Fixture Configuration Design for Sheet Metal Assembly with Laser Welding

by

Li Bing

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Declaration

I declare that this thesis contains no material, which has previously been presented for the award of any other degree or diploma in any other University or Institute. To the best of my knowledge, the material is original except where due reference is made in the text of this thesis.

(Li Bing)

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ABSTRACT

Sheet metal laser welding has gained acceptance for meeting the increasing demands for high weld quality in the assembly process due to its economic advantage and small thermal distortion caused. However, the application of laser welding in industry is still limited since many aspects of laser welding still require further investigation. Among such aspects metal fit-up is an important factor that affects the implementation of laser welding as well as the improvement of weld quality. Current stamping processes cannot meet the metal fit-up specification that laser welding requires. Assembly fixture will play a critical role in both control of assembly variation and improving Degree of Metal Fit-up(DMF).

With the introduction of Optical Coordinate Measuring Machine (OCMM) and the application of flexible fixtures, a new assembly system using OCMM and flexible fixtures for laser welding is proposed. The variational information of the locating areas on the assembled parts can be obtained by OCMM. This information can be fed into the in-process fixture design module. Different cycles of the same assembly will result in different fixturing schemes that can be accommodated by adjusting the flexible fixtures. The in-process fixture design module is an important part that determines whether the acceptable metal fit-up can be obtained. This thesis primarily focuses on this module.

In order to simplify the current complicated fixturing procedure a new locating scheme with both total locating and direct locating for welds is proposed. The total locating scheme is used to locate the entire sheet metal assembly. The direct locating scheme is used to locate the weld joints to meet the metal fit-up requirement.

A finite-element(FE) model and a prediction and correction method for direct locator configuration are developed in the general fixture design. By setting the weld nodes to nominal values the nodal variation of the locating area can be obtained. Then the locating nodes can be grouped by setting different variational values that are obtained from FEA.

Thus the feasible fixturing scheme can be obtained from applying the right group of direct locators.

In the optimization for fixture configuration design, both number and location of the locators concerned are taken as design variables. Considering the DMF to be a fuzzy quantity, a feasible evaluation criterion about DMF is also developed using a fuzzy synthesis evaluation method. Genetic algorithm(GA) is employed as the optimal procedure.

In order to reduce the sensitivity of the performance characteristic of DMF to the location fluctuation of designed locators, a two-stage response surface methodology is developed for the robust fixturing design. The first stage is to optimally find the Robust Design Space (RDS) where a relatively insensitive area can be reached. An optimal objective combining both robustness and performance is derived. Within the RDS a second-order response surface model is fitted by a 3^k fractional factorial design in the second stage.

Traditional experience-based determination of the weld pattern is easy to cause unexpected discrepancy from the quality requirements of the assembly weld. A new design approach of the assembly weld pattern is developed. A case study with the cross members assembly is presented, which demonstrates the feasibility of the proposed fixture design principles in industrial application. The results of the case study show that the proposed fixturing methodologies are reasonable and effective in meeting the requirement of sheet metal assembly with laser welding.

Keywords: Fixture Configuration Design; Sheet Metal Assembly; Laser Welding; Finite Element Analysis; Robust Design

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NOMENCLATURE

{a}:	weld location candidates for part *a*
{b}:	weld location candidates for part *b*
${}_6C_3$:	combination number of selection of 3 from 6
$Cov(x_i)$:	covariance of the *i* th variable x_i and the *j* th variable x_j
$\{C_w\}$:	intersection set between set {a} and set {b}
$\underset{\sim}{D}$:	fuzzy allowable section
f(x):	performance characteristic
F(X):	objective function with design variable X
f_i :	objective function value of the node *i*
F_c :	minimized objective with combination of robustness and performance
F_e :	average extrusion force applied on the weld location
$g_i(x)$:	the *i* th inequality constraint
g_k :	gradient vector with perturbation quantity ΔX_k
$G_i(X)$:	constraint vector for optimal fixturing
h:	mesh size on the locating area
$h_j(x)$:	the *j* th equality constraint
k:	quality loss coefficient
K:	resultant coefficient
L :	required weld length
L(f):	quality loss function
L_T:	minimum requirement of total weld length
M:	means of the control variables
M_d:	mesh density
n :	total number of welds
N_g :	total number of evolution generations
N_p:	number of patches
N_{TD}:	number of designed locators
N_v:	number of combined patch configurations
n_w :	nodal number of weld on upper panel
n_w' :	nodal number of weld on lower panel
n_x:	x component of the required normal vector
n_y:	y component of the required normal vector
n_z:	z component of the required normal vector

n_x^i: x component of the normal vector of the *i*th patch configuration

n_y^i: y component of the normal vector of the *i*th patch configuration

n_z^i: z component of the normal vector of the *i*th patch configuration

p : total number of levels for HLC

P*i*: the *i*th mating patches

P_i^a: the *i*th normal vector on part *a*

P_i^b: the *i*th normal vector on part *b*

$\tilde{R}$: evaluation matrix for Fuzzy Synthesis Evaluation(FSE)

t : thickness of the panel

U : factor set for FSE

V : selection set for FSE

$Var(x_i)$: variance of the *i* th variable x_i

V_i: variational value for the *i*th level

$\tilde{W}$: factor weight set for FSE

x_i: coordinates of the *i*th locator

X_i, $X_{i'}$: coordinate of the *i*th and *i*' th welding nodes

x_{ij}: DMF of the *i* th mating nodes on the *j* th weld

x_k^L: lower limit of the *k* th design variable

x_k^U: upper limit of the *k* th design variable

x_{opt}: optimal solution of the deterministic optimization

x_{robust}: optimal solution of the robust optimization

y: response function

y_i: variation of the *i*th locator

Δx: neighboring domain of the design location

ΔX_i: perturbation quantity of the *i*th variable

$\nabla f(x)$: difference of the performance characteristic

$\partial f_i/\partial x_j$: first-order derivative of the *i* th performance about the *j* th variable

$\partial g_i/\partial x_j$: first-order derivative of the *i* th constraint about the *j* th variable

$\frac{\partial y_i}{\partial x_i}$: derivative of the function y_i

θ_0: allowable angle limit

θ_i: angle between the normal vectors of the *i*th mating patches

α: proportional coefficient

γ_0: optimal level set for FSE

δ : range of evaluation for DMF

δ_i : value of the perturbation quantity for the *i*th variable

$\mu_{\tilde{D}}(\delta)$: membership function

μ_f: expected mean of the performance

σ: variance of the locations of the designed locators

σ_f: variance of the performance

σ_e : working extrusion stress

$[\sigma_e]$: upper limit of the allowable extrusion stress

λ : level value of variation

ε_x: upper bound of the perturbed minor quantity Δx

ξ: minor quantity for convergence checking

τ: target of the performance characteristic

ω_1, ω_2: weighting factors for the robustness and the performance

β_i, β_{ij}, β_{ii}: estimated parameters for the fitted quadratic response model

(x_1, y_1, z_1): weld node coordinates for part *a*

(x_2, y_2, z_2): weld node coordinates for part *b*

X1,X2,…,X7: coded variables of the designed locators

$(\Delta x_1, \Delta y_1, \Delta z_1)$: nodal deformation of weld joint on part *a*

$(\Delta x_2, \Delta y_2, \Delta z_2)$: nodal deformation of weld joint on part *b*

ΔX_i, $\Delta X_{i'}$: deformation of the *i*th and *i*'th welding node

CHAPTER ONE

INTRODUCTION

1.1 General Fixture Concept

Fixtures have close relationship with the manufacturing of discrete workpieces. In order to manufacture these workpieces economically, they must be located, positioned and fastened in some specified manners. Fixtures are utilized to ensure consistent orientation and confinement of the workpiece. They also provide quick loading/unloading, fastening and proper locating of the workpiece. The applications of the fixtures are not limited to machining processes but covered a wide variety of processes, they have been widely applied in assembly, welding and inspection processes.

There are different types of fixtures in applications, for example, milling fixture, grubbing fixture, broaching fixture, welding, riveting and assembly fixture, etc. They can be classified in a general way: **Standard fixture** components include locators, clamps etc. The general locating method is to make use of locating holes, two locating holes will completely fix the position of a workpiece. After the locating hole is determined, clamping points will be selected; locating and clamping should together fully restrain the workpiece. The main fixture elements in car body shop include pins and locators/clamps. The pins are used for positioning the sheet metals and also restraining the in-plane movement, while the locators/clamps are used to restrain the movement that is perpendicular to the cross-section of the metals. A logical extension to standard fixture components is the **modular fixture**. A modular fixture is constructed from building blocks that are accurately manufactured, hardened and ground for repetitive use. After each assignment, it can be disassembled for re-use. An **intelligent fixture** is equipped with sensors, mainly to enable accurate workpiece locating by an operating device(e.g., machine tool or robot). These sensors may be built-in or external to the system. The intelligent fixture enables some error recovery and adaptive response to these occurrences. An **automatic fixture** is one driven under program control while fixturing components are positioned or activated by computer commands without human intervention. A **flexible fixture** is one that is built-up of modular components that can be positioned, manually or automatically, and with embedded intelligence for precise locating of details.

The most significant factors that need to be considered in fixture design are the economic manufacture issue of the part. In mass production it is more cost effective to construct a set of fixtures to aid in holding the workpiece. Traditionally the fixture design is varied from one designer to another based on designer's experience and preference. With the development of computer and intelligence technologies, computer aided fixture design based on systematic methodologies is urgently required to cater for the tendency of using high speed, small volume agile manufacturing systems, by which the feasible fixture design schemes can be obtained automatically.

Recently extensive research work has been focused on automatic design of fixtures, most fixture designs for different kinds of machining processes oriented to the solid rigid workpiece. Very few focus on sheet metal assembly. Rearick, Hu and Wu(1993) and Cai, Hu and Yuan(1996) addressed the sheet metal fixturing issue and treated the sheet metal as being flexible. Their work is based on sheet metal Resistance Spot Welding(RSW). Fixturing design issue for sheet metal assembly with laser welding has never been addressed. This dissertation dedicates much effort on this aspect.

1.2 Laser Welding and Its Applications in Automotive Industry

Laser welding is a joining process that produces coalescence of materials with the heat generated by a laser beam. Laser beam can be focused to a small spot leading to high energy density. There are many practical applications in which laser welding has reached production status. Laser welding competes with many established techniques, like arc, resistance, and electron beam welding. In many cases, laser processing offers some important advantages (Ready, 1998). Among the advantages of laser welding are the following:

(a) laser welding is a high energy density process, so that the heating is very localized, this fact also influences several of the following characteristics;

(b) heat-affected zone is very small: this can be crucial when a weld must be made near a heat-sensitive element, like a glass-to-metal seal;

(c) welding can be performed in otherwise inaccessible areas, for example, for repairs inside an enclosed vacuum tube.

(d) no material contacts the workpiece, so that there is no contamination;

(e) total heat input into the sample is low: this is an important factor for applications like welding electronic packages, or when low distortion of the part is desired;

(f) because of the high energy density, welding rate can be high, so that the processing can be economical;

(g) laser welding may be performed in the atmosphere or with a simple shielding gas: there is no need to move parts into and out of vacuum;

These technical advantages, coupled with the fact that laser welding produces high quality welds at high seam rates in a wide variety of metals, in a process that is easily automated and can achieve high throughput, have led to the adoption of laser welding for many practical industrial applications, especially in high-volume production. The areas in which laser welding experiences some limitations include the relatively high cost of the equipment, the limitations on the thickness of the material that can be welded, and some difficulty in welding highly reflective metals. In recent years, laser welding in production applications has been expanding and displacing other techniques because of its merits. Currently, most laser welding applications are performed with either CO_2 lasers or Nd: YAG lasers, because these lasers are relatively mature and well developed. In future, other developing types of lasers with high radiance and short wavelength may become practical welding sources.

