Machining fixture locating and clamping position optimization using genetic algorithms

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Abstract

Deformation of the workpiece may cause dimensional problems in machining. Supports and locators are used in order to reduce the error caused by elastic deformation of the workpiece. The optimization of support, locator and clamp locations is a critical problem to minimize the geometric error in workpiece machining. In this paper, the application of genetic algorithms (GAs) to the fixture layout optimization is presented to handle fixture layout optimization problem. A genetic algorithm based approach is developed to optimise fixture layout through integrating a finite element code running in batch mode to compute the objective function values for each generation. Case studies are given to illustrate the application of proposed approach. Chromosome library approach is used to decrease the total solution time. Developed GA keeps track of previously analyzed designs; therefore the numbers of function evaluations are decreased about 93%. The results of this approach show that the fixture layout optimization problems are multi-modal problems. Optimized designs do not have any apparent similarities although they provide very similar performances.

Keywords: Fixture design; Genetic algorithms; Optimization

1. Introduction

Fixtures are used to locate and constrain a workpiece during a machining operation, minimizing workpiece and fixture tooling deflections due to clamping and cutting forces are critical to ensuring accuracy of the machining operation. Traditionally, machining fixtures are designed and manufactured through trial-and-error, which prove to be both expensive and time-consuming to the manufacturing process. To ensure a workpiece is manufactured according to specified dimensions and tolerances, it must be appropriately located and clamped, making it imperative to develop tools that will eliminate costly and time-consuming trial-and-error designs. Proper workpiece location and fixture design are crucial to product quality in terms of precision, accuracy and finish of the machined part.

Theoretically, the 3-2-1 locating principle can satisfactorily locate all prismatic shaped workpieces. This method provides the maximum rigidity with the minimum number of fixture elements. To position a part from a kinematic point of view means constraining the six degrees of freedom of a free moving body (three translations and three rotations). Three supports are positioned below the part to establish the location of the workpiece on its vertical axis. Locators are placed on two peripheral edges and intended to establish the location of the workpiece on the x and y horizontal axes. Properly locating the workpiece in the fixture is vital to the overall accuracy and repeatability of the manufacturing process. Locators should be positioned as far apart as possible and should be placed on machined surfaces wherever possible. Supports are usually placed to encompass the center of gravity of a workpiece and positioned as far apart as possible to maintain its stability. The primary responsibility of a clamp in fixture is to secure the part against the locators and supports. Clamps should not be expected to resist the cutting forces generated in the machining operation.

For a given number of fixture elements, the machining fixture synthesis problem is the finding optimal layout or positions of the fixture elements around the workpiece. In this paper, a method for fixture layout optimization using genetic algorithms is presented. The optimization objective is to search for a 2D fixture layout that minimizes the maximum elastic deformation at different locations of the workpiece. ANSYS program has been used for calculating the deflection of the part under clamping and cutting forces. Two case studies are given to illustrate the proposed approach.

2. Review of related works

Fixture design has received considerable attention in recent years. However, little attention has been focused on the optimum fixture layout design. Menassa and DeVries[1]used FEA for calculating deflections using the minimization of the workpiece deflection at selected points as the design criterion. The design problem was to determine the position of supports. Meyer and Liou[2] presented an approach that uses linear programming technique to synthesize fixtures for dynamic machining conditions. Solution for the minimum clamping forces and locator forces is given. Li and Melkote[3]used a nonlinear programming method to solve the layout optimization problem. The method minimizes workpiece location errors due to localized elastic deformation of the workpiece. Roy andLiao[4]developed a heuristic method to plan for the best supporting and clamping positions. Tao et al.[5]presented a geometrical reasoning methodology for determining the optimal clamping points and clamping sequence for arbitrarily shaped workpieces. Liao and Hu[6]presented a system for fixture configuration analysis based on a dynamic model which analyses the fixture–workpiece system subject to time-varying machining loads. The influence of clamping placement is also investigated. Li and Melkote[7]presented a fixture layout and clamping force optimal synthesis approach that accounts for workpiece dynamics during machining. A combined fixture layout and clamping force optimization procedure presented.They used the contact elasticity modeling method that accounts for the influence of workpiece rigid body dynamics during machining. Amaral et al. [8] used ANSYS to verify fixture design integrity. They employed 3-2-1 method. The optimization analysis is performed in ANSYS. Tan et al. [9] described the modeling, analysis and verification of optimal fixturing configurations by the methods of force closure, optimization and finite element modeling.

