Contact Analysis of Workpiece-Fixture System Under Time-Varying Machining Loads Using Finite Element Method

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Abstract
Proper fixture design is crucial to product quality in terms of precision, accuracy and finish of the machined part. Fixturing systems must be capable of positioning, holding and supporting the workpiece throughout the machining process. In this paper, modular fixture design verification analysis is carried out for time-varying machining forces using nonlinear finite element analysis. Chip removal effect is taken into account using element death technique and the frictional contact between workpiece and fixture elements is also considered. This paper also adresses applying optimal clamping forces in order to minimize the deformation. A case study is presented to demonstrate the suggested methodology.

Keywords: fixture, contact, finite element method (FEM)

1 INTRODUCTION

A fixture is a device used to locate, clamp and support a workpiece during machining, assembly or inspection. The most important criterias for fixturing are workpiece stability, position accuracy and workpiece deformation. A good fixture design is one that minimizes workpiece geometric error. Proper location insures perpendicularity and parallelism of the part. The fixture should minimize workpiece displacement during machining.

Fixture design verification involves with workpiece location principles, kinematic and force analysis to determine the workpiece location layout and to evaluate the required clamping forces against the cutting forces. Workpiece location principles are defined in terms of 3-2-1 fixturing which is widely used workpiece location method for prismatic parts in literature. Kinematic analysis is employed to determine whether fixture arrangement will correctly locate and hold a workpiece. Force analysis is concerned with checking whether the forces applied by the fixture and clamping are sufficient to maintain static equilibrium. Workpiece and fixturing elements are elastic and deformable, but most of the systems deal with location layout analysis by considering workpiece and fixturing elements as rigid. Most of the existing systems use the static load conditions to analyse the fixturing configuration and dynamic conditions are not taken into account in depth.

In this research, the workpiece stability and deformation analysis under dynamic machining conditions are taken into account for time varying machining loads. Chip removal effect is also taken into account. In order to verify the fixture configurations, machining operations are simulated on a finite element model. The model is analysed respect to tool movement and chip removal using element death technique. Frictional conditions at the interface between fixture elements and workpiece are also examined. Three dimensional nonlinear finite element analysis is carried out on the workpiece using contact elements.

2 REVIEW OF RELATED WORKS

Lee and Haynes [1] were amongst the first to use the finite element method for fixture design and analysis. They developed computer software to find the optimal design of the fixturing system by minimizing the total work done on the workpiece. Several researchers have carried out reallocation problems of fixturing positions [2-4]. Li and Melkote [2] presented a fixture layout optimization model for improving the location accuracy of the workpiece when clamped in a machining fixture. Roy and Liao [3] introduced a rational approach based on the use of both qualitative and quantitative reasoning tools to plan for the best supporting, locating and clamping positions. Krisnakumar and Melkote [4] implemented a genetic algorithm based fixture layout optimization approach. Tao et al. [5] presented a clamping analysis algorithm drawing on the metric of force closure.

Mijar and Arora [6] provided a review of elastostatic firictional contact problems. Some researchers carried out experimental investigation of coefficient of friction under dynamic machining condition [7,8].

Recently, many research can be found in the area of optimal clamping under dynamic machining environment. Tao et al. [9] and Meyer and Liou [9] developed a methodology that takes into account dynamic machining conditions to verify the fixture layout. Wang et al. [11] presented off-line simulations and on-line experimental verifications under dynamic machining environment. Nee et al. [12] introduced the architecture and functions of the intelligent fixturing system which provides on-line fixturing control strategy to perform an optimal workholding operation. A technique is presented to dynamically model and analyze the fixture-workpiece system subjected to time-varying machining loads [13]. Xiuwen et al. [14] presented a fixture-workpiece model in which both the workpiece and fixture elements are treated as deformable and friction forces are also taken into consideration. Li et al. [15] developed a model for analyzing the reaction forces and moments for machining fixtures with large contact areas. This model is then used to determine the minimum clamping forces necessary to keep the workpiece in static equilibrium. Yeh and Liou [16] established an analytical model to describe the clamping conditions between the workpiece and the fixture elements in a modular fixturing system. Roy et al. [17] proposed a system that generates fixture configuration and then analyzes for reallocation of fixture elements.

