

Fixture Layout Optimization for Large Metal Sheets Using Genetic Algorithm

Zeshan Ahmad, Matteo Zoppi, and Rezia Molfino

Abstract—The geometric errors in the manufacturing process can be reduced by optimal positioning of the fixture elements in the fixture to make the workpiece stiff. We propose a new fixture layout optimization method N-3-2-1 for large metal sheets in this paper that combines the genetic algorithm and finite element analysis. The objective function in this method is to minimize the sum of the nodal deflection normal to the surface of the workpiece. Two different kinds of case studies are presented, and optimal position of the fixturing element is obtained for different cases.

Keywords—Fixture layout, optimization, fixturing element, genetic algorithm.

I. INTRODUCTION

FIXTURES are very important component in the manufacturing system. A fixture is used to hold and locate the workpiece in the desired orientation during the manufacturing process. The components that hold and locate the workpiece are called fixture elements. The arrangement of these fixture elements is very important to reduce the errors in manufacturing process. According to Prabhakaran et al. the position of the fixturing elements in the fixture is called fixture layout, and the layout, which minimizes the workpiece deformation is called optimal fixture layout [1].

The most usual optimization methods implemented are mathematical programming approaches, penalty function methods, simulated annealing, genetic algorithm, and ant colony algorithm. The mathematical programming methods can be classified as linear programming (LP), linear & quadratic integer programming (LQP), dynamic programming (DP), goal programming (GP) and sequential quadratic programming (SQP).

Menassa et al. proposed a method to determine the position of the fixture supports in a fixture. The objective function is the minimization of the workpiece deflection at specific points. The deflection is calculated by using the FEA. The method is verified with three numerical examples [2]. Meyet et al. presented a method to synthesize a fixture using dynamic conditions. Linear programming is used to solve the layout optimization. The objective function in this method is to minimize the deflection of the workpiece and this is achieved

by using the minimum clamping force [3]. Roy et al. presented a technique based on the qualitative and quantitative reasoning to find the optimal supporting, locating, and clamping positions [4]. Tao et al. presented a computational geometry approach for arbitrarily shaped workpieces. All the possible clamping points are automatically found, and then optimal clamping points are chosen from a feasible clamping region. The method is verified by case studies [5]. Li et al. presented a fixture-workpiece elastic contact model to increase the workpiece location accuracy. Nonlinear programming method is used for solving the problem. The objective is to minimize the rigid body motion of the workpiece [6]. Liao et al. presented a technique for fixture layout optimization subjected to the dynamic conditions. The parameters affecting the fixturing stability are analyzed. These parameters are the clamping force magnitude, the application sequence, and the placement of the fixturing clamps. The deformation of a flexible workpiece under clamping and machining loads is estimated under dynamic conditions [7]. Li et al. presented an approach for fixture layout and clamping force optimization. This approach considers the workpiece dynamics during machining. The objective function of this approach is to minimize the maximum positional error at the machining point during machining. An iterative fixture layout and clamping force optimization algorithm yields the best results that are verified by simulations [8]. Tan et al. described an approach for the modeling, analysis and verification of optimal fixture design. The methods of force closure, optimization and finite element modeling (FEM) are used in this approach [9]. Amaral et al. developed a method to analyze the deformation of the contact area between modular fixture and tool to find the optimum support locations, using finite element analysis (FEA). ANSYS has been used for the analysis and optimization. The locators are placed in 3-2-1 principle. The objective function of this methodology is to minimize the maximum resultant deflection and assessing workpiece stability [10]. Most of the above studies are applied to the rigid bodies and use linear or nonlinear programming methods. The few studies applied to sheet metal parts are given below.

