geometrical errors of the machined plates using the CMM are compared and discussed.

The geometrical errors of the machined plate after machining are identified by the analysis of measurement results of the geometrical profiles of thin plates before and after the machining tests, as described in the previous chapter. The analysis of the measurement results is presented as following.

In fact, the center point of the top-face of workpiece is identified as the reference point to determine the depth of cut for machining as shown in Figure 4.3. Therefore, the nominal depth of the plate at a certain position before machining $(D_i)_0$ is virtually constructed by the vertical distance between that location on the bottom-face and the reference point as shown in Figure 4.4. The thickness of plate at certain position *$(D_i)_0$* before machining is now identified as,

$$(D_i)_0 = (z_R)_0 - (z_i^D)_0 \tag{4.1}$$

where, $(z_R)_0$ is the z – coordinates of the reference point on top surface and $(z_C^D)_0$ is z – coordinates of the certain position on the bottom surface.

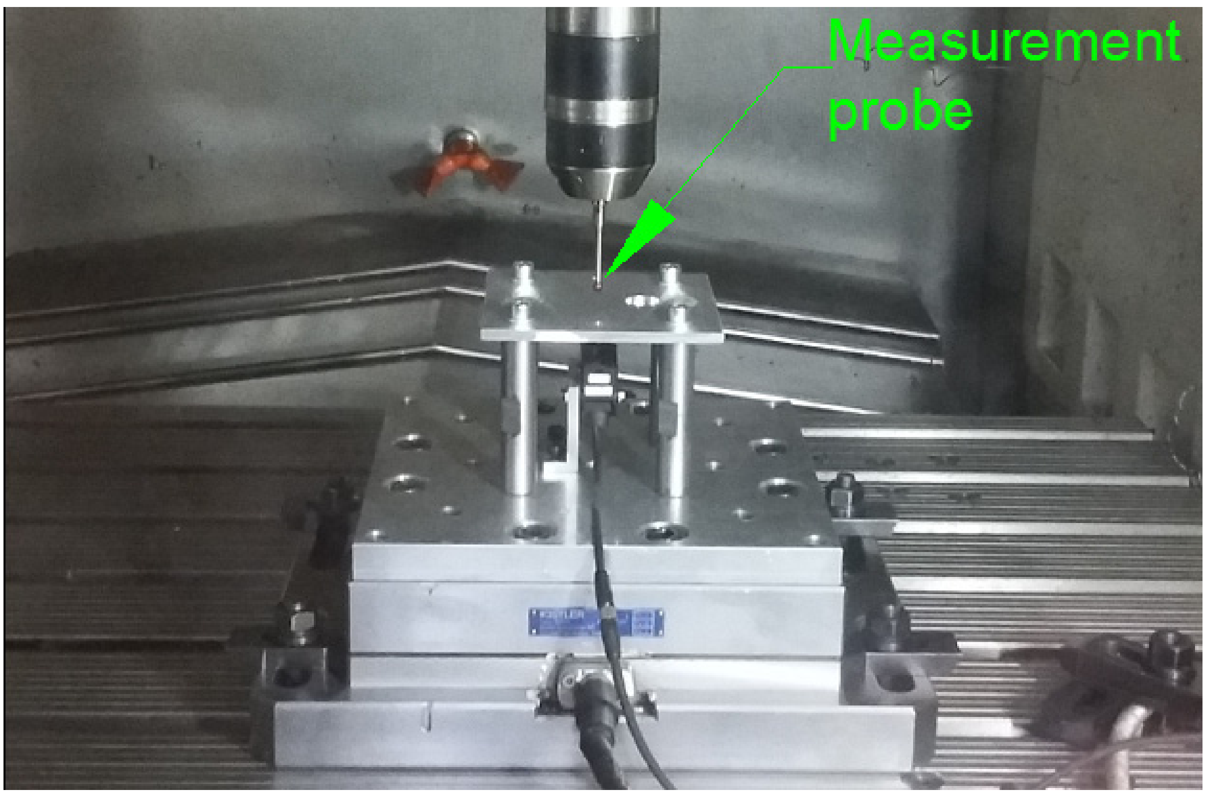


Figure 4.3. Identification of the reference point for the depth of cut during machining