In literature, fixturing is generally considered in the sense of rigid workpiece concept, however, workpiece and fixturing elements are elastic and deformable. Clamping forces are estimated for static condiitons and direction of machining forces are assumed constant in most of the previous works.

It is seen that most of the systems [1,2,11,12,13,16,17] are focused on FEM analysis of workpiece but less system consider the time-varying cutting forces and frictional contact analysis and no approach has been found to treat the chip removal from the workpiece during machining operation.

In this paper, as an example, a workpiece is analyzed with FEM including frictional contact and time-varying machining forces are taken into account.

3 FEM CONTACT MODELLING

Contact problems are highly nonlinear and require significant computer resources to solve. Most contact problems need to account for friction. There are several friction laws and models to choose from and all are nonlinear. Frictional response can be chaotic, making solution convergence difficult. Elastic Coulomb friction model allows both sticking and sliding conditions. Rigid Coulomb friction model behavior allows only sliding friction; the contact areas cannot stick. Node-to-node contact element are typically used to model point-to-point contact applications. To use node-to-node contact elements, the location of contact need to be known beforehand. These types of contact problems usually involve small relative sliding between contacting surfaces. ANSYS elements CONTAC12 and CONTAC52 are node-to-node contact elements and support infinitesimal sliding and Coulomb's friction law. There are also node-to-surface and surface-to-surface contact elements. These elements support large deformations with a significant amount of sliding and friction and require more contact elements resulting in more disk space, CPU time and convergence problems [18]

Node-to-node contact elements represent two surfaces which may maintain or break physical contact and may slide relative to each other. The element is capable of supporting only compression in the direction normal to the surfaces and shear in the tangential direction.The element has three degrees of freedom at each node; translations in the nodal x, y and z direcitons.The element may be initially preloaded in the normal direction or it may be given a gap specification. A specified stiffness acts in the normal and tangential directions when the gap is closed and not siliding. Two stiffnesses, KN and KS are used in contact elements. The normal stiffness (KN) is used in the gap resistance and sticking stiffness is used for sticking resistance. If the interface is closed but sliding, KN is used in the gap resistance and the constant friction force μFN is used for sliding resistance. KN should be large enough that is reasonably restra,ins the model from over-penetrations, yet it should not be so large that it causes ill-conditioning. In the normal direction, when the normal force (FN) is negative, the interface remains in contact and respond as a linear spring. As the normal force becomes positive, contact is broken and no force is transmitted. In that case, contact element can be behave as a weak spring across an aopen interface which is useful for preventing rigidbody motion that could occur in a static analysis.The weak spring stiffness is computed by multiplying the normal stiffness KN by a reduction factor. In the tangential direction, for FN<0 and the absolut value of the tangential force (FS) less then μ|FN|, the interface sticks and responds as a linear spring. For FN<0 and FS=μ|FN|, sliding occurs. If contact is broken, FS=0 [18].

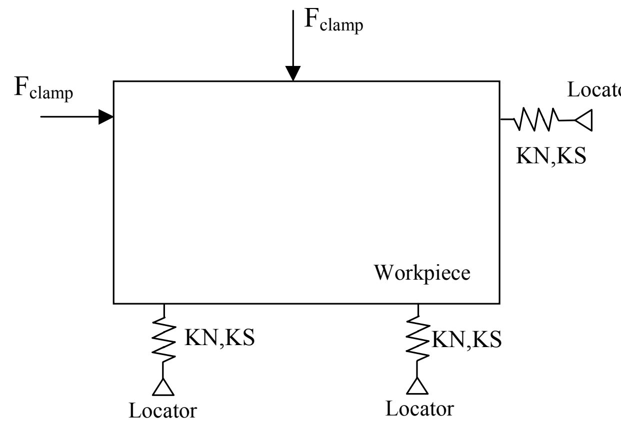

Figure 1: 2D workpiece-fixture contact model.