Cai et al. proposed N-2-1 locating principle algorithm for deformable sheet metal parts. It uses the finite element analysis and nonlinear programming methods to find the optimal location of the locators. The objective function for the optimization is the sum of the square of the nodal deflections. The total deformation of the sheet metal is minimized in this way [11]. Li et al. proposed the first method to determine the

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optimal fixture configuration design for sheet metal assembly with laser welding. This is the first method that considers both the number and the location of the locators. A powerful optimization technique using a genetic algorithm is used. A case study is presented to verify the effectiveness of the proposed method [12]. Li et al. developed a fixture configuration methodology based on a new proposed locating scheme for sheet metal laser welding. The case study of automotive assembly is investigated by applying the fixture configuration design method [13]. Cai developed a method for fixture optimization for sheet panel assembly considering welding gun variations. A fixture optimization model is formulated to minimize the assembly dimensional variations under welding gun variations. The method is verified by numerical examples [14]. Ma et al. proposed a new method for compliant fixture layout design using a topology optimization method. The objective function is to minimize the overall deformation of the workpiece. Both 2-D and 3-D numerical examples are presented to verify the effectiveness of the proposed approach [15]. Cheng et al. developed a fixture layout method to minimize the assembly variation of Aeronautical Thin-Walled Structures (ATWS). This approach uses a genetic algorithm and ant's algorithm (GAAA) to optimize the fixture layout [16]. Xiong et al. proposed a new fixture layout optimization method N-2-1-1 for flexible aerospace workpiece. The objective function of the optimization algorithm is to minimize the maximum elastic deformation at the machined point [17].

We propose a new method for fixture layout optimization using the genetic algorithm. The propose method is verified by two different case studies. The results obtained by these case shows the fixture optimal layout.

II. N-3-2-1 FIXTURING PRINCIPLE

A rigid body is fully constrained with minimum fixture elements by the 3-2-1 locating principle. This principle is the traditional principle for locating the prismatic shaped workpieces. According to this principle, 3, 2, 1 locators are enough to constrain the workpiece. The locating principle 3-2-1 constrains the rigid body motion (six degree of freedom).

Let us consider a sheet metal plate. The dimensions of the sheet metal are 800mm x 600mm x 1mm. The finite element model of the plate is shown in Fig. 1. We analyze the deformation under the self weight of the plate in 3-2-1 fixturing principle. The deformation results show that deformation of the plate is very high 11.0mm under self weight as shown in Fig. 2. This high value of deformation produces the geometric errors in manufacturing process, which is not acceptable.

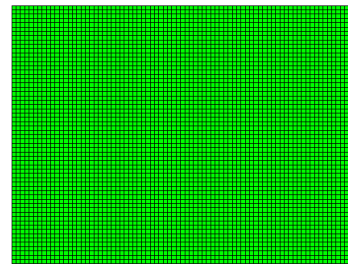


Fig. 1 Finite element model of plate

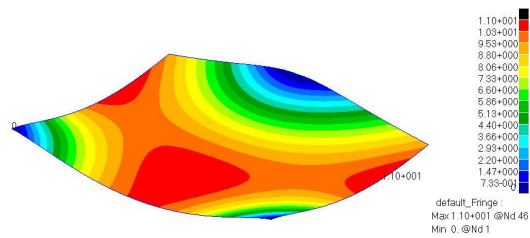


Fig. 2 Deformation in 3-2-1 Fixturing principle

Let us add one more locator in order to analyze the deformation of the plate under self weight. The deformation value obtained is 2.43mm as shown in Fig. 3. The deformation value in this fixturing principle 1-3-2-1 is 4.5 times less than the 3-2-1 fixturing principle, which seems to be acceptable to the manufacturing process. We can reduce this deformation more by adding more locators.

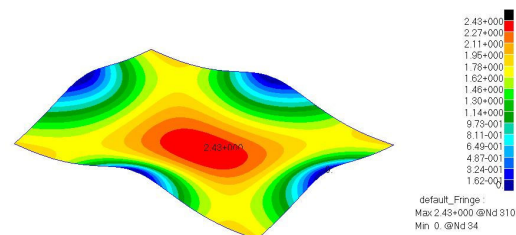


Fig. 3 Deformation in 1-3-2-1 Fixturing principle

The above discussion shows that 3-2-1 fixturing principle is not valid for metal sheet due to their flexible nature. So, more than 3 locators are required to reduce the deflection of the workpiece normal to the surface. When a force is applied to the metal sheet, like a drilling force or a resistance spot welding, the sheet deflects in direction normal to its surface.