Most of the above studies use linear or nonlinear programming methods which often do not give global optimum solution. All of the fixture layout optimization procedures start with an initial feasible layout. Solutions from these methods are depending on the initial fixture layout. They do not consider the fixture layout optimization on overall workpiece deformation.

The GAs has been proven to be useful technique in solving optimization problems in engineering [10–12]. Fixture design has a large solution space and requires a search tool to find the best design. Few researchers have used the GAs for fixture design and fixture layout problems. Kumar et al. [13] have applied both GAs and neural networks for designing a fixture. Marcelin [14] has used GAs to the optimization of support positions. Vallapuzha et al. [15] presented GA based optimization method that uses spatial coordinates to represent the locations of fixture elements. Fixture layout optimization procedure was implemented using MATLAB and the genetic algorithm toolbox. HYPERMESH and MSC/NASTRAN were used for FE model. Vallapuzha et al. [16] presented results of an extensive investigation into the relative effectiveness of various optimization methods. They showed that continuous GA yielded the best quality solutions. Li and Shiu [17] determined the optimal fixture configuration design for sheet metal assembly using GA. MSC/NASTRAN has been used for fitness evaluation. Liao [18] presented a method to automatically select the optimal numbers of locators and clamps as well as their optimal positions in sheet metal assembly fixtures.

Krishnakumar and Melkote [19] developed a fixture layout optimization technique that uses the GA to find the fixture layout that minimizes the deformation of the machined surface due to clamping and machining forces over the entire tool path. Locator and clamp positions are specified by node numbers. A built-in finite element solver was developed.

Some of the studies do not consider the optimization of the layout for entire tool path and chip removal is not taken into account. Some of the studies used node numbers as design parameters.

In this study, a GA tool has been developed to find the optimal locator and clamp positions in 2D workpiece. Distances from the reference edges as design parameters are used rather than FEA node numbers. Fitness values of real encoded GA chromosomes are obtained from the results of FEA. ANSYS has been used for FEA calculations. A chromosome library approach is used in order to decrease the solution time. Developed GA tool is tested on two test problems. Two case studies are given to illustrate the developed approach. Main contributions of this paper can be summarized as follows:

(1) developed a GA code integrated with a commercial finite element solver;
(2) GA uses chromosome library in order to decrease the computation time;
(3) real design parameters are used rather than FEA node numbers;
(4) chip removal is taken into account while tool forces moving on the workpiece.

3. Genetic algorithm concepts

Genetic algorithms were first developed by John Holland. Goldberg [10] published a book explaining the theory and application examples of genetic algorithm in details. A genetic algorithm is a random search technique that mimics some mechanisms of natural evolution. The algorithm works on a population of designs. The population evolves from generation to generation, gradually improving its adaptation to the environment through natural selection; fitter individuals have better chances of transmitting their characteristics to later generations.

In the algorithm, the selection of the natural environment is replaced by artificial selection based on a computed fitness for each design. The term fitness is used to designate the chromosome's chances of survival and it is essentially the objective function of the optimization problem. The chromosomes that define characteristics of biological beings are replaced by strings of numerical values representing the design variables.

GA is recognized to be different than traditional gradient based optimization techniques in the following four major ways [10]:

1. GAs work with a coding of the design variables and parameters in the problem, rather than with the actual parameters themselves.

2. GAs makes use of population-type search. Many different design points are evaluated during each iteration instead of sequentially moving from one point to the next.

3. GAs needs only a fitness or objective function value. No derivatives or gradients are necessary.

4. GAs use probabilistic transition rules to find new design points for exploration rather than using deterministic rules based on gradient information to find these new points.

4. Approach

4.1. Fixture positioning principles

In machining process, fixtures are used to keep workpieces in a desirable position for operations. The most important criteria for fixturing are workpiece position accuracy and workpiece deformation. A good fixture design minimizes workpiece geometric and machining accuracy errors. 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. Without adequate fixture support, machining operations do not conform to designed tolerances. Finite element analysis is a powerful tool in the resolution of some of these problems [22].

Common locating method for prismatic parts is 3-2-1 method. This method provides the maximum rigidity with the minimum number of fixture elements. A workpiece in 3D may be positively located by means of six points positioned so that they restrict nine degrees of freedom of the workpiece. The other three degrees of freedom are removed by clamp elements. An example layout for 2D workpiece based 3-2-1 locating principle is shown in Fig. 4.