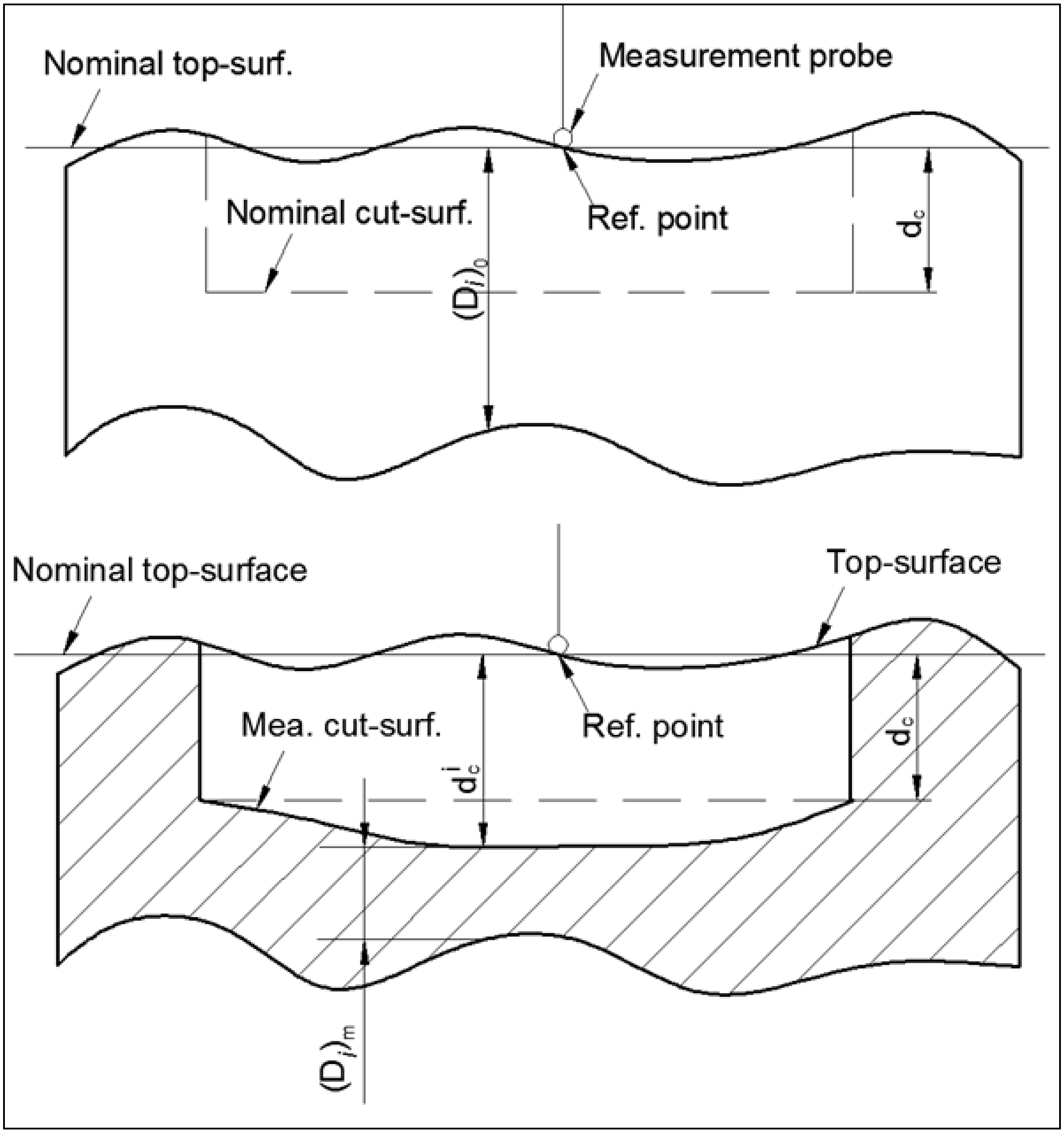


Figure 4.4. Measurement analysis

The geometrical error of the center is calculated by comparing the thickness of plates before and after machining. The thickness of plate at a certain position after machining ($(D_i)_m$) is calculated as,

$$(D_i)_m = (z_i^T)_m - (z_i^D)_m \tag{4.2}$$

where $(z_i^T)_m$, $(z_i^D)_m$ are the z – coordinates of that loaction on top-surface and bottom-surface from CMM results, respectively.

The actual depth of cut at this location (d_c^i) is now determined as,

$$d_c^i = (D_i)_0 - (D_i)_m \tag{4.3}$$

Finally, the measured geometrical error at a certain position (ε_m^i) is now calculated as,

$$\varepsilon_m^i = d_c - d_c^i \tag{4.4}$$

where d_c is the nominal depth of cut as designed.

The displacements resulted from finite element simulation are compared with the measurement results calculated from equation (13), as shown in Figure 4.5. The figure shows the simulated and measured results for the three plates referring to different machining conditions along the y-axis central cross-section of the machined area as shown in Figure 3.3.

From the figure, both simulated and experimental geometrical errors respectively increase from each end of the slot to the center and reach the maximum value at the center of the slot. This is because the distance of the cutting point to location pins is increasing when the tool moves from any end to the center of the slot.

The errors are not symmetric between the two sides respectively from the center of the cutting area. This is because the geometrical profile of the workpiece is changing as the material is removed through the machining process. Therefore, the geometrical profiles are differents from one side (negative side of Y axis) to the other side (positive side of Y axis) of the center (origin of Y axis). The geometrical errors in the positive y – direction are greater than their opposite locations in the negative side.