High power lasers have been widely used in industries such as automotive, consumer products, aerospace and electronics industries to join a variety of materials. Since the welding of thin steel sheets is a major job in car-body shops, one of the most important applications of laser thin materials welding is on car-body steel sheets. As shown in Figure 1.1, it is a typical Body-In-White(BIW) assembly process. General automotive bodies contain 3000- 4000 resistance spot welds along 40m of pinch weld flanges. This welding process employs about 250-300 robots in a modern plant together with numerous spot welding guns, controls and other ancillary equipments (Roessler and Uddin, 1996). The drawbacks of this process include an inherent inflexibility: significant equipment modifications are needed when changes are made to vehicle programs. Such changes are now occurring at more frequent intervals because of the automobile industry's interest in being fast-to-market. By contrast, the laser offers great flexibility.

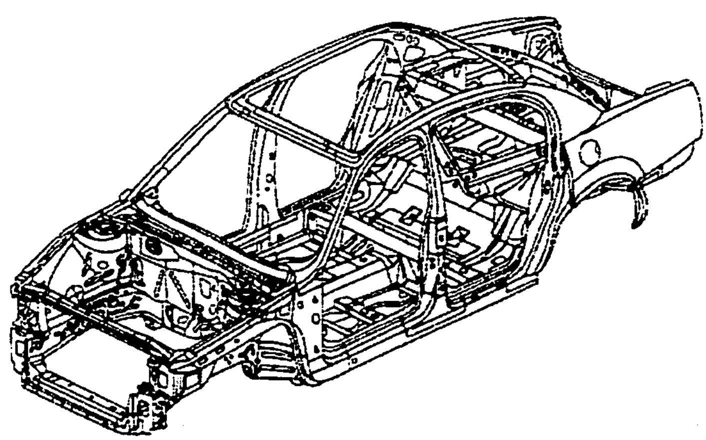


Figure 1.1 Typical Body-In-White assembly process

The laser offers potential advantages and unique opportunities to improve structural properties and weld consistency, while reducing weight and costs at the same time. The high welding speeds are obtainable with lasers. Typically in full penetration lap welds of body sheet metal with a few kilowatts of laser power, the welding speed can reach 5m/min or more. Laser welding is several times, even ten times faster than the best that can be achieved by the robotic spot welding(Irving, 1995). This indicates that one laser welder can replace several resistance welders(Rossler and Uddin, 1996). The study by Keller(1994) shows that a 3kW robotic laser welding at 200 in/min can replace four resistance welding robots. The evaluation of the benefit of both CO_2 and Nd:YAG lasers for welding in the body shop by General Motors shows an overall conclusion that CO_2 laser body shop would cost about 80% of the traditional shop, while a Nd: YAG laser body shop could cost less than 70% (Rossler and Uddin, 1996). The inconsistency in strength of spot welds, which is one of the biggest problems and which has been brought to the attention of the industry, can be avoided by laser welding.

1.3 Problem Statement

As noted above laser welding exhibits many advantages vs. resistance spot welding and offers an attractive alternative to the resistance spot welding. However, millions of spot welds are still being made everyday in US automotive industry (Xie, 1998). This is because some of the potential advantages of lasers are not being obtained in practice and are often offset by the particular problems posed by body sheet metal. For example, the high reflectivity of laser beams by sheet metals, laser weldability of sheet metals, etc. Although some work on laser welding of sheet metals has been done by researchers and engineers, this work is insufficient. Currently one of the key issues is the poor metal fit-up issue is one of the key problems. This issue can largely offset benefits anticipated from one-sided access.

Generally, the maximum acceptable degree of metal fit-up for laser welding is within (0.1-0.15) IMT, where IMT refers to the thickness of the part that laser first impacts(Havrilla, 1996). Currently the quality of stamping process cannot meet the requirement of tight tolerance on the weld joint for laser welding. In 1974, United Technologies Corp. delivered a 6-kW CO_2 laser to Ford Motor for underbody welding and the equipment never went into production because of the fit-up problem experienced (Irving, 1992). The persisting problem of poor fit-up makes the fixturing and clamping more extensive and expensive (Roessler and Uddin, 1996).

In the sheet metal assembly with RSW, weld gun will cause heat and high local weld tip pressure during the welding process, the fixture has little effect on the implementation of weld operation. However, in sheet metal laser welding, fixtures play a critical role for meeting the welding quality specification. This thesis will focus on fixture configuration design issues to meet the metal fit-up requirement for sheet metal assembly with laser welding.

1.4 Research Objective

The basic methods for laser welding in car-body manufacturing are shown in Figure 1.2 (Benzinger, 1990). Actually these weld joints can be regarded as two basic weld joints: lap joint and butt joint. To some kind of butt joint, by adding filler materials the gap caused by poor fit-up can be bridged without the use of complicated and expensive fixtures. While to lap joint there is no way to solve the fit-up problem without the aid of proper fixturing. Laser welding is most often an autogenous process (with no filler material added); this is especially true for precision manufactured components for which fit-up need to be well controlled. So fixture design will play important role in this case.

scheme using standard fixture elements is strongly desired. Since the fixture design for sheet metal laser welding is case-dependent due to its special requirement of metal fit-up, to the same assembly, different assembled parts may result in different fixturing schemes. This cannot satisfy the productivity requirement of automotive workshops and will limit its application in industry.

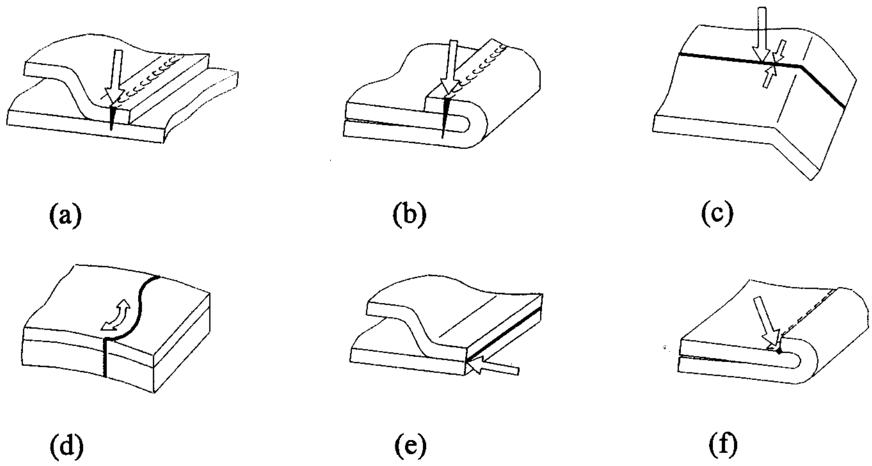


Figure 1.2 Typical laser welding joints for car body parts (Benzinger, 1990)

With the introduction of Optical Coordinate Measuring Machine (OCMM) and the application of flexible fixtures (Ceglarek and Shi, 1996), the in-process fixture configuration design for sheet metal laser welding becomes possible. A new assembly cycle with OCMM and flexible fixture for RSW has been proposed for in-process assembly quality control (Pasek, 1993). In the assembly system, flexible fixtures can be adjusted for the requirements of assembly quality. In sheet metal laser welding, the assembly quality is significantly affected by the implementation of laser welding operation. If a similar adaptive assembly cycle is applied in the sheet metal laser welding, the acceptable metal fit-up can be obtained and the welding quality can be also well guaranteed.

The logical structure of this adaptive assembly system is shown in Figure 1.3. The variation information of the locating areas of the assembled parts can be obtained by

The logical structure of this adaptive assembly system is shown in Figure 1.3. The variation information of the locating areas of the assembled parts can be obtained by OCMM. This information can be fed into the in-process fixture design module. The resultant new fixturing scheme can be applied to the assembly by flexible fixtures. To the same assembly, the resultant fixturing schemes for different cases may be different and these differences can be accommodated by the adjustments of flexible fixtures.

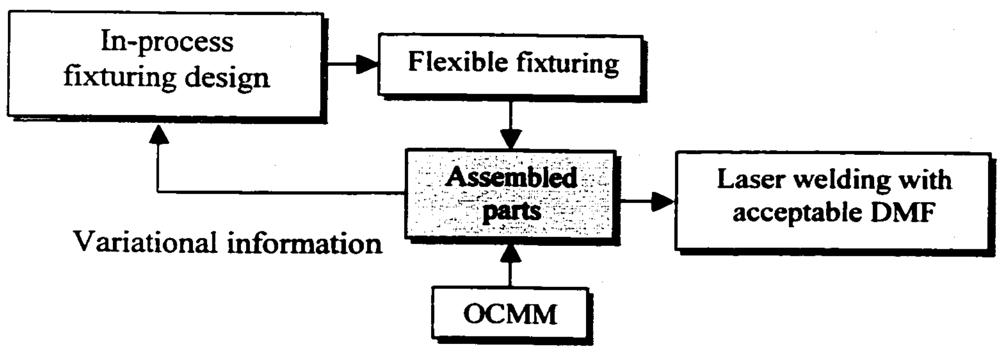


Figure 1.3 Logical structure of the new sheet metal laser welding system

In this assembly cycle there are three main modules: obtainment of variation information, fixturing design and adjustment of flexible fixture. In order to obtain the required variation information, the OCMM in the assembly system can be configured by the following ways: one scheme for measurement is based on the actual assembly location as the components are loaded. Since the variation information is often about the flange edge, in order to measure the variation of the lower panel, the configuration of OCMM will be very flexible. Thus the application of this measuring scheme is limited. There is the second measuring scheme proposed in this thesis. As shown in Figure 1.4 it is an illustration of the proposed assembly system with distributed measuring scheme. From the figure we can see that P1 and P2 are raw material for the assembled parts. After stamping process, the parts are required to be put on a platform with OCMM configured, where the variation information on the weld area can be easily obtained. Each part will be labeled with a series number. In Figure 1.4, P11, P12 and P13 refer to three pieces of part1 and P21, P22 and P23 represent three pieces of part 2 after stamping. After the measurement by OCMM separately, the variational data