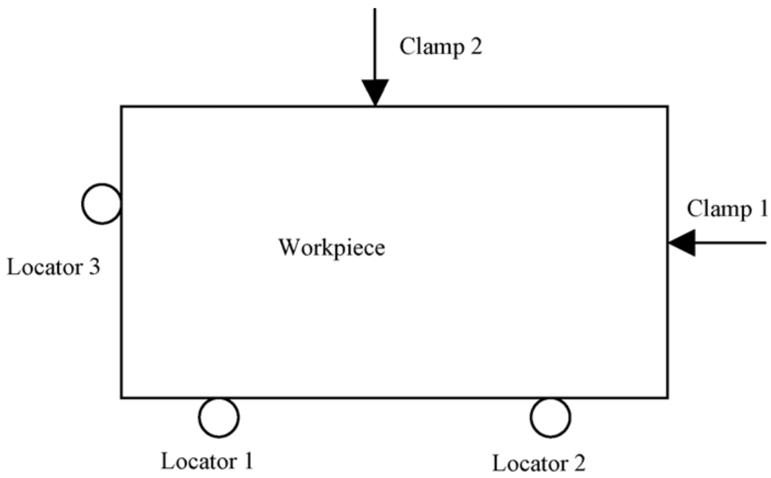

Fig. 4. 3-2-1 locating layout for 2D prismatic workpiece

The number of locating faces must not exceed two so as to avoid a redundant location. Based on the 3-2-1 fixturing principle there are two locating planes for accurate location containing two and one locators. Therefore, there are maximum of two side clampings against each locating plane. Clamping forces are always directed towards the locators in order to force the workpiece to contact all locators. The clamping point should be positioned opposite the positioning points to prevent the workpiece from being distorted by the clamping force.

Since the machining forces travel along the machining area, it is necessary to ensure that the reaction forces at locators are positive for all the time. Any negative reaction force indicates that the workpiece is free from fixture elements. In other words, loss of contact or the separation between the workpiece and fixture element might happen when the reaction force is negative. Positive reaction forces at the locators ensure that the workpiece maintains contact with all the locators from the beginning of the cut to the end. The clamping forces should be just sufficient to constrain and locate the workpiece without causing distortion or damage to the workpiece. Clamping force optimization is not considered in this paper.

4.2. Genetic algorithm based fixture layout optimization approach

In real design problems, the number of design parameters can be very large and their influence on the objective function can be very complicated. The objective function must be smooth and a procedure is needed to compute gradients. Genetic algorithms strongly differ in conception from other search methods, including traditional optimization methods and other stochastic methods [23]. By applying GAs to fixture layout optimization, an optimal or group of sub-optimal solutions can be obtained.

In this study, optimum locator and clamp positions are determined using genetic algorithms. They are ideally suited for the fixture layout optimization problem since no direct analytical relationship exists between the machining error and the fixture layout. Since the GA deals with only the design variables and objective function value for a particular fixture layout, no gradient or auxiliary information is needed [19].

The flowchart of the proposed approach is given in Fig. 5.

Fixture layout optimization is implemented using developed software written in Delphi language named GenFix. Displacement values are calculated in ANSYS software [24]. The execution of ANSYS in GenFix is simply done by WinExec function in Delphi. The interaction between GenFix and ANSYS is implemented in four steps:

(1) Locator and clamp positions are extracted from binary string as real parameters.

(2) These parameters and ANSYS input batch file (modeling, solution and post processing commands) are sent to ANSYS using WinExec function.

(3) Displacement values are written to a text file after solution.

(4) GenFix reads this file and computes fitness value for current locator and clamp positions.

In order to reduce the computation time, chromosomes and fitness values are stored in a library for further evaluation. GenFix first checks if current chromosome’s fitness value has been calculated before. If not, locator positions are sent to ANSYS, otherwise fitness values are taken from the library. During generating of the initial population, every chromosome is checked whether it is feasible or not. If the constraint is violated, it is eliminated and new chromosome is created. This process creates entirely feasible initial population. This ensures that workpiece is stable under the action of clamping and cutting forces for every chromosome in the initial population.

The written GA program was validated using two test cases. The first test case uses Himmelblau function [21]. In the second test case, the GA program was used to optimise the support positions of a beam under uniform loading.