We propose an N-3-2-1 locating principle and show that this principle is valid for large sheet metal parts due to their flexible nature. According to this principle, 2-1 locators are enough to constrain the sheet metal in the secondary and tertiary plane, but N+3 locators are required to constrain the metal sheet in the primary plane due to its flexible nature. The value of the N locators must be equal to or greater than 1. This number of locators depends on the geometry and dimensional specification of the workpiece.

N-3-2-1 fixturing principle satisfies the two conditions

required for fixturing the workpiece.

1. It constrains the workpiece fully in six degree of freedom.
2. It also satisfies that, deformation of the workpiece is in the elastic range.

The arrangement of locators is very important because the success of this principle depends on it. This arrangement can be achieved by fixture layout optimization method.

III. FIXTURE LAYOUT OPTIMIZATION

A. Problem Formulation

The fixture layout optimization problem may be defined as: finding the position of the locators, so that the stiffness of the workpiece is maximized. This stiffness is achieved in terms of deflection of the workpiece.

The formulation of the fixture layout optimization problem is

$$\text{Minimize } F = \sum_{i=1}^n u_i \quad i = 1, 2, 3 \dots n \quad (1)$$

$$\begin{aligned} & a_j \leq x_j \leq b_j \\ \text{Subject to } & c_j \leq y_j \leq d_j \quad j = 1, 2, 3 \dots m \quad (2) \\ & g_j \leq z_j \leq k_j \end{aligned}$$

where,

F : objective function

u : nodal deflection

n : number of nodes

m : number of locators

$a_i, b_i, c_i, d_i, g_i, k_i$: limitation of locator in the x, y, z direction

The objective function of the optimization is defined as the sum of the nodal deflection normal to the surface of the workpiece. The fixture layout optimization problem is solved by genetic algorithm, which is one of the most efficient optimization algorithms. The design variables are the positions of the locators.

B. Fixture Layout Optimization Process Using Genetic Algorithm

Genetic algorithms are the evolutionary algorithms (EA) which use the techniques inspired by natural evolution. Genetic algorithm is different from traditional gradient based optimization techniques: (1) No gradient information is required, it requires only the fitness value (2) GA does not move sequentially from one point to the next one, but many new points are evaluated during the iteration. The GA convergence is controlled by few parameters: the population size (Ps), the probability of crossover (Pc) and the probability of mutation (Pm).

The population of randomly individual is generated. The fitness or objective function value of every individual in the population is evaluated. The fitness is usually the value of the

objective function in the optimization problem. The fitness value is evaluated, if the fitness satisfies the convergence condition, the process is terminated, and otherwise it will go for the next iteration. More individual is selected from the current population and mutated to form the new population. This new population is sent to calculate the fitness by finite element analysis and this fitness value is send for evaluation, and process is repeated until the problem is converged. The algorithm converges when number of generations reaches the maximum number of iterations.