4 FINITE ELEMENT ANALYSIS OF WORKPİECE SUBJECT TO TIME-VARYING MACHINING LOADS

Another fixturing requirement is that the fixture must limit deformation of the workpiece. It is important to consider the cutting forces as well as the clamping forces on the workpiece. Without adequate fixture support, machining errors can occur and workpiece may slip from fixture elements. Finite element analysis (FEA) is well-suited tool to resolve some of these problems.

In order to minimise part distortion during clamping and machining, it is often desired to predict the minimum clamp actuation intensities necessary to keep the workpiece in totally restrained throughout machining [10]. The application of clamping forces is largely experience based and often results in over tightening of parts and may cause serious geometric and dimensional problems. On the other hand, insufficient clamping may permit the part to slip or detach from the support or locator during machining process. In this research, the clamping forces is adjusted to optimal values according to cutter position and cutting forces during machining.

Since the machining forces travel along the feature, it is necessary to ensure that the reaction forces at contact points are positive for all the time. Any zero reaction force indicates loss of contact or the separation between the workpiece and fixture element. Positive reaction forces at the supports and locators ensure that the workpiece maintains contact with all the locators and supports from the beginning of the cut to the end. All reaction forces at supports and locators must be positive during machining.

The clamping forces should be just sufficient to constrain and locate the workpiece without causing distortion or damage to the workpiece. If the clamping forces are too large, the machined workpiece may warp significantly when released from the fixture [11].

5 AN EXAMPLE

An example is provided to illustrate the application of the proposed methodology. The modular fixture configuration for this setup is shown in figure 2. The modular fixture layout is generated on the basis of the 3-2-1 locating principle. An open slot feature is machined in this setup.

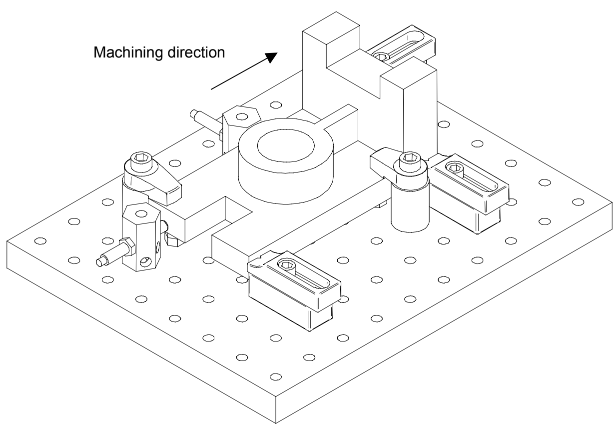

Figure 2: Modular fixture configuration of example part.

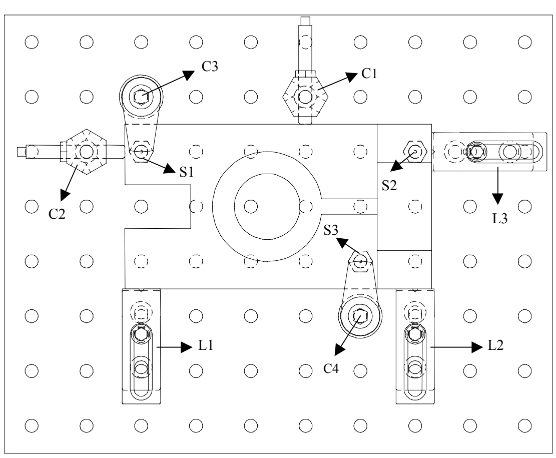

Figure 3: Modular fixture elements of setup.

ANSYS [18] FEA program is used in order to verify this fixture configuration. Verification process is carried out on the open slot feature. The chip removal effect and frictional contact are taken into account using contact elements.

The finite element model of the workpiece is shown in figure 4. The nearest nodes to supports and locators are selected as contact nodes which is shown in figure 5. Supports and locators are modelled using node-to-node contact elements. Friction coefficient is assumed identical for each contact with μ=0.3.

One of the major problem in contact analysis is the assignment of values to the normal (KN) and tangential (KS) stiffness which affects the convergence and accuracy of the solution. The values of KN and KS are required to be very large. However, the use of very high values of KN and KS results in ill-conditioned global stifness matrices leading to numerical errors and divergence. On the other hand, the use of smaller values results in convergence to wrong solution. In this example, appropriate values of KN and KS are taken as 10^{10} and 10^{10}, respectively.