5. Fixture layout optimization case studies

The fixture layout optimization problem is defined as: finding the positions of the locators and clamps, so that workpiece deformation at specific region is minimized. Note that number of locators and clamps are not design parameter, since they are known and fixed for the 3-2-1 locating scheme. Hence, the design parameters are selected as locator and clamp positions. Friction is not considered in this paper. Two case studies are given to illustrate the proposed approach.

6. Conclusion

In this paper, an evolutionary optimization technique of fixture layout optimization is presented. ANSYS has been used for FE calculation of fitness values. It is seen that the combined genetic algorithm and FE method approach seems to be a powerful approach for present type problems. GA approach is particularly suited for problems where there does not exist a well-defined mathematical relationship between the objective function and the design variables. The results prove the success of the application of GAs for the fixture layout optimization problems.

In this study, the major obstacle for GA application in fixture layout optimization is the high computation cost. Re-meshing of the workpiece is required for every chromosome in the population. But, usages of chromosome library, the number of FE evaluations are decreased from 6000 to 415. This results in a tremendous gain in computational efficiency. The other way to decrease the solution time is to use distributed computation in a local area network.

The results of this approach show that the fixture layout optimization problems are multi-modal problems. Optimized designs do not have any apparent similarities although they provide very similar performances. It is shown that fixture layout problems are multi-modal therefore heuristic rules for fixture design should be used in GA to select best design among others.

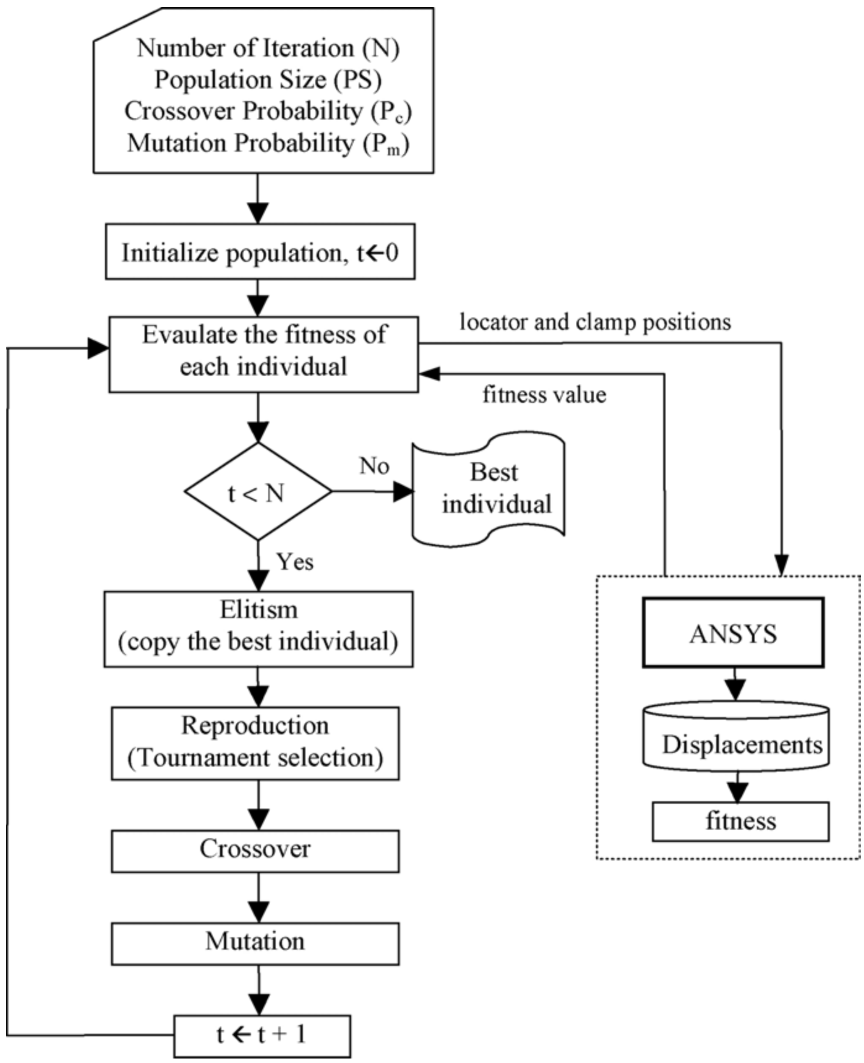

Fig. 5. The flowchart of the proposed methodology and ANSYS interface.