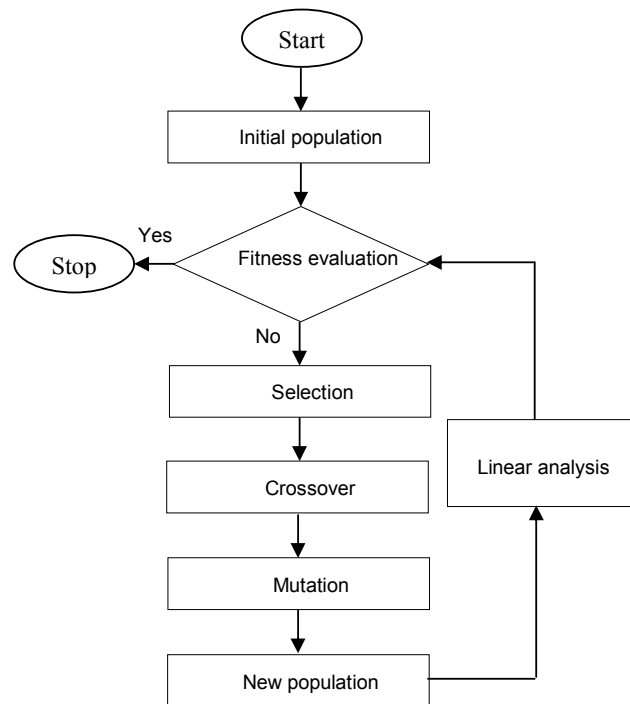


Fig. 4 Flow chart for fixture layout optimization

Genetic algorithm consists of the following steps:

Step 1. Random population of the design variables is generated.

Step 2. The finite element analysis is performed to calculate the fitness or objective function value. This value is passed for fitness evaluation.

Step 3. By using the FEA results, fitness evaluation is performed. Convergence is checked, if the problem is converged, process is terminated. If no, then it will go to the next step.

Step 4. Selection: The parents are selected by tournament selection to generate a new population.

Step 5. Crossover: It is the process of combining two chromosomes with their genetic material to produce a new offspring which have both their characteristics. Single point, two point, multipoint, and uniform crossover are possible. We will use the single point crossover. Single point crossover will create the cut line in the two parents, and combines the first part of the

first parent to the second part of the second parent and vice versa to produce two offspring.

Step 6. Mutation: Mutation changes one or more string values in a chromosome. The solution may change completely from the previous solution in mutation. Therefore better solution can be achieved by using mutation. The mutation probability defines how often the parts of the chromosome will be mutated. The mutation probability should be set low. If mutation probability value is set too high, the search will turn into a random search.

Step 7. New population has been generated by above process.

Step 8. Go to the step 2 with new population, and repeat the process until the convergence criteria is satisfied.

IV. FIXTURE LAYOUT OPTIMIZATION CASE STUDIES

Two different kinds of case studies are presented to verify the propose method. The preprocessing is done in Hypermesh, analysis in MSC NASTRAN, and optimization process in Matlab. A genetic algorithm is used as optimization method.

The objective function of the propose method is the sum of the nodal deflection normal to the surface of the workpiece. It has been verified by FEA that four clamps are enough to constrain it in primary plane for each case study. So, the locating principle will be 1-3-2-1. Three different sub cases are solved for each case study. In case 1, two locators will be used as design locator, and each locator will be moved independently. In case 2, four locators will be used as design variable, and these four locators L4, L6, L5, and L7 will be moved in two pairs. In case 3, four locators are design variable, and these four locators will be moved together.

The material used for optimization is steel having young's modulus of elasticity 207 GPa and Poisson ratio 0.3. These material properties are used for all case studies.

A. Case Study 1 – Plate Example

The workpiece used here is a sheet metal plate. The dimensions of the sheet metal are 800mm x 600mm x 1mm. The finite element model of the plate is shown in Fig. 5. The finite elements are QUAD4 element with size 10mm x 10mm. O (0, 0, 0) is the origin point. A force of magnitude 50 N is applied on the sheet at (300, 200, 0) in the Z-direction.

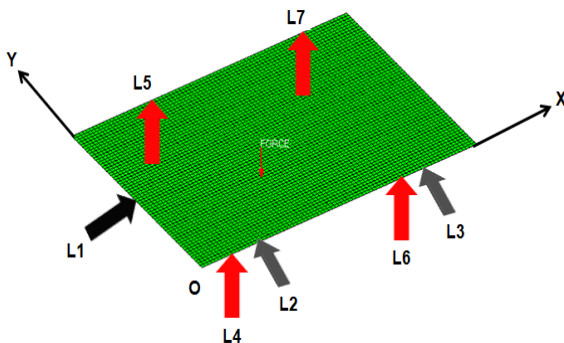


Fig. 5 Finite element model of plate example

The fixed locators L1 constraint the workpiece in X and the locators L2 and L3 constrain the workpiece in the Y direction, while the other locators L4, L5, L6 and L7 constrain the workpiece in the Z direction. The clamping length of each design locator is 300 mm along the long edge of the workpiece from the corner point of the workpiece. The two locators L4 and L6 move on the edge along the X axis and the other two locators L5 and L7 move on the other edge parallel to the X axis. The initial position of the locators with their optimal position obtained by fixture layout optimization is given in Table I for all cases.