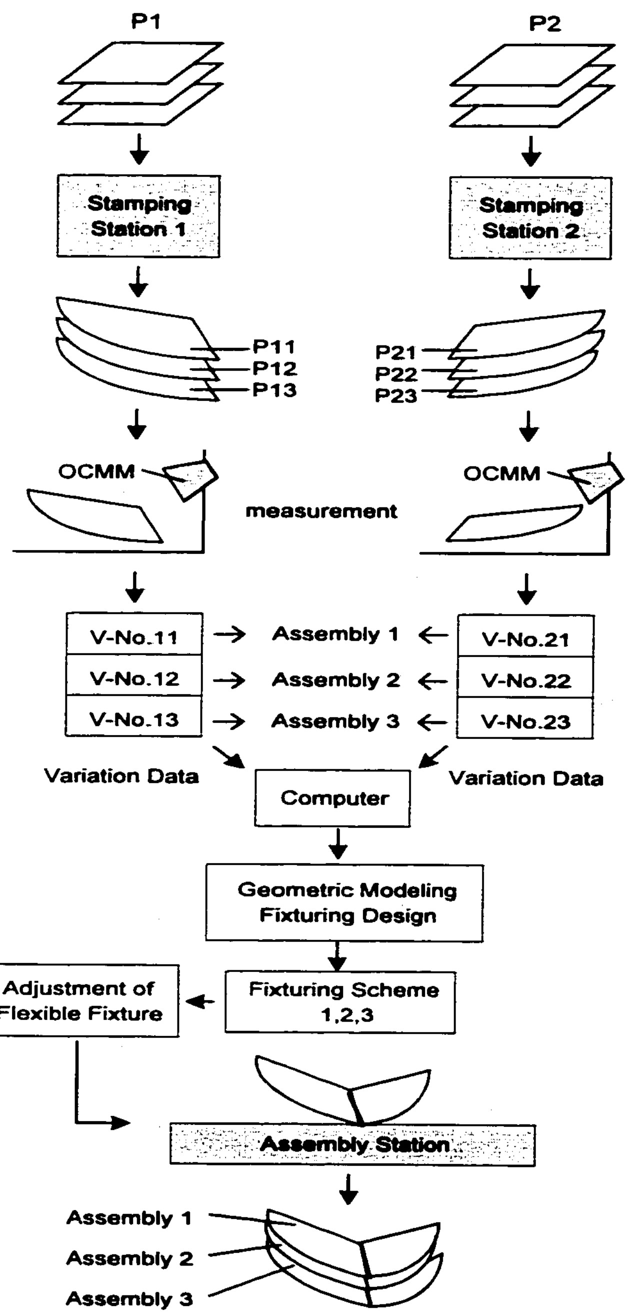


Figure 1.4 Illustration of an assembly system with distributed measuring scheme

corresponding to three sets of the assembled parts will be delivered to computer. During geometric modeling, in order to place the assembled parts into the position as they are loaded, three corresponding points of each part on weld area are required to be specified. By connecting the three points together the actual assembly location can be obtained. Then fixturing design follows. Using the second scheme a computer-aided assembly scheduling system is required. Because a prior determination of the assembled parts will be given in the fixturing design module, thus only the application of the right assembled parts in the assembly process can guarantee the right function of the fixturing scheme can be served. The hardware of the flexible fixture can take a platform-type mechanism with 6 degree-of-freedom to implement the adjustment of position and orientation of the fixturing point.

In the new assembly system with laser welding, the in-process fixture design module is an important module that determines whether the acceptable metal fit-up can be obtained. This thesis primarily focuses on this module. The objective of this thesis will focus on developing systematic methodologies for fixture configuration design for sheet metal laser welding. The quality of the fixturing design is specific focused in this research.

1.5 Research Contributions

As an important module of the adaptive assembly system, the fixturing design issue for improving metal fit-up in the laser assembly process is studied in detail in this thesis. The desired contributions of this thesis are described as follows:

- To propose a new locating scheme which is appropriate for sheet metal laser welding by using standard fixture elements: this will replace the extensive and complex fixtures which is not cost justified and also lack of flexibility.

- To develop finite element models for evaluating the quality performance of metal fit-up: the assembled panels in the finite element model are not flat planes but surfaces with source variations.
- To propose a generic approach for fixture configuration design of sheet metal laser welding: the number and the location of the designed locators can be obtained.
- To develop an optimal fixturing design model and find the optimum locating scheme with minimum designed locators: this will save tooling cost.
- To develop a proper robust design model for the fixturing design so that the performance characteristic of DMF corresponding to the resultant locating scheme will be less sensitive to the locations of locators, this will enhance the locating reliability.
- To develop a new design approach for determining assembly weld pattern of sheet metal laser welding: this makes the designed weld location more reasonable.
- To provide an industrial case study to demonstrate the feasibility of the proposed methodologies in practical application.

1.6 Organization of the Dissertation

Totally there are 8 chapters included in the thesis: Chapter 1 is introduction and problem statement. Chapter 2 reviews the literature that includes three aspects of this research: fixture design, laser welding and robust design. In chapter 3, a new locating scheme with both total locating and direct locating for welds is proposed and a prediction and correction method is given. In chapter 4, an optimal fixture configuration design model is proposed based on the new locating scheme and the fixturing scheme with optimal performance is obtained. In chapter 5, a two-stage response surface methodology is developed for robust design and the robust fixture configuration design is carried out based on the presented method. In chapter

6, the assembly weld pattern design approach is proposed; the weld location and the weld length can be determined for fixture configuration design. In chapter 7 an industrial case study is given and Chapter 8 summaries the dissertation and proposes future work.

1.7 Chapter Summary

In this chapter a general fixture concept and the laser welding and its application in automotive industry are given first, then the problem met in the sheet metal laser welding is stated, the research objective, research contributions and organization of dissertation then follow. A new adaptive assembly system with the application of OCMM and flexible fixtures is proposed and a distributed measuring scheme with this assembly system is also proposed in this chapter. As an important module, fixturing design module of the assembly system will be focused in the research of this thesis.

CHAPTER TWO

REVIEW OF LITERATURE

2.1 Introduction

The function of fixtures is to locate and hold workpieces for machining, assembly, inspection and other operations. The theoretical analysis of fixture design can be envisaged as an evaluation of the following aspects: (a) repeatability — fixtures are capable of repeatedly locating workpieces from the same batch to a specific location and orientation; (b)accessibility — fixtures allow part loading/unloading without conflicting with fixturing elements; (c) stability — fixtures restrict part's degrees of freedom in translation and rotation; (d) rigidity — fixture components deflect minimally under the clamping reaction forces and the machining forces, which is a function of the fixture material and the geometry of fixturing elements; (e) deflection — the workpiece deflects minimally under the clamping and machining forces, which is a function of the proper position, geometry of the fixturing elements, material and geometry of workpieces.

Fixture design technologies can be classified into fixture hardware design and fixture layout design. Traditional design of fixture components includes material type, geometric shape, locator and clamp size and the power sources of clamping force. Advanced fixture hardware design focuses on enhancing the fixturing efficiency, accuracy or flexibility, such as using robot manipulators to automate the fixture assembly, employing computers and sensors to the fixturing process and designing the fixture components adaptable to workpiece geometry (Pong, 1994). Fixture layout design manipulates the fixture components to accomplish the workholding purpose. The fundamental instructions developed by a fixture layout design are the placement of locators, supports and clamps. The layout design of machining fixture involves the determination of the locating and clamping faces on the workpiece and the respective positions of fixturing components on these faces. The fixture layout design for sheet metal assembly is often to determine the locations of the designed locators to meet the specified variational requirements. In what follows the literature review of fixture design technologies, sheet metal laser welding and robust design are given in detail.

2.2 Fixture Design Technologies

2.2.1 "3-2-1" Locating Principle

The purpose of locating is to position a workpiece to ensure static stability; the orientation of the workpiece is fixed. At this stage the magnitudes of acting forces are not considered, only their directions. A "3-2-1" locating scheme is enough to locate a rigid part with the minimum requirement of number of locators. A "3-2-1" locating scheme as shown in Figure 2.1 is used to represent the "3-2-1" locating principle. There are three locators at the base of the workpiece, two locators on one side and another locator at another side. As shown in the figure, A1, A2 and A3 are defined in the primary datum plane A and restrain translation in z direction, rotation about x axis and y axis; B1 and B2 are defined in the secondary datum

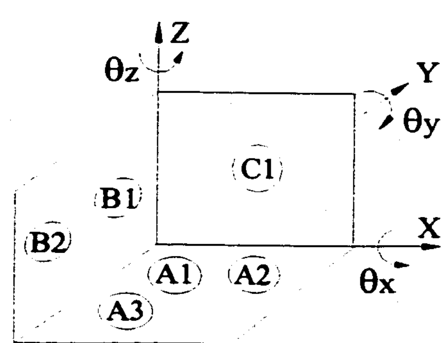


Figure 2.1 "3-2-1" locating scheme

plane B and restrain translation in x direction and rotation about z axis; C1 is defined in the tertiary datum plane C and restrains translation in y direction.

2.2.2 Manual and Variant Design Methods

Manual method is a conventional design method in which fixture design engineers roughly sketch their design on a piece of paper and then draft it on a drafting table or by using a CAD system. This method is very time-consuming and requires effort from experienced design engineers. Variant method can slightly reduce the designing time and effort. The designers can retrieve an existing fixture design from a database and then modify it according to the new specifications. However, using variant method the same error from the existing fixture may be duplicated.

2.2.3 Screw Theory, Kinematic Analysis and Static Analysis

A workpiece in 3D space can be represented by a translational motion in one direction and the rotation along the translational axis, so it is analogous to a screw. Screw theory is a useful tool for the analysis of an object's mobility in 3D space. It was first proposed by Ball (1990) and elaborated by several other researchers. Based on screw theory a lot of research work were carried out; for example, some reports are the applications of finger configuration (Salisbury and Roth, 1983), automatic configuration of machining fixtures (Chou, Chandru and Barash, 1989), geometric accuracy of mechanical parts (Weill, Darel and Laloum, 1991), the stability of parts (Linder and Cipra, 1993), fixture design and analysis (Sayeed and Demeter, 1994), etc.

Accessibility and deterministic positioning requirements are included in kinematic analysis. Kinematic analysis is first conducted systematically for automatically reconfigurable fixtures by Asada and By (1985). Mani and Wilson (1988) proposes an approach to decompose the 3-D fixture design problem to two dimensions by considering the workpiece cross sections. King and Hutter (1993) used similar methodology to develop an optimal design procedure for prismatic parts considering the workpiece stiffness, resistance to slip and stability. Lee and Haynes (1987) proposed a finite element model of the fixturing system analysis for prismatic parts. Static analysis studies the stability of a workpiece during the fixturing process. Stability analysis of a fixturing system is conducted by the workpiece equilibrium theory including force and moment balance constraints. Chou, Chandru and Barash(1989) formulated the force and moment balance constraints in very simple forms by applying wrench vectors expressed in screw coordinate system.

2.2.4 Dynamic Analysis and Optimal Fixture Design

Dynamic analysis deals with the dynamic response of a workpiece with respect to the fixturing system as well as the machining environment. Daimon,Yoshida, Kojima, Yamamoto and Hoshi(1985) developed a fixture design procedure for milling thin plate and box-like castings regarding the workpiece's dynamic response during machining operations. Mittal(1990) presented a series of computer simulations of dynamic analyses on fixture-workpiece systems using a computer software, named Dynamic Analysis and Design System.

In the research conducted by Soman(1989), an optimum fixture layout design problem was formulated as a linear programming problem. Menassa and DeVries(1991) developed a fixture design synthesis and analysis approach that uses the "3-2-1" locating principle for prismatic parts. By using the minimization of the workpiece deflection at selected points as the design criterion, the design optimization problem is determining the positions of the fixture supports. It was the first to use optimization techniques to position supports to minimize deflections. Pong(1994) presented a systematic approach to optimally configure the layout of machining fixtures for prismatic parts. The objective function to be minimized is defined as the maximum workpiece deflection. The design variables are identified as the positions of locators and clamps, and the magnitude of clamping forces. Wang and Nagarkar(1999) proposed a systematic method for the optimal design of sensor locations for an automated coordinate checking fixture.

2.2.5 Expert System Methodology

As an intelligent design method, expert system was applied into fixture design by many researchers. Markus, Markusz, Farkas and Filemon(1984) described an expert system program MODBUILD which is used to build up modular fixtures for fixture construction. Ferreira, Kochar, Liu and Chandru(1985) analysed the feasibility of using an expert system AIFIX for designing fixtures. Gandhi and Thompson (1986) proposed an expert system for the automated design of modular fixtures for flexible manufacturing systems. Pham and Lazaro(1990) worked on another expert system AUTOFIX, which can integrate the knowledge-based reasoning with the traditional CAD techniques. Brost and Goldberg (1994) used expert system for automated analysis and design of a fixture system that can resist maximum applied forces based on commercially available fixture modules. Rong and Zhu (1994) presented a computer-integrated manufacturing system that can maximize the number of possible fixture layout using the minimum number of fixture modules. Krishnakumar and Melkote(2000) presented a fixture layout technique that uses the genetic algorithm to find the fixture layout that minimizes the deformation of the machined surface due to clamping and machining forces over the entire tool path.