The measured geometrical errors in the first test were observed to be the greatest while the lowest deviation was observed for the third test. This is because the difference between feedrate in the first test is greater than in the other tests due to the fact that the greatest material deformation occurs with the greatest cutting force in the z-direction of the first test. It is confirmed by the simulation results for all three tests.

In fact, at the beginning period of the cutting process, when the tool starts removing the workpiece's material, the cutting forces appear consequently to the removal process. Under the application of cutting forces, the workpiece is deformed as its material behavior. However, there is a time delay when the material is fully deformed to the displacement value corresponding to the cutting force. Therefore, the measured geometrical errors at this time period are small and different to the simulated results. It is because in this static model, the analysis process neglected that behavior.

The correlation between the modeled displacements of the workpiece and the measured geometrical errors shown in the figure confirms that the force induced displacement of the workpiece is the main reason of cutting deviations during machining of thin components using flexible setup.

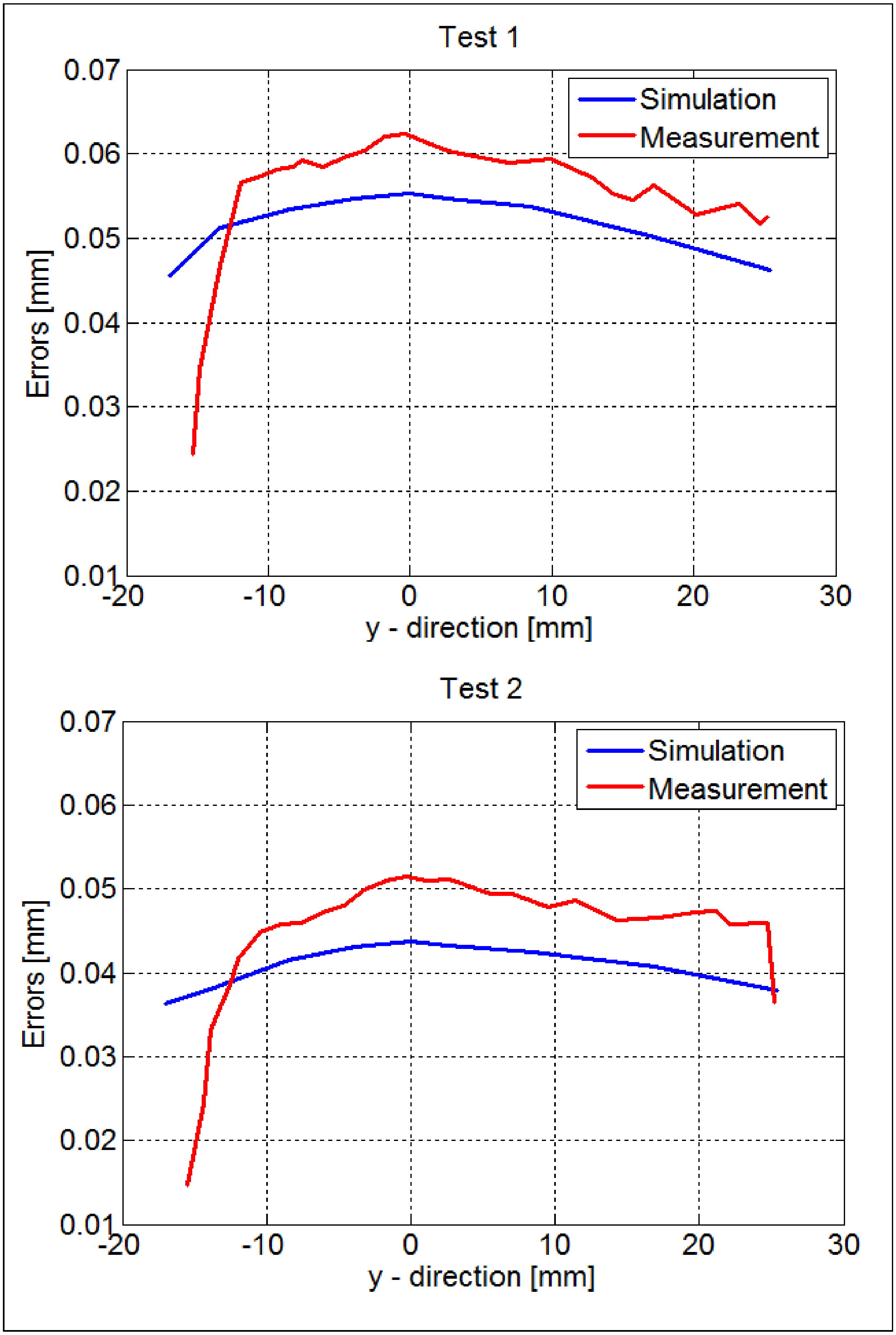
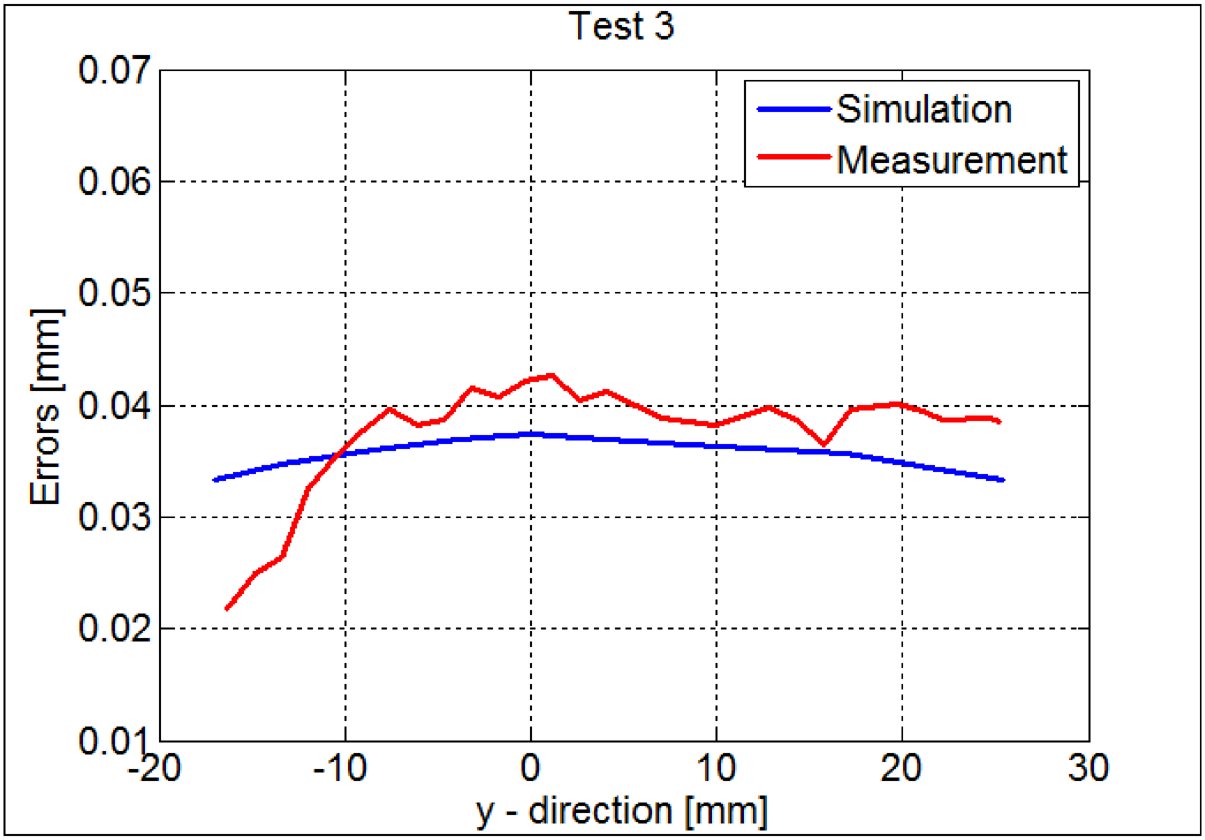