TABLE I
INITIAL AND OPTIMAL CLAMPING POSITION OF THE LOCATORS

Cases	Locator type	Locator	Initial position(mm)	Optimal position (mm)
All Cases	Fixed Locator	L1	(0,300,0)	
		L2	(100,0,0)	
		L3	(700,0,0)	
Case-1	Fixed Locator	L5	(200,600,0)	
		L6	(600,0,0)	
	Design Locator	L4	(0,0,0)	(150,0,0)
		L7	(800,600,0)	(530,600,0)
Case-2	Design Locator	L4	(0,0,0)	(120,0,0)
		L5	(0,600,0)	(120,600,0)
		L6	(800,0,0)	(510,0,0)
		L7	(800,600,0)	(510,600,0)
Case-3	Design Locator	L4	(0,0,0)	(200,0,0)
		L5	(0,600,0)	(200,600,0)
		L6	(800,0,0)	(600,0,0)
		L7	(800,600,0)	(600,600,0)

B. Case Study 2 – Spacer Grid

The second case study selected to verify the propose method is the spacer grid. The Z and the X dimensions of the workpiece are 800mm x 640mm. The finite element model of the spacer grid is shown in Fig. 6. The finite elements are QUAD4 elements. The point O (0,0,0) is the origin. The force of magnitude 200 N is applied to the sheet metal in the Y-direction.

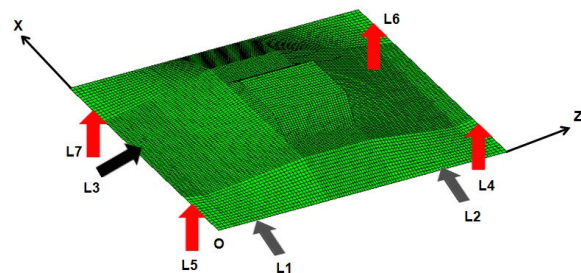


Fig. 6 Finite element model of spacer grid

The fixed locators L1 and L2 constraint the workpiece in X and the locator L3 constrain the workpiece in Z direction, while the other locators L4, L5, L6 and L7 constrain the workpiece in the Y direction. The clamping length of each design locator is 200mm along the short edge of the workpiece

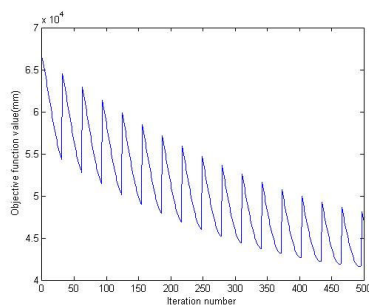
from the corner point of the workpiece. The two locators L5 and L7 move along the edge on the X axis, while the other two locators L4 and L6 move along the edge parallel to the X axis. The initial position of the locators with their optimal position is given in Table II for all cases.

TABLE II
INITIAL AND OPTIMAL CLAMPING POSITION OF THE LOCATORS

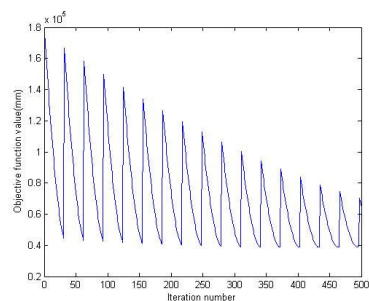
Cases	Locator type	Locator	Initial position(mm)	Optimal position (mm)
All Cases	Fixed Locator	L1	(0, 0,100)	
		L2	(0,0,700)	
		L3	(320,0,0)	
Case-1	Fixed Locator	L5	(105,0,0)	
		L6	(440,0,800)	
	Design Locator	L4	(0,0,800)	(115,0,800)
		L7	(640,0,0)	(460,0,0)
Case-2	Design Locator	L4	(0,0,800)	(115,0,800)
		L5	(0,0,0)	(115,0,0)
	Locator	L6	(640,0,800)	(525,0,800)
		L7	(640,0,0)	(525,0,0)
Case-3	Design Locator	L4	(0,0,800)	(115,0,800)
		L5	(0,0,0)	(115,0,0)
	Locator	L6	(640,0,800)	(525,0,800)
		L7	(640,0,0)	(525,0,0)