2.2.6 Flexible Fixturing

Flexible fixturing involves employing a single fixturing system that can hold parts of different geometries and size subject to the wide variety of external forces and torques caused by manufacturing operations. Different kinds of flexible fixture hardware were categorized by Gandhi and Thompson(1985) as shown in Figure 2.2. The flexible fixturing requirements in a flexible manufacturing cell are as follows (Pong, 1994): (a) reconfiguration of conformable surface — the intermediate medium between the fixture and the workpiece surface should be changeable to make it adaptive to various part geometry; (b) clearance from machining path — flexible fixtures tend to occupy more surface space on the workpiece in certain locations; (c) clearance of workpiece loading/unloading — flexible fixtures should avoid wear of the conformable fixture surface at the contact interface, owing to the process of loading and unloading of the workpiece; (d) easy to operate by a robot manipulator — flexible fixtures should be designed to allow robot manipulators operating in the fixture elements; (e) communication with the controller — communications between the fixturing system and the robot controller are necessary to guarantee a correct interaction between each subsystem of the flexible manufacturing cell; (f) actuation — the fixtures should be self-contained.

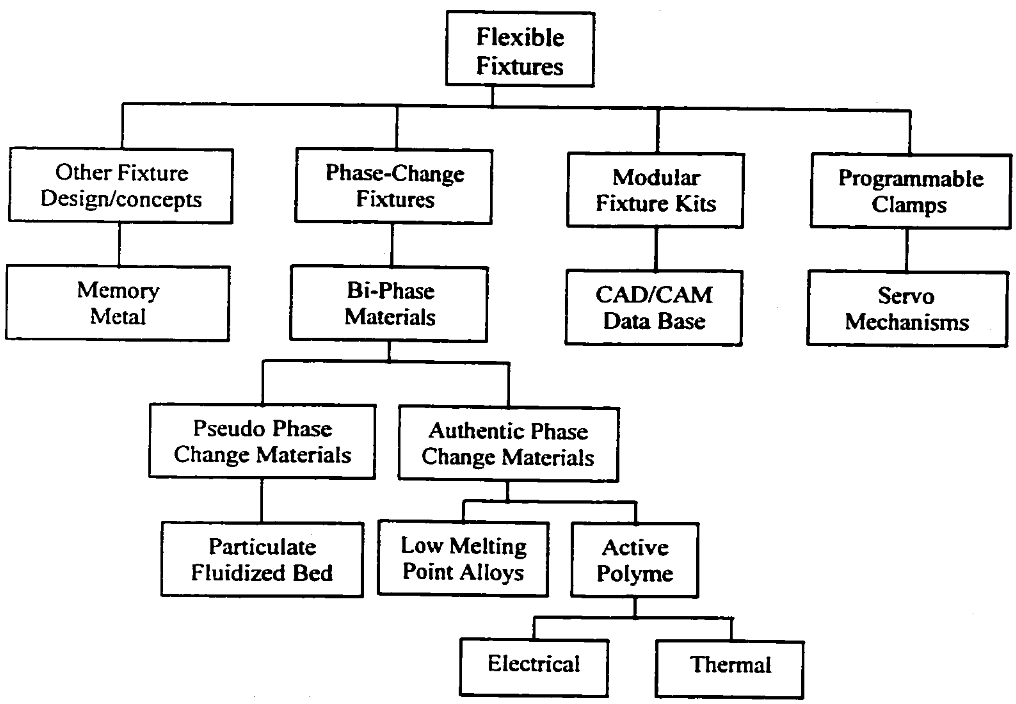


Figure 2.2 Flexible fixturing methodology(Gandhi and Thompson, 1985)

2.2.7 Hardware Considerations for Fixture Design

Due to relatively small focused spot size and depth of focus of the laser beam, accuracy and repeatability of production tooling must be carefully examined prior to implementation (Havrilla, 1996).

When considering component clamping, the following factors are important: the wear-resistant steel should be used to maximize tool life and insure proper part clamping and locating. In order to avoid being distorted due to the relief of residual forming stresses, design the clamps such that they provide a heat sink for the weld energy. Water-cooling of clamps may also be considered when this effect is critical. In addition, when welding low mass to higher mass components, thermally induced gaps may result during welding. A high speed, low penetration weld or spot tack welds prior to the full penetration weld can keep these gaps, and the resultant undercut, to a minimum. Avoid off-sets or force moments when designing clamp and fixture tooling. This will minimize unequal loading that may induce gaps at the weld joint. Welding precision manufactured components which contain press fit weld joints simplified part loading and fixturing requirements.

2.3 Research on Laser Process Parameters

The quality of laser welding is determined by the success of laser welding process. The success of laser welding process strongly depends on the careful consideration of the two primary areas. They are laser process parameters and the welding process requirements. The degree of metal fit-up required is dependent on primarily two parameters, the first being the required strength of the weld. A large gap will result in a reduced weld cross-sectional area, via undercut or voids, which decreases both the static and fatigue strength of the weld. The second parameter that influences fit-up requirements is the focused spot size. A small focused spot cannot bridge a gap as well as a larger one because it produces a narrower fusion zone with less molten material. Voids that result from reliefs, chamfers and fit-up gaps can only be filled by molten parent material. Therefore, increasing the size of any of these voids, the weld strength will be reduced. In the following part the research on laser process parameters is reviewed.

Yilbas, Davies and Yilbas(1991) examines the mathematical analysis of a one-dimensional heat-transfer model for the Nd: YAG laser welding process. Huang, Kullberg and Skoog(1994) presented a pulsed Nd:YAG laser-robot system for spot and seam welding as shown in Figure 2.3. In the study the laser beams behavior for welding was evaluated, then the pulsed Nd:YAG laser spot and seam welding process were investigated. Xie(1998) developed a mathematical model for the melt depth due to a stationary laser beam. A relationship among the melt depth, laser intensity and irradiation time is obtained. Another mathematical model is developed for the weld width and weld pool shape due to a moving Gaussian laser beam.

The neural network technique is employed for predicting the laser welding parameters for butt joints(Jeng, Mau and Leu, 2000a). Back propagation and learning vector quantization networks are used. The results show a comprehensive and usable prediction of the laser welding parameters for butt joints using BP and LVQ networks. Jeng, Mau and Leu(2000b) employed a vision technique for laser butt joint welding for gap inspection and alignment. A CCD camera and several image process techniques are used to capture the welding seam track and determine the proper welding path and gap size.

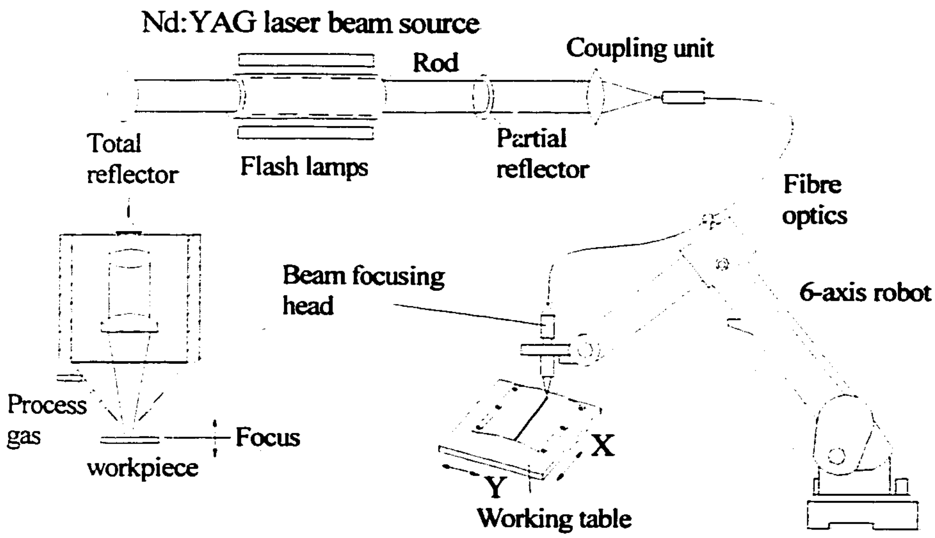


Figure 2.3 Nd:YAG laser robot system for material processing(Huang, 1994)

The research on laser process parameters is important for the understanding of not only the relationships of parameters in laser welding but also the improvements of the quality of laser welding.

2.4 Optimal Fixturing for Sheet Metal Assembly with RSW

Sheet metal parts are widely applied in apparatus, furniture, aircraft and automotive industries. Due to the flexible nature of the sheet metal part, it has frequently experienced dimensional problem in practical applications. In this case, the fixture will function not only to stop rigid body motion but also to restrain excessive workpiece deformation. Rearick, Hu and Wu(1993) proposed a technique for the design and evaluation of fixtures for deformable sheet metal workpieces. Their technique combines the use of nonlinear programming and finite element analysis in determining best fixture locations. The results from their optimization study have been used in a cost function analysis to determine the optimal number of fixture elements in an automotive assembly process. The cost function weighs the value of reduced deformation against the cost associated with using additional fixtures. In their work, no specific locating principle for sheet metal fixturing is adopted, nor explained. A remeshing problem that can lead to analysis difficulties in structural optimization is identified but not solved.

Cai, Hu and Yuan(1996) systematically described the principles, algorithms and simulations of fixture design for single sheet metal part. They proposed the "N-2-1" locating principle for sheet metals and developed algorithms for fixture optimization as well as simulation software. In their research the numerical difficulties from remeshing have been identified and avoided by using MPC feature. As an extension of the design optimization for a single part, the optimal fixture design algorithm has been developed for sheet metal assembly to minimize the assembly variations, springback and welding variations are taken into account by Cai and Hu(1996). The existing research on sheet metal assembly process is based on resistance spot welding, so the load in the finite element model is the clamping force by welding gun: a fixed load(say, 100N) is fed into the finite element analysis. The fixturing design for sheet metal assembly with laser welding has never been addressed. This will be the main focus of this research.

2.5 Robust Design and Fixturing Quality

2.5.1 Robust Design and Its Engineering Applications

Robust design is an efficient and systematic methodology that applies statistical experimental design for improving product and manufacturing process design(Tsui,1992). There are two kinds of factors that have influence on performance variation of the product and their manufacturing process (Shoemaker, Tsui and Wu, 1991; Parkinson, 1995): one is called *control factors* or *design parameters*, the other is called *noise factors*, say, environmental conditions, raw material properties etc. The main idea of robust design is to reduce the output variation from the target by making product and process performance insensitive to disturbances of noise factors.

The ideas of robust design were brought to the attention of statisticians by Taguchi(Clarke and Kempson,1997). By employment of orthogonal arrays techniques the expected loss caused by the noise factors is minimized. Robustness is considered to be classified into two parts (Parkinson,1995): *feasibility robustness,* which refers to insuring that design constraints are satisfied despite variation; *sensitivity robustness*, where we wish to reduce the sensitivity of the design to variation. Chen, Allen, Tsui and Mistree(1996) summarized the problems associated with simultaneously minimizing performance variations and bringing the mean on target, two types of the categories are outlined: *type I* refers to minimizing variations in performance caused by variations in noise factors; *type II* refers to minimizing variations in performance caused by variations in control factors. Robust design can be also classified into three levels: robust conceptual design, robust parametric design and robust tolerance design.