Machined region (open slot feature) is meshed with block elements is showin in figure 4. In order to simulate the machining process, this elements are removed by element death technique step by step at each analysis. In this example, open slot feature is analysed at 24 step (12 step in first pass, 12 step in second pass).

Proposed analysis steps are as follows:

1. Apply machining forces to the four nodes which are in front of the first element,
2. Analyze the model,
3. Store the results and contact element forces,
4. Kill the block element (if there is next one, otherwise goto step 7),
5. Move the forces to the next four nodes,
6. Goto step 2,
7. Finish

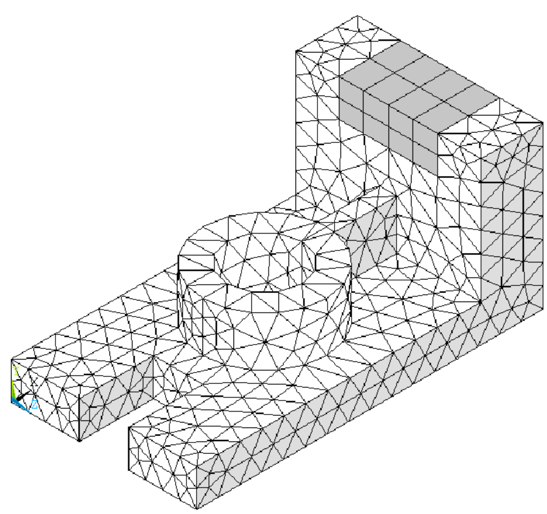

Figure 4: Workpiece and open slot finite element model.

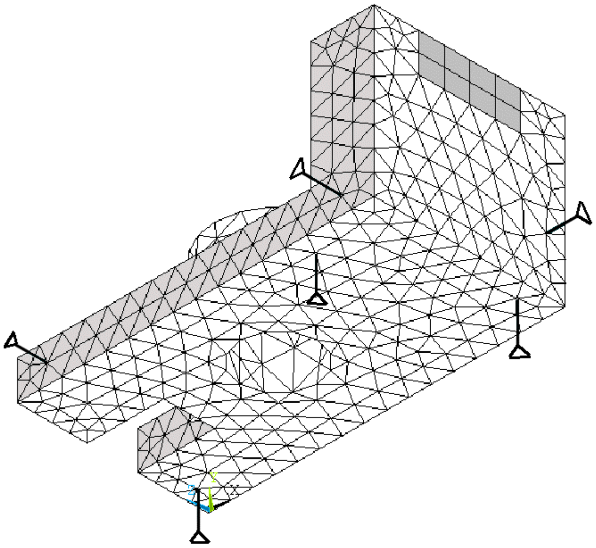

Figure 5: Contact elements and boundary conditions.

A fixture-workpiece system is subject to two main forces: clamping forces and cutting forces. The deformation of the workpiece is directly related to these forces acting on it. The cutting forces are dependant on the machine tool, workpiece material, cutter and cutting conditions.

Forces generated during machining must be known to determine the minimum clamping forces and to predict the distortion of a fixture-workpiece system. A number of well-validated models are reported in the literature. Machining forces for open slot has been computed as F_s=429 N, F_R=386 N and F_v=150 N [19]. These forces are distributed equally to four nodes as shown in figure 6. Initial clamping forces are selected as F_{C1}=750 N, F_{C2}=250 N, F_{C3}=750 N and F_{C4}=250 N which are applied to clamping nodes.

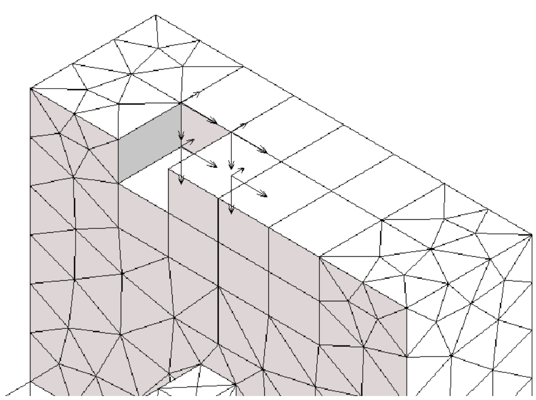

Figure 6: Open slot machining forces at step 2.