V. OPTIMIZATION RESULTS

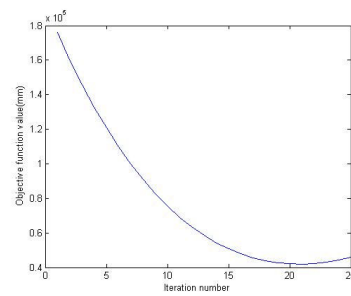
The fixture layout optimization is performed as shown in Fig. 4. The optimization process is started from the initial layout, and an optimum position is achieved in many iterations. The convergence of the objective function value from initial position to optimum position is shown in Fig. 7 and Fig. 8 for three cases of the both case studies.



(a) Case 1

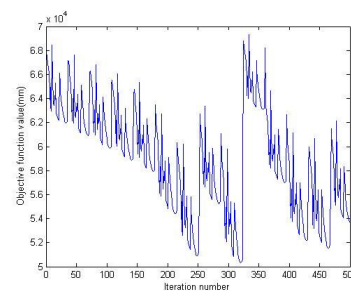


(b) Case 2

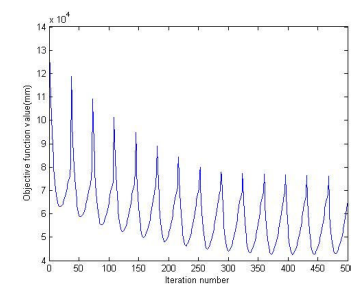


(c) Case 3

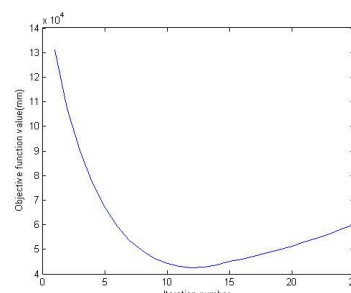
Fig. 7 Convergence results of case study 1



(a) Case 1



(b) Case 2



(c) Case 3

Fig. 8 Convergence results of case study 2

The fixture layout optimization is performed and different kinds of parameters are calculated like initial and optimal layout objective function values, number of iterations in which the problem is converged is given in Table III.

The optimum value of the objective function F is less than

the objective function value of the initial position. The workpiece is stiffer in the optimal position as compared to the initial layout. This reduces the errors in the manufacturing process. The convergence criterion is the maximum number of iterations.

TABLE III
OPTIMIZATION RESULTS OF TWO CASE STUDIES

Sr. No.	Parameters	Case-1	Case-2	Case-3
Case Study 1	F (Initial)	6.63E+04	1.76E+05	1.76E+05
	F (Optimum)	4.16E+04	3.87E+04	4.20E+04
	Number of Iterations	500	500	25
Case Study 2	F (Initial)	6.79E+04	1.31E+05	1.31E+05
	F (Optimum)	5.03E+04	4.25E+04	4.25E+04
	Number of Iterations	500	500	25

VI. CONCLUSION

A new N-3-2-1 fixture layout optimization method is introduced especially for large metal sheet. According to this principle, 2-1 locators are enough to constrain the sheet metal in the secondary and tertiary plane, but N+3 locators are required to constrain the workpiece in the primary plane. The value of the N locators must be equal to or greater than 1. Two kinds of case studies are solved to verify the proposed fixture layout optimization method. The optimal fixture layout is obtained by using the genetic algorithm. The results show that deflection of workpiece is reduced, so, the geometric errors in the workpiece during the manufacturing process are reduced.