Figure 4.5. Cutting errors (Test 1 and Test 2)

Figure 4.5. Cutting errors (Continued – Test 3)



CHAPTER 5

COMPEANSTIONS OF CUTTING DEVIATIONS IN MILLING OF THIN COMPONENTS USING THE FLEXIBLE SETUP

5.1 Methodology

The close correlation between simulated displacement results of the workpiece during machining and geometrical errors after machining proves that the workpiece deformation is the major reason of cutting deviations in milling of thin plates using the flexible configuration setup. In this chapter, a compensation method of the cutting deviations during machining process of the thin floor components using flexible setup is presented. The method is developed by creating a new tool path with the depth of cut updated as the predicted results of the workpiece displacements obtained from the prediction model in chapter 2. A new tool path is updated with modifying the depth of cut to the new value that differed from nominal values by applying the mirror technique as shown in Figure 5.1.

In a certain position, a value of Δd is proposed to add to the designed cutting depth (d_n) to compensate the cutting deviations. The compensated depth of cut (d_c) therefore would be,

$$d_c^i = d_n + \Delta d^i \tag{5.1}$$

where (d_n) is the designed depth of cut and Δd^i is the cutting error at the location.

Please note that the value of Δd^i is different at each position, the value is the displacement of this position obtained by the result of the finite element analysis of material deformation for the workpiece.

The updated cutting path is now obtained by collecting all the depth of cut at different positions on the cut slot.