Robust design covers a large range of engineering design. A very popular way to apply robust in engineering problem is the use of sensitivity analysis. Sensitivity analysis is a post-optimal method and is used to investigate the changes in the recommendations of the model as a result of perturbation effects. For example, some reports are the applications in mechanism balancing(Li,1998), structural shape optimization (Sienz and Hinton,1997; Song and Baldwin,1999), etc. Beard and Sutherland(1993) presented a model for the kinematic behavior of a suspension system. Considering the interaction of sources of variation, Yu and Ishii(1998) propose the concept of Manufacturing Variation Pattern(MVP), based on MVP the optimality of performance robustness and design feasibility especially for applications with correlated variations of design variables can be assured.

Some researchers carry out robust design by employment of Taguchi method(Tsui,1992; Yang and Tarng,1998; Otto and Antonsson,1993; Dowey and Matthews,1998). A main branch about robust design is about robust tolerance design (Parkinson, Sorensen and Pourhassan, 1993; Lewis and Parkinson, 1995; Emch and Parkinson,1993; Lee, Gilmore and Ogot,1993; Zhang and Wang,1998; Jeang,1999; Bernardo and Saraiva,1998). Some researchers work on robust design for multi-criteria(Chen, Wiecek and Zhang, 1999; Oakley, Sues and Rhodes,1998; Plante,1999; Kunjur and Sundar, 1997; Bras and Mistree,1993), in this case a compromise procedure is employed for evaluation of multiple aspects of robust design. Kazmer and Roser(1999) evaluate the robustness of product and process design, which improve product quality and eliminate flaws in the product design. Cai, Hu and Yuan(1997) developed a robust fixture configuration design for 3-D workpieces by a variational method. A closed-form analytical solution is required. By robust fixture design the positional accuracy of the workpiece can be improved.

2.5.2 Current Research on Fixturing Quality

Quality design is most important in engineering design because it identifies a best design from all feasible designs. In the research of fixture design few were involved with quality. Using screw theory, Weill, Darel and Laloum(1991) analyzed workpiece positional errors where an optimal method for discrete variables was employed to choose the best locating set-up from randomly selected ones based on the locally linear workpiece geometry. Cai, Hu and Yuan(1997) proposed a robust fixture design approach to ensure that the source errors from locators or workpiece surfaces can be best compensated to achieve a minimum error workpiece positioning. Ceglarek and Shi(1999) presented a fault diagnosis method for sheet metal assembly fixtures, where measurement data was used to detect and isolate dimensional faults of part caused by fixture.

In order to carry out on-line quality improvement, Pasek(1993) proposed an adaptive tooling concept to cope with the problem of locating a part with uncertain geometry(part-to-part variation) in a constrained environment. The adaptive assembly system is shown in Figure 2.4, this figure is got from Dr. Pasek's homepage. The adaptive tooling can change the relative positions of component parts to be assembled through on-line compensation, allowing control of both the mean and the variance of the assembly process. In the assembly system, the flexible fixture is composed of a 6 degrees-of-freedom parallel manipulator. OCMM can be used to identify the relative spatial positions of the components to be assembled. The control system uses this information to generate appropriate fine adjustments for the assembly trajectory. These adjustments finalize the required part locations prior to joining operations.

It is highly desirable that more intelligent tasks can be performed automatically, such as selection of locating and clamping points on workpiece surfaces when carrying out fixture design for sheet metal assembly. Moreover, the fixturing design methods for the assembly process with laser welding is quite different from that with resistance spot welding. It is also important that the quality performance corresponding to the resultant locating scheme is insensitive to the fluctuation of the locations of locators. So all these issues will be discussed in this thesis.

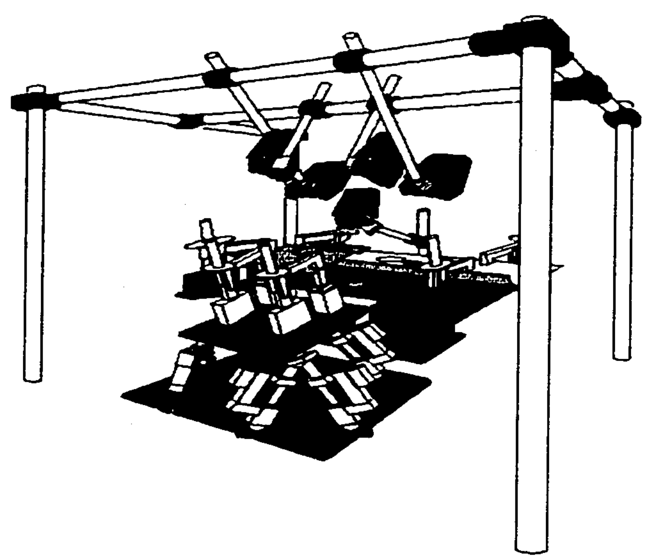


Figure 2.4 An assembly system with adaptive tooling (Dr. Pasek's homepage)

2.6 Chapter Summary

This chapter reviews literature related to fixture design, sheet metal laser welding and quality design. Comparing to the rigid part, fixture design for sheet metals is quite different due to the flexible nature of sheet metal. There is less work focusing on fixture design for sheet metal assembly. However, the existing work in this aspect described the assembly process with resistance spot welding. There is no fixture design for sheet metal assembly with laser welding. This dissertation initiates systematic approaches of fixturing design for sheet metal assembly with laser welding.

CHAPTER THREE

GENERAL FIXTURE CONFIGURATION DESIGN

The research on assembly fixture design for sheet metal assembly with laser welding is rather limited. In this chapter a new locating scheme by using standard fixture elements is proposed first; a generic assembly fixturing design method for sheet metal assembly with laser welding is then proposed. The main objective is to carry out fixture configuration design for direct locators to meet the desired metal fit-up requirement of laser welding. Since the workpiece rotation due to fixturing force is often quite small the fixturing design will focus on fixture location design.

3.1 A New Locating Scheme

Referring to the traditional "3-2-1" locating scheme based on rigid workpiece that has been shown in Figure 2.1, there are six degrees of freedom and twelve directions of motion for any rigid body(Nee, Whybrew and Kumar, 1995). Each locator prohibits the movement in one degree of freedom. Therefore for complete part location, six locators are required. As shown in the figure, A1, A2 and A3 are defined in the primary datum plane A and restrain translation in z direction, rotation about x and y axis; B1 and B2 are defined in the secondary datum plane B and restrain translation in x direction and rotation about z axis; C1 is defined in the tertiary datum plane C and restrains translation in y direction.

A typical "3-2-1" locating scheme is enough to locate a rigid body with the minimum number of locators. However since sheet metals exhibit compliant property, the "3-2-1" locating scheme cannot satisfactorily meet the tolerance specification. In order to get better assembly quality in the assembly process with RSW, a "N-2-1"($N \geq 3$) locating scheme has been proposed by Cai, Hu and Yuan(1996).

In the sheet metal assembly with laser welding fixtures not only function to control the assembly variation but also need to keep fit-up of the mating surfaces to ensure proper laser welding operation and the improvement of laser welding quality. However, the current process of stamping cannot meet the degree of metal fit-up required. For the panels with poor stamping quality, the laser welding can only be carried out with the aid of the complex die fixture, which corresponds to an "infinite-2-1" locating scheme. An illustrative diagram of laser welding with complex fixtures is shown in Figure 3.1. Although by this scheme the welding quality can obviously be improved, the tooling cost is too expensive and also lacks flexibility. These drawbacks will limit its industrial applications.

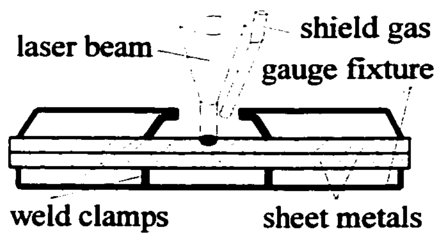


Figure 3.1 Laser welding with complex fixtures

In this research a new locating scheme with *both total locating and direct locating for welds* is proposed instead of the "infinite-2-1" locating scheme. The total locating scheme is used to locate the entire sheet metal assembly. The direct locating scheme is used to locate the weld joints to meet the metal fit-up requirement. By using this new locating scheme an illustration of laser welding process for the lap -joint sheet metal assembly is shown in Figure 3.2. From Figure 3.2(a) we can see that two mating panels are located by total fixtures while direct locators are not applied. In this case poor metal fit -up on the welding area will result; In Figure 3.2(b) direct locators are applied and the metal fit-up degree is improved on the weld area; In Figure 3.2(c) laser welding joins the two parts together.

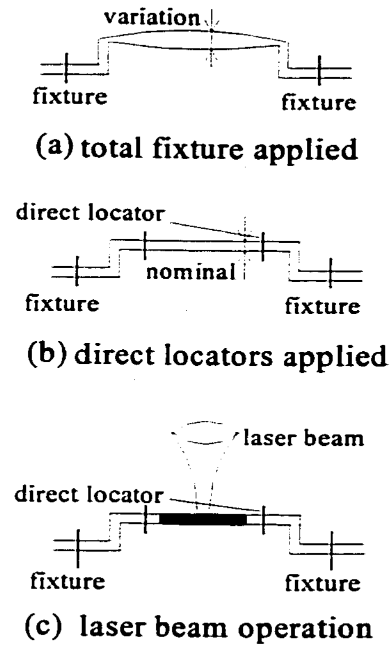


Figure 3.2 Illustration of the new locating scheme

Laser welding process does not require pressure but require intimate metal contact at the surface interface to ensure a successful laser welding process. The metal fit-up is critical for ensuring both a proper implementation of the weld operation and the precision with which sheet metals are manufactured. A large joint gap will result in a reduced weld cross-sectional area, hence reducing both the static and fatigue strength of the weld(Havrilla,1996). The main task of fixture configuration for sheet metal laser welding is the development of a direct locating scheme for welds. The configuration design for direct locators includes the determination of the number and the location of designed locators. A "3-2-1" locating scheme for the overall assembly is applied for total locating.

3.2 Finite Element Modeling

The fixture configuration design for sheet metal assembly with resistance spot weld as described by Rearick, Hu and Wu(1993) and Cai, Hu and Yuan(1996) controls the total deformation of the nodes involved when weld force is applied regardless of the source variation of the nodes from stamping process or assembly process, in this way the sheet metal is just modeled as flat plane without variational tolerance. However it is different from the fixturing design with laser welding. The degree of metal fit-up is process-dependent, so the quality of stamping process directly affects variation of the panel.

3.2.1 Geometric Modeling

Theoretically the more the information of source variation, the better the modelling accuracy. In BIW process it is not economically or logistically feasible to measure too many points, so a certain measuring density (say, 30mm) should be specified for geometric modeling. A flowchart of geometric modeling is shown in Figure 3.3, in which measurement data matrix $[A]_{m\times n}$ is used to construct the surface of the panel with source variation, where *m* and *n* refer to the number of measurement points in row and column respectively. There are many ways to generate the curve, but to ensure the smoothness of the curve, a spline curve is adopted with on-curve modeling data. Based on the Parasolid Geometry Engine (MSC/NASTRAN), a lofted surface between a series of curves can be fitted. The advantage of this engine is that the fitted curves will be on the constructed surface. After this step a finite element mesh is generated. As far as the metal fit-up requirement of laser welding is concerned, the mesh size should be high enough, say 4m×4n. Then a normal distribution test for all mesh nodes is carried out to see if the number of measured points are enough for ensuring the normality of the data on the surface. From the normal probability plot, the linearity of the relevant data can be seen. If the data satisfy the normal distribution, the plot should be linear. If it does not, the number of measured points should be increased. Thus a geometric model for Finite Element Analysis (FEA) is set up.