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REFERENCES

- [1] G. Prabhakaran, K. P. Padmanaban, R. Krishnakumar, "Machining fixture layout optimization using FEM and evolutionary techniques," *International Journal of Advanced Manufacturing Technology*, vol. 32, pp. 1090-1103, 2007.
- [2] R.J. Menassa, W.R. DeVries, "Optimization methods applied to selecting support positions in fixture design," *ASME Journal of Engineering for Industry*, vol. 113, pp. 412-418, 1991.
- [3] R.T. Meyer, F.W. Liou, "Fixture analysis under dynamic machining," *International Journal of Production Research*, vol. 35, no. 5, pp. 1471-1489, 1997.
- [4] U. Roy, J. Liao, "Geometric reasoning for re-allocation of supporting and clamping positions in the automated fixture design system," *IEEE Transactions*, vol. 31, pp. 313-322, 1999.
- [5] Z.J. Tao, A.S. Kumar, A.Y.C. Nee, "A computational geometry approach to optimum clamping synthesis of machining fixtures," *International Journal of Production Research*, vol. 37, no. 15, pp. 3495-3517, 1999.
- [6] B. Li, S.N. Melkote, "Improved workpiece location accuracy through fixture layout optimization," *International Journal of Machine Tools and Manufacture*, vol. 39, pp. 871-883, 1999.
- [7] Y.J. Liao, S.J. Hu, "Flexible multibody dynamics based fixture-workpiece analysis model for fixturing stability," *International Journal of Machine Tools and Manufacture*, vol. 40, pp. 343-362, 2000.
- [8] B. Li, S.N. Melkote, "Optimal fixture design accounting for the effect of workpiece dynamics," *International Journal of Advanced Manufacturing Technology*, vol. 18, pp. 701-707, 2001.
- [9] E.Y.T. Tan, A.S. Kumar, J.Y.H. Fuh, A.Y.C. Nee, "Modeling, analysis and verification of optimal fixturing design," *IEEE Transactions on Automation Science and Engineering*, vol. 1, no. 2, pp. 121-132, 2004.
- [10] N. Amaral, J.J. Rencis, Y. Rong, "Development of a finite element analysis tool for fixture design integrity verification and optimization," *International Journal of Advanced Manufacturing Technology*, vol. 21, pp. 411-419, 2004.
- [11] W. Cai, S. J. Hu, and J. X. Yuan, "Deformable sheet metal fixturing: principles, algorithms, and simulations," *Journal of Manufacturing Science and Engineering*, vol. 118, issue 3, pp. 318-324, 1996.
- [12] B. Li and B. W. Shiu, "Principle and simulation of fixture configuration design for sheet metal assembly with laser welding. Part 2: optimal configuration design with the genetic algorithm," *International Journal of Advanced Manufacturing Technology*, vol. 18, pp. 276-284, 2001.
- [13] B. Li, B. W. Shiu and K. J. Lau, "Fixture configuration design for sheet metal assembly with laser welding: A case study," *The International Journal of Advanced Manufacturing Technology*, vol. 19, pp. 501-509.
- [14] W. Cai, "Fixture optimization for sheet panel assembly considering welding gun variations," *Journal of Mechanical Engineering Science*, vol. 222, pp. 235-246, 2008.
- [15] J. Ma, M. Y. Wang, "Compliant fixture layout design using topology optimization method," *2011 IEEE International Conference on Robotics and Automation*, Shanghai, China, May 9-13, 2011.
- [16] H. Cheng, Y. Li, K.F. Zhang, C. Luan, Y.W. Xu, M. H. Li, "Optimization method of fixture layout for aeronautical thin-walled structures with automated riveting," *Assembly Automation*, vol. 32, pp. 323-332, 2012.
- [17] L. Xiong, R. Molfino, M. Zoppi, "Fixture layout optimization for flexible aerospace parts based on self-reconfigurable swarm intelligent fixture system," *The International Journal of Advanced Manufacturing Technology*, pp. 1-9, 2012.