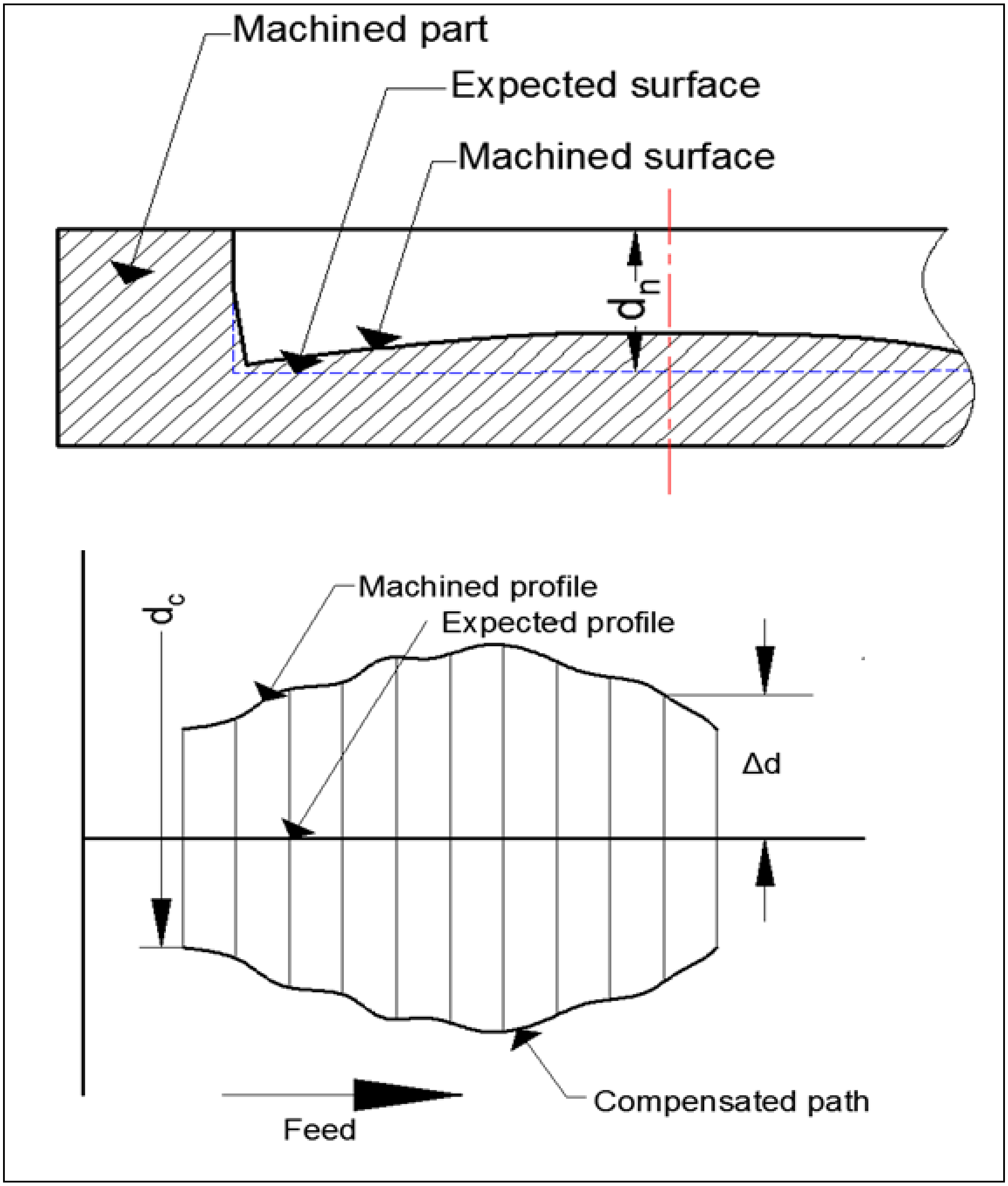


Figure 5.1. Mirror technique

The process proposed for the compensation of cutting errors is described in Figure 5.2. The process begins with the raw material preparation and CMM measurement that are carried as described in chapter 3.