An example for geometric modeling is shown in Figure 3.4. The figure illustratively shows the finite element model for the two mating panels with "3-2-1" locating scheme applied. From this figure we can see that the two panels are not planes but two surfaces with source variation. Actually in the process of assembly the two panels will be connected together, for illustration purpose, in this figure the two panels are deliberately moved apart. The dimensions of the two panels are the same, being 200mm×100mm×1mm. The measurement data is generated by Monte-Carlo simulation with a statistical distribution. To a good stamping workshop, the 6σ value of 1.5mm can be obtained, this value is used as the distribution value of this study. Thus the source variation is along the z direction and the measurement density of 20mm is along the edges.

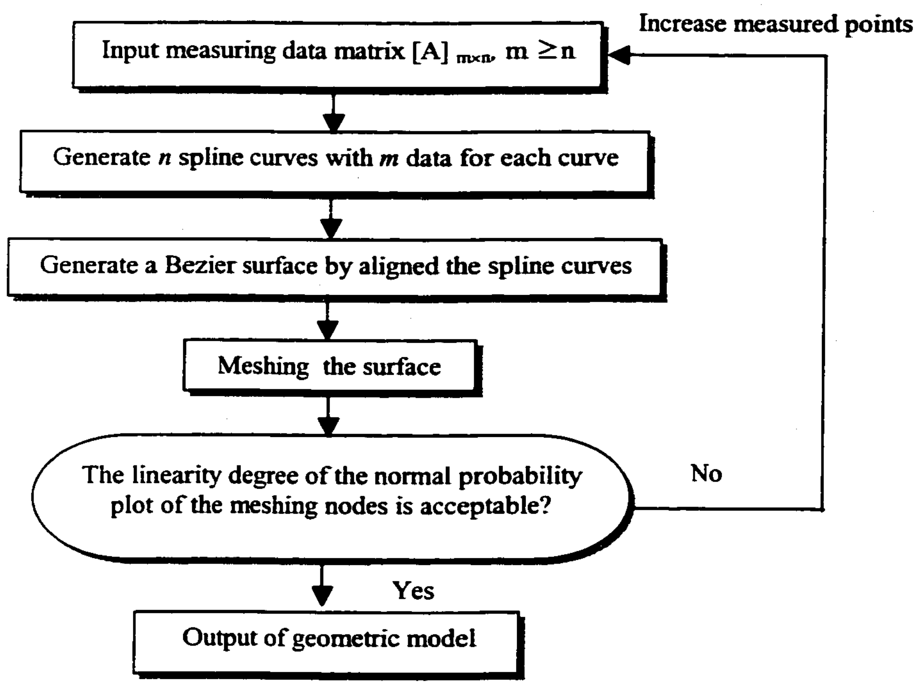


Figure 3.3 Flowchart of geometric modeling

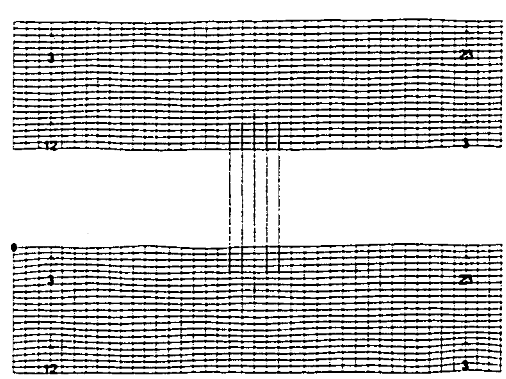


Figure 3.4 Illustrative finite element model

The measured points on each panel are 6 columns by 11 rows. The mesh size of the generated surface is set at 5mm, the generated nodes are 41 nodes by 21 nodes. A normal probability plot of source variation for one panel is shown in Figure 3.5, which shows that the linearity is acceptable for the assumption of the normal distribution.

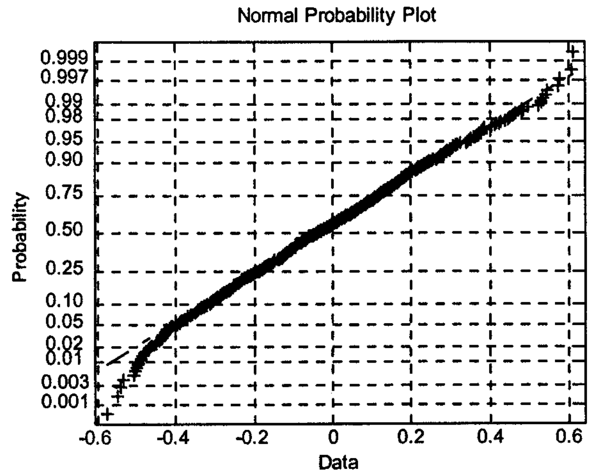


Figure 3.5 Normal probability plot for one panel

3.2.2 Element, Constraint and Load

Sheet metal can be modeled by plate or shell elements for finite element analysis. In this study a quadrilateral plate element is employed for sheet metal modeling. For sheet metal assembly, the gap elements (MSC/NASTRAN) are used to model the weld joint connecting corresponding nodes on the weld location. As shown in Figure 3.4, five mating nodes which represent a 20mm-long weld are connected by five gap elements. Gap element represents points or surfaces that can separate, close or slide relative to each other. The element may be initially given a gap specification and a specified stiffness acts in the normal and tangential directions when the gap is closed and not sliding. In the property definition of the gap element, initial gap is just set as the actual distance between the two weld nodes; the stiffness of tension should be small enough to ensure that the effect of locators are well taken and the orientation of the element can be the direction orientation of the element can be the direction normal to the panels; the stiffness of compression should be big enough to ensure that the two mating weld nodes will move together when the gap is closed. In sheet metal assembly with RSW, the applied pressure of the weld gun is an external load. In laser weld assembly no such external load is applied. Hence the fixture will play a more important role than in the case of RSW.

Generally the fixture elements include pin and locator/clamp in the applications of automotive industry. The "2-1" locating scheme is realized by a 4-way pin and a 2-way pin. An illustrative example of the two pins for a simple sheet metal assembly is shown in Figure 3.6. From this figure we can see that the 4-way pin restrains the movement of the two sheet metals along the x-axis and the y-axis, and the 2-way pin restrains the movement only along the y-axis. It is appropriate that the two pins are modeled as constraints for in-plane motion in the FE model. In the FE model, the constraints of the 4-way pin and 2-way pin are labeled respectively as "12" and "2" as shown in the figure. The function of a locator has two aspects: one is to constrain the nodal motion so can be modeled as a constraint. The other function is to press contact points to designed nominal values by proper clamping force. Hence only modeling the locator as a constraint is not enough. In order to resolve this issue one can determine the indeterministic clamping force on the panel applied by the locator. Due to the non-linear influence of geometry, material and boundary etc., a trial-and-error approach has to be taken in order to get the minimum clamping force. Note that the fixture configuration design is a continuous design process with minor human interaction, however when determining the clamping force with the trial-and-error approach it will be very time-consuming since the clamping force for each locator will need a lot trials, so the determination of the indeterministic force is not a suitable method for the modeling of locators. Enforced displacement in MSC/NASTRAN is employed for the modeling of locators. The enforced displacement can fulfil the dual functions of locators. It is treated as an applied load(this is important to ensure the true representation of the FEA process). However, it is actually a displacement constraint and is therefore a boundary condition. In FEM the locator is assumed to be point contact without thermal effect, thus the frictional force at the contacts is relatively small and is neglected. Due to the employment of gap element a nonlinear static analysis based on the FE model is carried out.

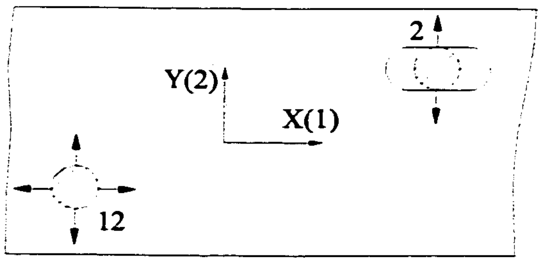


Figure 3.6 Two pins of a simple assembly

3.2.3 Criterion for Degree of Metal Fit-up (DMF)

Degree of Metal Fit-up(DMF) is a measurement of intimity of the weld joint interface. DMF can be evaluated by the maximum distance between the mating nodes on the weld joint. Generally speaking it is acceptable if the degree of metal fit-up is within 15% of the Impact Metal Thickness (IMT)(Havrilla, 1996). IMT refers to the thickness of the part that the laser first impacts. As shown in the Figure 3.2 (c), in order to form a lap joint, the laser will first impact the upper part, in this way the thickness of the upper part is just the IMT. In this study the evaluation criterion of DMF is stringently set as follows:

$$DMF \leq 0.1\ IMT \quad \text{or} \quad \max\left(abs(DIS_{ii'}^{j})\right) \leq 0.1 IMT \qquad (3.1)$$

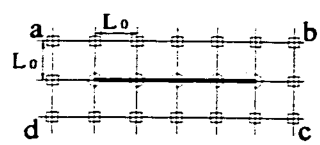
$$i=1,2,\ldots,n_w,\ i'=1',2',\ldots,n_w',\ j=1,2,\ldots,n$$

Where $DIS_{ii'}^{j}$ refers to the distance between the *i*th node on the upper panel and the *i'*th mating node on the lower panel to the *j*th weld stitch. n_w and n_w' represent the nodal number on the weld stitch of the two panels and n represents the total number of weld stitches.

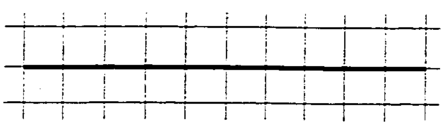
The calculation of $DIS^{j}_{ii'}$ is described as follows: from geometrical model, the nodal coordinates X_i and $X_{i'}$ on the weld stitch with source variation can be obtained. After fixture is applied the deformation ΔX_i and $\Delta X_{i'}$ of the corresponding weld nodes can be obtained from FEA calculation, then the distance $DIS^{j}_{ii'}$ can be written as:

$$DIS^{j}_{ii'}=(X_i+\Delta X_i)-(X_{i'}+\Delta X_{i'}) \quad i=1,2,\ldots,n_w, \; i'=1',2',\ldots,n_w', \; j=1,2,\ldots,n \tag{3.2}$$

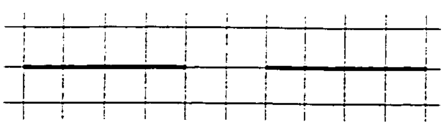
In this research the locating area of the direct locators is defined as Direct Locating Area(DLA). The DLA is generally located around the weld stitch. As shown in Figure 3.7(a), DLA is a curve along a-b-c-d and the weld stitch is labeled with " o ". If the weld stitch is not a straight line, the DLA can be an arbitrary curve around the weld stitch. The actual locator has structural dimension and the mesh size L_0 is specified by the designer. In this research it is limited to $L_0 \geq 5mm$.



(a) single short weld



(b) single long weld



(c) two short welds

Figure 3.7 Local weld models for the three cases

3.3 Prediction and Correction Method

It has been mentioned above that the application of direct locators for weld is critical for satisfying DMF laser welding requires. If direct locators are applied on all nodes distributed on DLA, this locating scheme corresponds to the "infinite-2-1" locating scheme. It is unreasonable to adopt this scheme considering the cost and flexibility. So a new method called prediction and correction method is proposed for finding the number and the location of the direct locators.