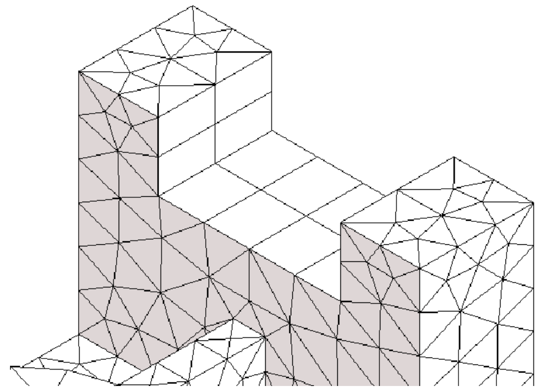

Figure 7: Finite element model after machining.

Finite element model after machining is given in figure 7. Normal forces at supports and locators are shown in figure 8 and 9.

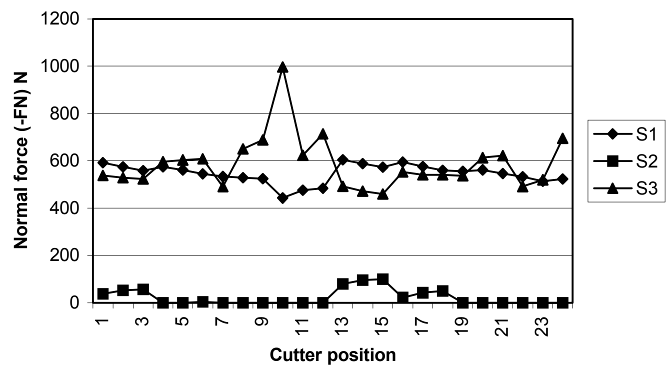

Figure 8: Normal force at supports.

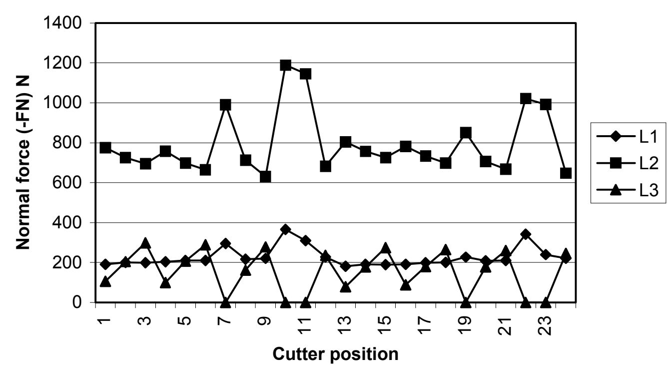

Figure 9: Normal force at locators.

The following obsevation can be made from the figure 8 and figure 9.

In figure 8, a plot of normal forces at supports versus cutter position for S2 indicates that the workpiece loses contact with the S2 at most steps. There is no separation at other support points. In order to prevent this separation, since the most critical support is S2, clamp force of C3 over S2 should be increased.

In figure 9, the most critical locator is L3 since its normal force is zero some steps during machining. C2 holds the part in contact with L3. Clamp force of C2 should be such a magnitude that L3 should maintain contact during machining. Clamp force of C2 also should be increased.

It is clear that the configuration which is generated using locating and clamping rules needs to be verified. This prevents the possible locating errors during design cycle.

6 CONCLUSION

This paper adresses the fixture design verification issue. In this research, the workpiece stability under dynamic machining and frictional conditions at the interface between fixture elements and workpiece are taken into account. Concluding contributions of this research in the area of fixture design are follows as:

- fixture design stability analysis under chip removal effect,
- application of stability and deformation analysis for time-varying machining forces,
- determination of frictional effects at the interface between fixture elements and workpiece,

Several research works have been carried out in fixture design but this research is different in the way that considers dynamic machining, frictional contact and chip removal issues together.

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