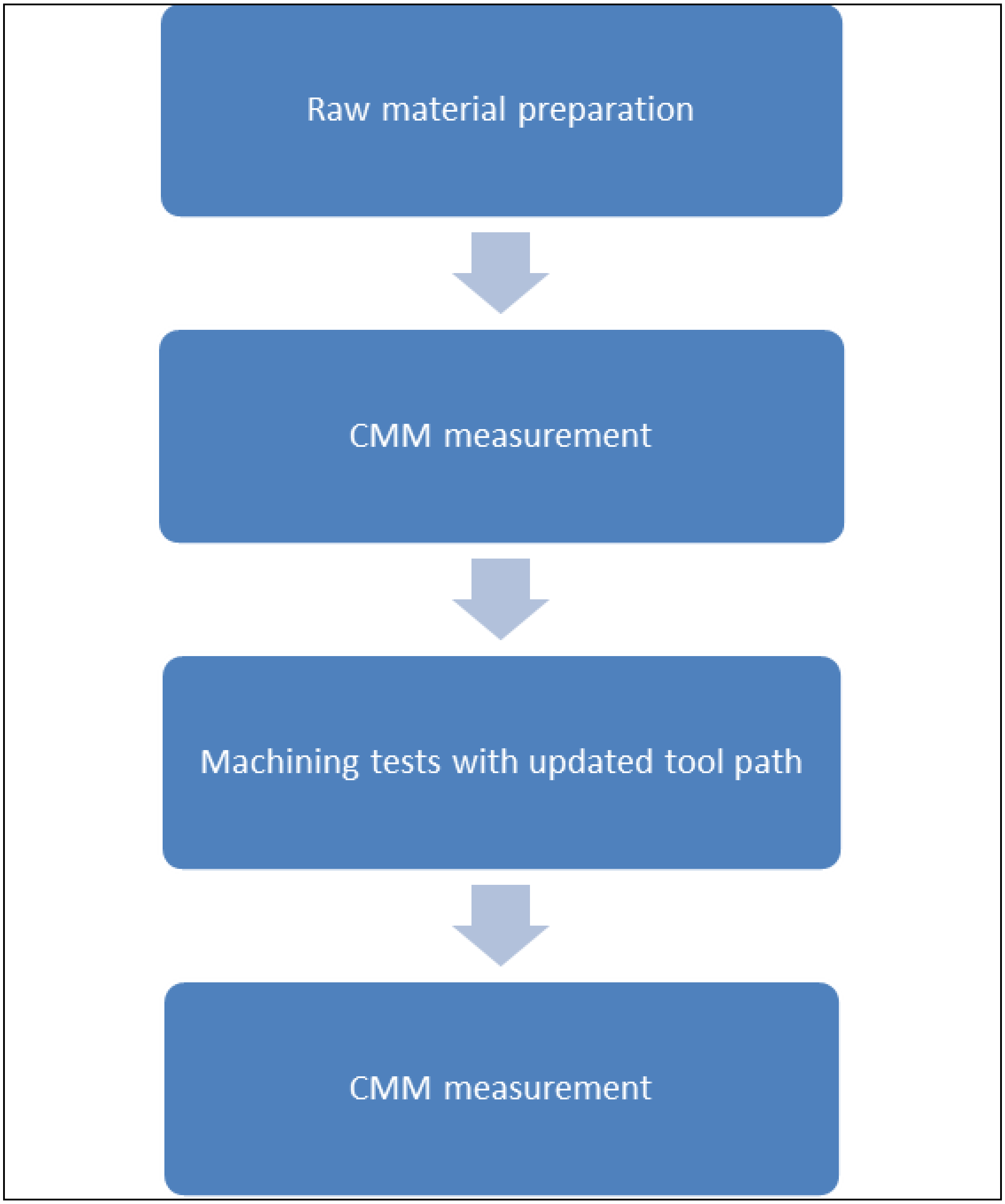


Figure 5.2. Experimental process with cutting errors compensation

The material preparation consists in the drilling of four holes in the plate corners and two reference holes for the CMM measurement. As opposed to the preparation of previous plates, the depth of the lead-in pocket is now different from the nominal depth of cut. Its value must equal the new updated cutting depth.

Experiments are conducted with the same cutting conditions as the tests performed before but with an updated depth of cut calculated using the mirror technique.

The cutting conditions considering the cutting errors compensation are shown in Tables 5.1 and 5.2.

Table 5.1. Cutting conditions

Test	Thickness of plates (mm)	Cutting tool's diameter (mm)	Cutting speed (rpm)	Feed rate (mm per turn)
1	6.35	15.875	4584	0.3386
2	6.35	15.875	4889	0.3175
3	6.35	15.875	5317	0.2919

Table 5.2. Depth of cut at certain positions on the slot

Test # \ Y cor.	-16.96	-8.48	0	8.46	16.93	25.4
1	4.04559	4.05346	4.05633	4.05373	4.05021	4.04618
2	4.0365	4.04173	4.04482	4.04268	4.04089	4.03805
3	4.03327	4.03604	4.03741	4.03651	4.03573	4.03342

5.2 Results and discussions

The workpieces are also measured by CMM to determine their geometrical profiles before and after machining to determine cutting deviations during the machining with the updated tool path.

As similar to section 3.2 regarding to the identification of nominal depth of the plate at a certain location, the actual depth of cut in this location is determined, by comparing to the design depth of cut, the cutting error (ε_i) at this position is identified as,

$$\varepsilon_i = d_a^i - d_n \tag{5.2}$$

where, d_a^i is the actual depth of cut at this position and d_n is the design depth of cut.