The main points of this method are as follows: when the designed locators are applied on the nodes of DLA, different nodes on which locators are applied will have different contributions to the satisfaction of DMF on weld area. If we know the information about the relative contribution of these nodes, it will be easier to carry out locator configuration. Since

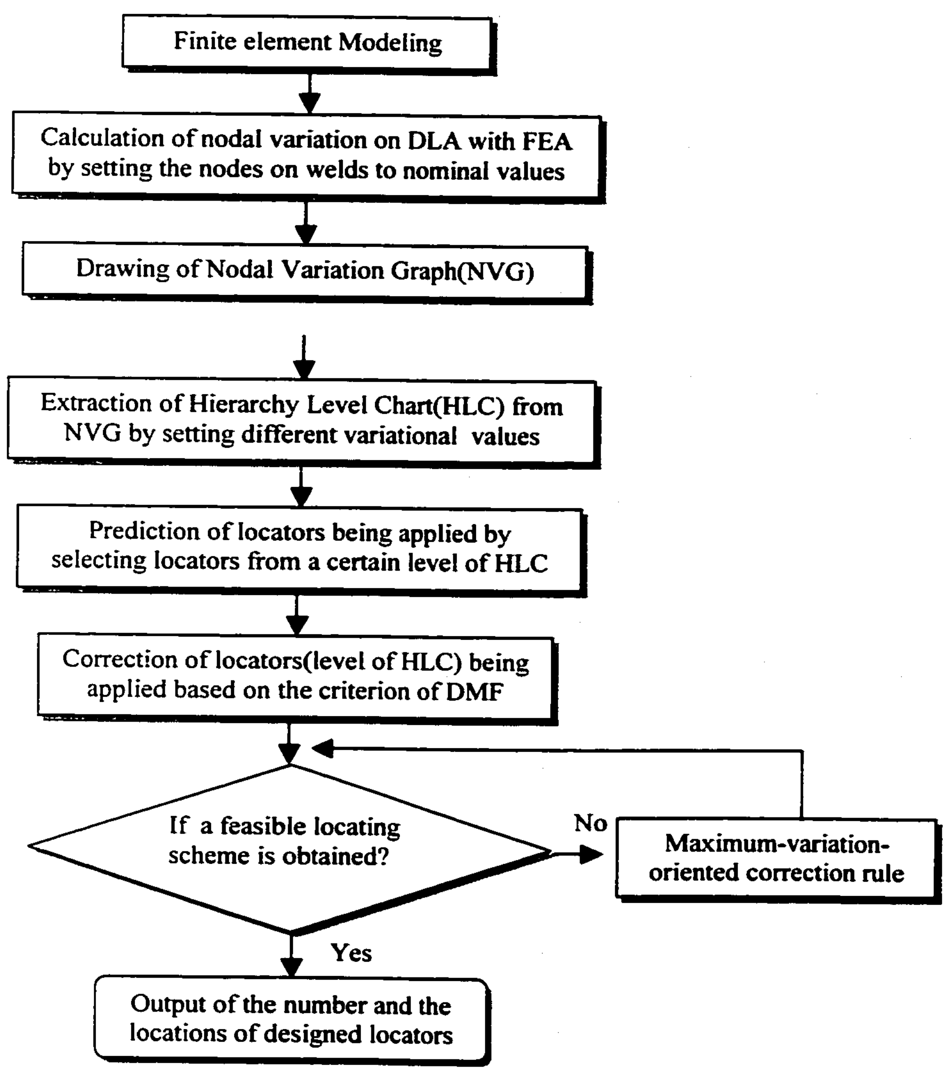


Figure 3.8 Flowchart of the prediction and correction method

the aim of the fixture configuration is to obtain satisfied DMF on the weld nodes, a method with reverse logic is proposed. We first simulate the ideal status of the two panels being welded together and set all weld nodes to the designed nominal values. Then the variational information about the nodes on DLA can be obtained by FEA. If the designed locators are applied on the nodes with relatively big variation, the variation of the nodes on weld joint will be significantly reduced. Based on this idea, we can group the nodes on DLA according to their contribution to DMF. Then the fixture configuration can be carried out according to these groups. The flowchart of the prediction and correction method is shown in Figure 3.8. To the whole sheet metal assembly, a "3-2-1" locating scheme is applied. The three main steps of this method are discussed in details.

1. *Drawing of Nodal Variation Graph (NVG).* First, the nodes of weld stitch are set to the designed nominal values, thus the variation of the welding nodes will be zero. After running FEA the variations of nodes on DLA can be extracted from the output file of FEA. According to Eq. (3.2) the distances between mating nodes on DLA can be calculated, thus a Nodal Variation Graph under the zero variation of the weld nodes can be obtained. Figure 3.9 shows the drawing of a NVG for the case of single short weld. The two mating panels have the same dimension: 200mm×100mm×1mm. The length of weld stitch is 20mm and the total number of mating nodes on DLA is 16.

2. *Extraction of Hierarchy Level Chart (HLC).* From NVG as shown in Figure 3.9 we can see that different nodes on DLA have different variations. The nodes with big variations will contribute more to the metal fit-up of the overall assembly. Thus different fixture configuration levels/groups can be predicted by setting different level value on the NVG, the level value is set to satisfy the following equation:

$$|\lambda| \geq V_i \tag{3.3}$$

or $$\begin{cases} \lambda \geq V_i \\ \lambda \leq -V_i \end{cases} \quad i=1,2,\ldots,p$$

where λ is the level value of the variation, V_i is the maximum variational value corresponding to the *i*th level, *p* is the total number of levels. In Eq. (3.3) the zero axis of NVG is taken as the symmetric axis. Different fixture configuration levels can then be set, as shown in Figure 3.9, if V_1 is set at 0.3mm and at the range of $\lambda \geq 0.3$mm and $\lambda \leq -0.3$mm, the predicted locating ID numbers of DLA nodes are 4,5 and 13. Similarly it is 4, 5, 13, 14, 3, 12, 15, 6, 2 and 1 with the value of V_4 equals to 0.1mm. Some rules for extracting HLC from NVG are described below:

a. Different levels of HLC are obtained by setting different variational values V_i (i=1,2,...,p) on NVG. The variational values are decreased with the grouped level from low to high. This series of variational values may not be equal interval since the nodal variations on DLA are random.

b. The subsequent level must include more nodes than previous level. From low level to high level the number of included nodes(the number of locators applied) will increase gradually. The low configuration level corresponds to less direct locators applied.

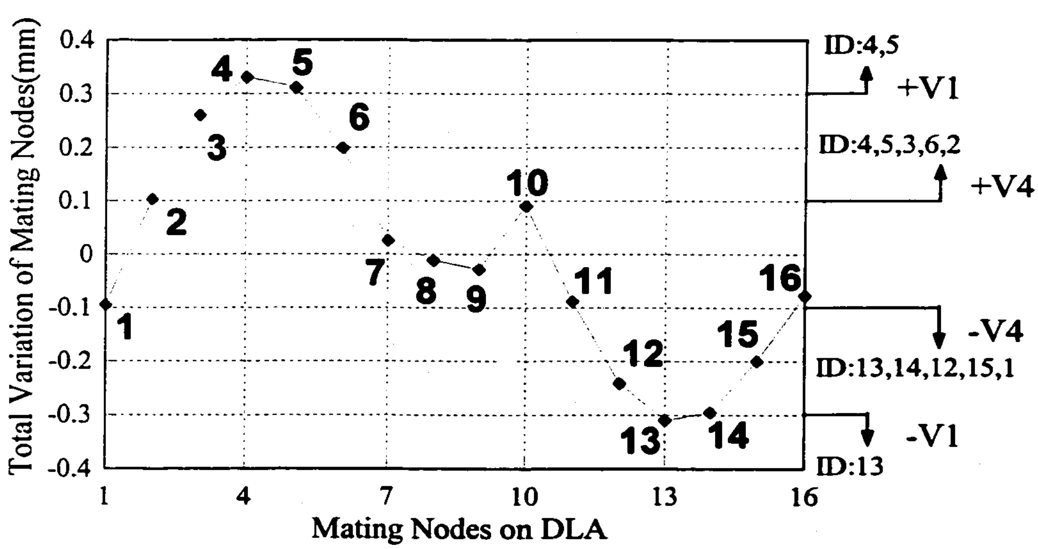


Figure 3.9 Nodal variation graph for single short weld

The highest configuration level is the case that the locators are applied on all DLA nodes and this corresponds to an "infinite-2-1" locating scheme.

c. We set equal level values for positive and negative direction, which means the contribution to DMF from this two variational directions are equal. To the first level at least two locators are applied to limit the variation in two directions and to each variation direction at least one locator is applied.

d. To a certain level value on the NVG, there is a case that under a certain variational value V_i the node(s) are all with positive or negative variational direction, in this case the smaller variational value will be set in order to obtain the node group including two variational direction; thus the nodes included in one single level will increase more. To solve this problem we can define sub-level, say, 2^1 and 2^2 to level 2. To each level, there are at most two sub-levels and the total number of locators will be no more than 3. To the sub-levels of one certain level, the variational value can take the same value. An independent level without sub-level should include DLA nodes controlling two variational directions.

e. The determination of the ID number of the nodes on DLA is described as follows: an arbitrary starting node on DLA is defined as No. 1, generally DLA is a loop around the weld, so along clockwise direction the ID numbers ranged from 1 to N can be defined. The variation of these nodes on DLA can be positive and negative, so to express this feature a superscript of the locating ID number is used, say, for example, 5^+ is to show the ID number of a node with positive variation is 5. To the case of multiple weld stitches, the defined DLA should include all sub-DLAs of the weld stitches, thus the nodal ID number should not be duplicated. To the two panels of one assembly, the mating nodes on DLA are taken the same ID number. The HLC corresponding to Figure 3.9 is shown in Table 3.1.

3. *Maximum-variation-oriented correction rule.* After the formation of multi-level HLC, we can apply locators to the nodes listed in the lowest level of HLC, then by FEA to check if the criterion of DMF is satisfied; if not it is necessary to carry out configuration correction based on the DMF criterion. Theoretically, we can take the order from low level to high level in order to find the configuration level metal fit-up requires. However it is a time-consuming process. A maximum-variation-oriented correction rule is used to solve this issue. Assuming that level i cannot satisfy the criterion of DMF, then find locating ID number of the nodes with maximum variation from the nodes being applied in this level. Then the designer needs to observe the subsequent levels and see if there is a nearest level j with locator(s) near to the maximum variational nodes. Thus the locators will be applied to the nodes that are listed in that level of HLC. If one finds it effective to improve the DMF while still the DMF criterion cannot be satisfied, that means the variation is too big. Thus one needs to use this maximum-variation-oriented rule again on the subsequent level that includes more nodes and find the other appropriate level desired. Based on the prediction and correction method, a feasible direct locating scheme based on "3-2-1" total locating is obtained without experiencing tests of all levels from the lowest level to the current level.

Table 3.1 HLC for single short weld

Level i	V_i (mm)	Number of Applied locators	Nodal ID Number
1	0.3	3	$4^+, 5^+, 13^-$
2	0.25	5	$4^+, 5^+, 13^-, 14^-, 3^+$
3^1	0.2	7	$4^+, 5^+, 13^-, 14^-, 3^+, 12^-, 15^-$
3^2	0.2	8	$4^+, 5^+, 13^-, 14^-, 3^+, 12^-, 15^-, 6^+$
4	0.1	10	$4^+, 5^+, 13^-, 14^-, 3^+, 12^-, 15^-, 6^+, 2^+, 1^-$
5	0.05	13	$4^+, 5^+, 13^-, 14^-, 3^+, 12^-, 15^-, 6^+, 2^+, 1^-, 10^+, 11^-, 16^-$
6^1	0.02	14	$4^+, 5^+, 13^-, 14^-, 3^+, 12^-, 15^-, 6^+, 2^+, 1^-, 10^+, 11^-, 16^-, 9^-$
6^2	0	16	$4^+, 5^+, 13^-, 14^-, 3^+, 12^-, 15^-, 6^+, 2^+, 1^-, 10^+, 11^-, 16^-, 9^-, 7^+, 8^-$

3.4 Example

Sheet metal assembly with laser welding is suitable for long linear rows of welds, so a lap joint is used in the illustrative example of laser weld assembly process. Three different weld configurations are employed in this study: (a) one single short weld 20mm in length; (b) one single long weld 50mm in length; (c) two short welds 20mm in length each. In each case, the weld stitches are located in the centering line of the panel and the mesh size is L_0=5mm.