Please note that the design depth of cut is not the setting depth of cut as shown in Table 5.2. It is the nominal depth of cut of the slot machining. In these tests, this nominal depth of cut is,

$$d_n = 4 \text{ (mm)} \tag{5.3}$$

Cutting errors of machining thin plates in different cutting conditions obtained after measurements are shown in the Figure 5.3. With the compensated cutting depth which is updated using the predicted results of the workpiece's displacements, the cutting errors still appear as shown in the figure.

We can explain this discrepancy by the fact that the updated depth of cut is determined by compensating exactly the predicted value. However, when increasing the depth of cut as we did, the cutting forces are also increasing to greater values than the ones utilized to determine the compensation (old values). This greater cutting forces lead to greater geometrical errors then predicted values, so that the cutting errors still are appeared after compensation. Despite this, we find almost 60% (0.026 mm vs 0.062 mm) improvement in the cutting error, which is very good.

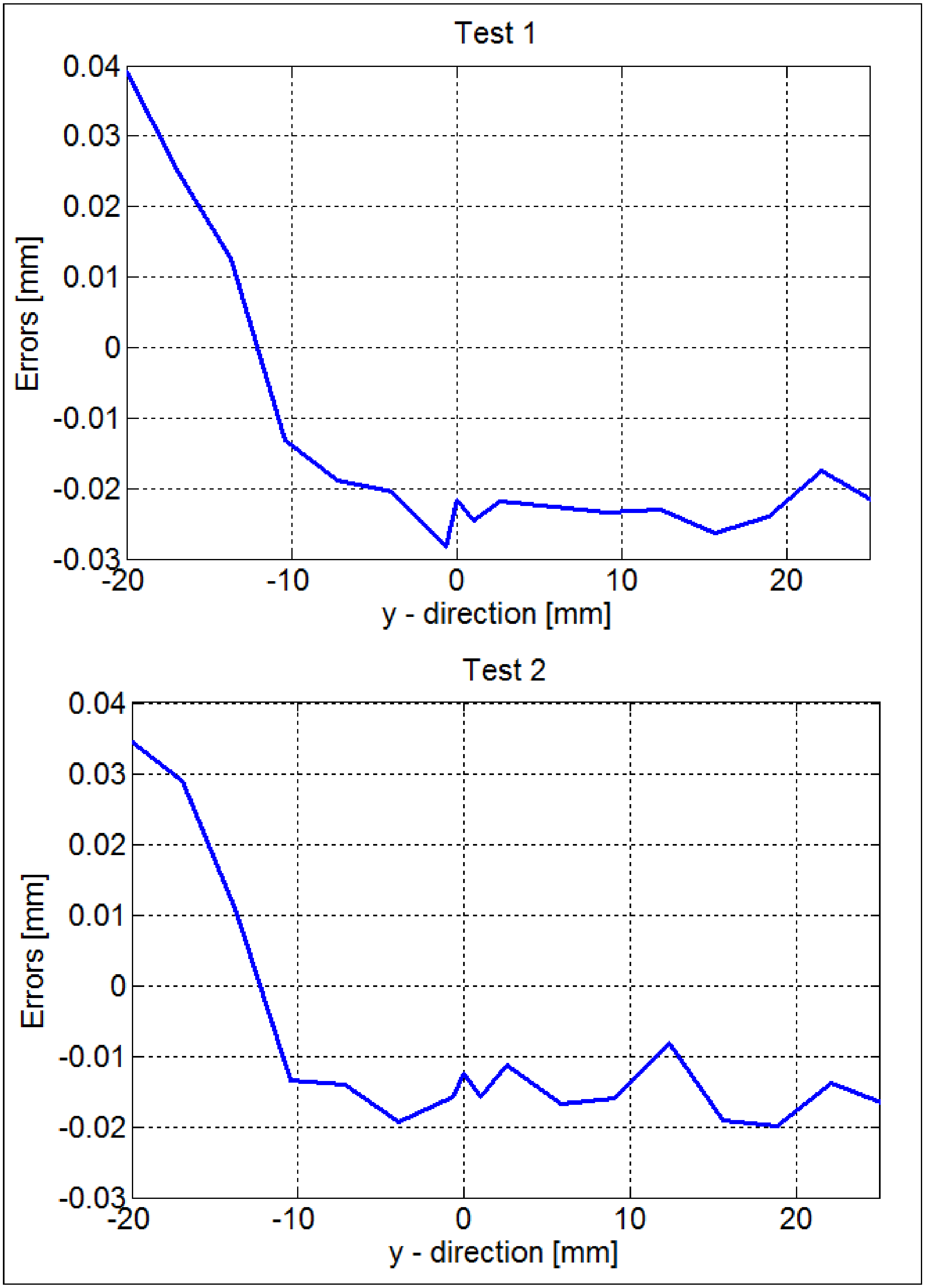
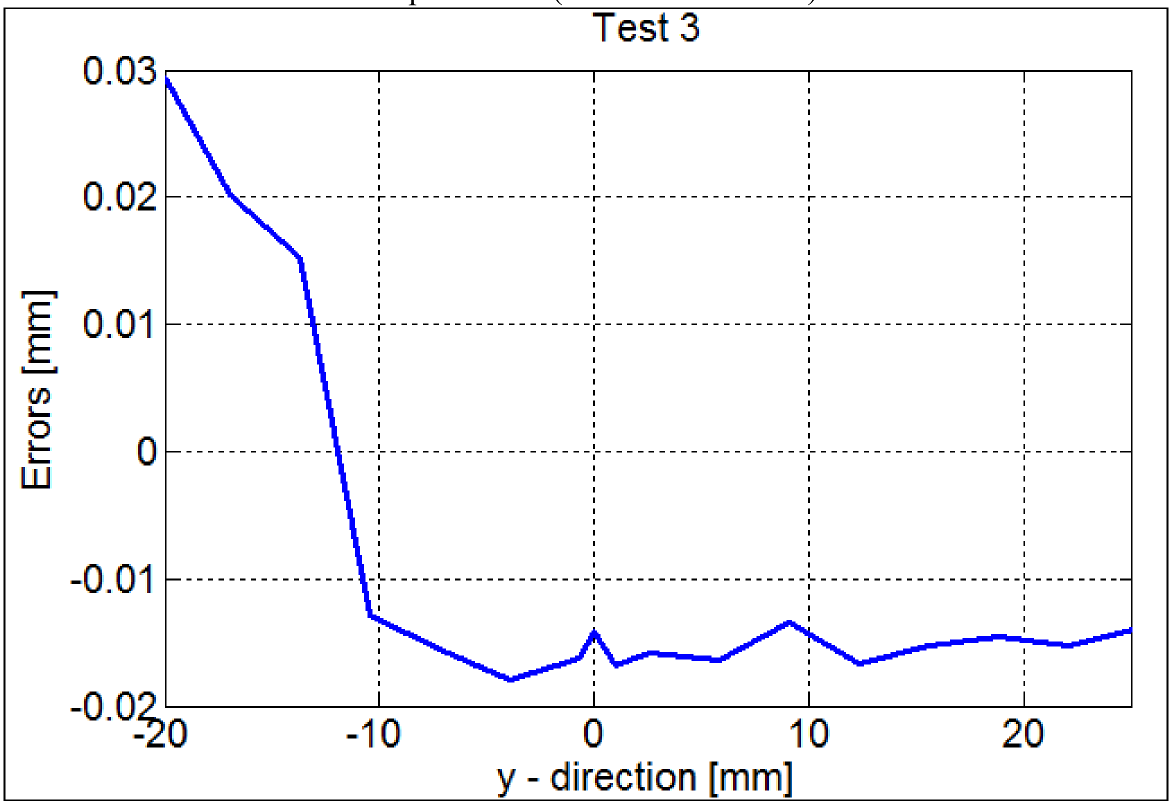


Figure 5.3. Cutting errors of machined workpieces after machining processes with compensations (Test 1 and Test 2)

Figure 5.3. Cutting errors of machined workpieces after machining processes with compensations (Continued – Test 3)



CONCLUSION

Using a flexible setup configuration for machining thin floor components leads to geometrical errors, with their magnitude depending on the position of the tool with respect to the locations of the support pins, as a result of material deformations during machining. A tool-path compensation model should be envisaged to reduce the deflection of cutting points during machining with flexible setups, in order to fully take advantage of this technology.

In this research, a simplified static approach is utilized for the development of a numerical model to predict the deflections during the slot milling of a 6 mm thin plate. A cutting force model was also proposed to simulate the cutting force in the z –direction during the cutting process, and the result was utilized for the prediction model of cutting deflections.

The cutting deflections were predicted by applying the finite element method in modeling the material deformation of the workpiece under effect of the cutting force in the z – direction. In this study, the cutting process is considered as a static model, which has the inconvenience of neglecting all effects of change in the cutting depth and consequently, the geometrical profiles due to cutting deflection.

The comparison between the predicted and the experimental results proves that the material deformation of the workpiece is the major reason of the cutting deviation in milling of thin components using a flexible setup. However, there is a difference between the predicted workpiece's displacements and the measured geometrical errors. It is because of assumptions with only considering the elastic deformation and static model of cutting process.

Compensation method with applying mirror technique is then utilized to compensate the cutting errors based on the results obtained from the prediction model. The depth of cut is updated with a value equaling to the cutting error. By applied the compensation method with using the predicted results, the cutting errors are effectively reduced by almost 60% from maximum value of error of 0.062 mm into maximum error of 0.026 mm.

However, even with the compensation factor applied, the geometrical errors are still significant. This is observed as the difference between the predicted displacement results and the measured geometrical errors. This difference is explained by the force which is not updated following the modification of the cutting conditions in the compensation process.. Only a dynamic model considering the change of the cutting conditions in time within the prediction model could overcome such discrepancies in the results. This will be developed in further research works.

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