The finite element model for case (a) is shown in Figure 3.4, in which a "3-2-1" locating scheme is employed for locating the whole assembly. The finite element models for the other two cases are similar to that shown in Figure 3.4, the only difference is that in different cases, different number of gap elements that reflect different length of weld stitch is applied. The local models of the weld stitch for the three cases are shown in Figure 3.7. The source variation is along the direction normal to the panel and by generating normal distributed random number with zero mean and 1.5mm as 6σ values, the statistical data are simulated. The length, width and thickness of the two panels are 200mm×100mm× 1mm. The material of the two panels are mild steel with Young's modulus E=20,7000 N/mm^2 and Poisson's ratio ν=0.3.

In the case with single weld stitch, the NVG and HLC for locator configuration prediction has been shown in Figure 3.9 and Table 3.1. The NVGs for single long weld and two short welds are shown in Figure 3.10. The HLCs corresponding to single long weld and two short welds are shown in Table 3.2 and Table 3.3. The design results of the configuration of direct locators for the three cases are summarized in Table 3.4. By the application of designed locators shown in Table 3.4, the DMF curves for both single long weld and two short welds are shown in Figure 3.11. For the case of two short weld stitches, there is crossed area between two DLAs. In Table 3.4 we can see that the locating number 7 and 16 of weld stitch 1 and locating number 1 and 10 of weld stitch 2 are shared nodes; actually there are only two locators applied. From Table 3.4 we can see the maximum variations on the weld stitch of the three cases are all within the specification of 0.1IMT. We can also see if a long weld stitch is applied then 10 direct locators are required while when we use two short weld stitches on the same welding area the number of locators is reduced to 7, which means a 30% cost reduction. This is because shared nodes locate on the two direct locating areas. So if the weld locations are set properly, the use of multi-short weld stitches is much more reasonable.

Table 3.2 HLC for single long weld

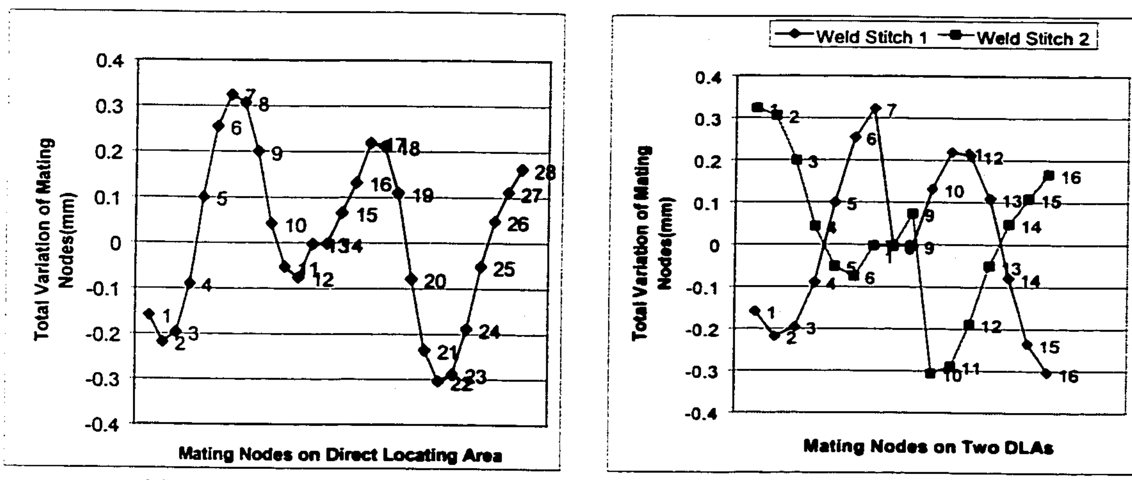
Level i	V_i (mm)	Number of Applied locators	Nodal ID Number	Level i	V_i (mm)	Number of Applied locators	Nodal ID Number
1	0.3	3	$7^+,8^+,22^-$	6^1	0.1	17	$7^+,8^+,22^-,23^-,6^+,21^-,17^+,2^-,9^+,18^+,1^-,24^-,28^+,16^+,19^+,27^+$
2	0.25	5	$7^+,8^+,22^-,23^-,6^+$	6^2	0.08	19	$7^+,8^+,22^-,23^-,6^+,21^-,17^+,2^-,9^+,18^+,1^-,24^-,28^+,16^+,19^+,27^+,5^+,4^-$
3^1	0.22	6	$7^+,8^+,22^-,23^-,6^+,21^-$	7^1	0.07	21	$7^+,8^+,22^-,23^-,6^+,21^-,17^+,2^-,9^+,18^+,1^-,24^-,28^+,16^+,19^+,27^+,5^+,4^-,12^-,20^-$
3^2	0.22	9	$7^+,8^+,22^-,23^-,6^+,21^-,17^+,18^+,2^-$	7^2	0.07	22	$7^+,8^+,22^-,23^-,6^+,21^-,17^+,2^-,9^+,18^+,1^-,24^-,28^+,16^+,19^+,27^+,5^+,4^-,12^-,20^-,15^+$
4^1	0.2	10	$7^+,8^+,22^-,23^-,6^+,21^-,17^+,18^+,2^-,9^+$	8^1	0.05	24	$7^+,8^+,22^-,23^-,6^+,21^-,17^+,2^-,9^+,18^+,1^-,24^-,28^+,16^+,19^+,27^+,5^+,4^-,12^-,20^-,15^+,11^-,25^-$
4^2	0.18	12	$7^+,8^+,22^-,23^-,6^+,21^-,17^+,18^+,2^-,9^+,3^-,24^-$	8^2	0.05	26	$7^+,8^+,22^-,23^-,6^+,21^-,17^+,2^-,9^+,18^+,1^-,24^-,28^+,16^+,19^+,27^+,5^+,4^-,12^-,20^-,15^+,11^-,25^-,10^+,26^+$
5	0.15	14	$7^+,8^+,22^-,23^-,6^+,21^-,17^+,18^+,2^-,9^+,3^-,24^-,1^-,28^+$	9	0	28	$7^+,8^+,22^-,23^-,6^+,21^-,17^+,2^-,9^+,18^+,1^-,24^-,28^+,16^+,19^+,27^+,5^+,4^-,12^-,20^-,15^+,11^-,25^-,10^+,26^+,13^+,14^-$

Table 3.3 HLC for two short welds

Weld stitch 1				Weld stitch 2			
Level i	V_i (mm)	Number of Applied locators	Nodal ID Number	Level i	V_i (mm)	Number of Applied locators	Nodal ID Number
1	0.3	2	$7^+,16^+$	1	0.3	3	$1^+,2^+,10^-$
2^1	0.24	3	$7^+,16^+,6^+$	2^1	0.28	4	$1^+,2^+,10^-,11^-$
2^2	0.24	4	$7^+,16^+,6^+,15^-$	2^2	0.2	5	$1^+,2^+,10^-,11^-,3^+$
3	0.2	7	$7^+,16^+,6^+,15^-,2^-,11^+,12^+$	3	0.15	7	$1^+,2^+,10^-,11^-,3^+,12^-,16^+$
4^1	0.15	9	$7^+,16^+,6^+,15^-,2^-,11^+,12^+,1^-,3^-$	4^1	0.1	8	$1^+,2^+,10^-,11^-,3^+,12^-,16^+,15^+$
4^2	0.1	11	$7^+,16^+,6^+,15^-,2^-,11^+,12^+,1^-,3^-,10^+,13^+$	4^2	0.08	10	$1^+,2^+,10^-,11^-,3^+,12^-,16^+,15^+,6^-,9^+$
5^1	0.1	12	$7^+,16^+,6^+,15^-,2^-,11^+,12^+,1^-,3^-,10^+,13^+,5^+$	5	0.05	12	$1^+,2^+,10^-,11^-,3^+,12^-,16^+,15^+,6^-,9^+,5^-,14^+$
5^2	0.08	14	$7^+,16^+,6^+,15^-,2^-,11^+,12^+,1^-,3^-,10^+,13^+,5^+,4^-,14^-$	6	0.04	14	$1^+,2^+,10^-,11^-,3^+,12^-,16^+,15^+,6^-,9^+,5^-,14^+,4^+,13^-$
6	0	16	$7^+,16^+,6^+,15^-,2^-,11^+,12^+,1^-,3^-,10^+,13^+,5^+,4^-,14^-8^+,9^-$	7	0	16	$1^+,2^+,10^-,11^-,3^+,12^-,16^+,15^+,6^-,9^+,5^-,14^+,4^+,13^-,7^+,8^-$

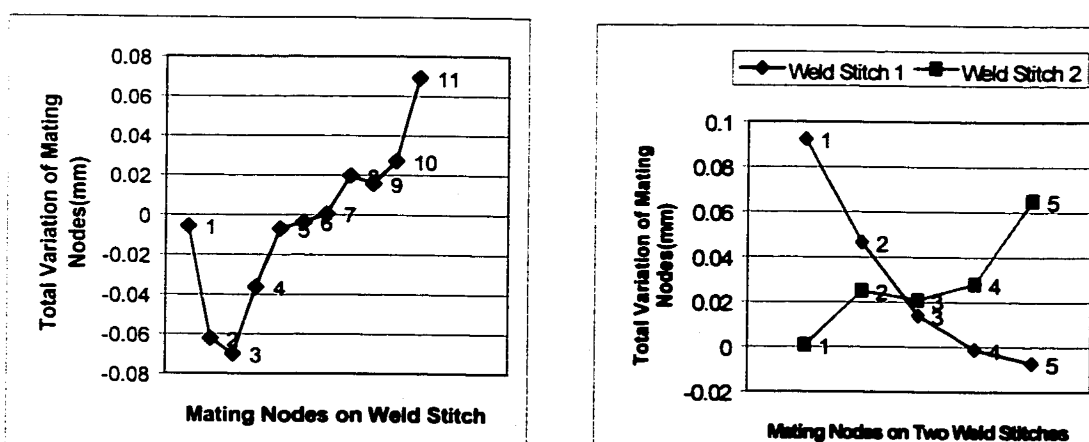
Table 3.4 Design results for the example

	Level (Number) of locators applied	X- and Y- Coord. of locators applied (mm)	Max. variation on weld stitch (mm)
Single short weld	Level 1 (3)	(100,-45),(105,-45) (100,-55)	-0.088
Single long weld	Level 4[1] (10)	(75,-45),(95,-45) (100,-45),(105,-45) (110,-45),(75,-55) (80,-55),(95,-55) (100,-55),(105,-55)	-0.070
Two short welds	(Level 2^2)$_1$ (Level 2^2)$_2$ (7)	(95,-45),(100,-45) (95,-55),(100,-55) (105,-45),(110,-45), (105,-55)	0.092



(a) single long weld (b) two short welds

Figure 3.10 NVGs for single long weld and two short welds



(a) single long weld (b) two short welds

Figure 3.11 DMF curves for single long weld and two short welds

3.5 Chapter Summary

A generic methodology for fixture configuration design with laser welding for sheet metal assembly is proposed in this chapter. A new locating scheme with both total locating and direct locating for welds is first proposed instead of the "infinite-2-1" locating scheme which is currently applied for sheet metal assembly with laser welding. The total locating scheme is used to locate the whole assembly and the direct locating for welds is used to locate the weld location by which the metal fit-up specification can be met. A finite element model is then developed. The geometric model in this case is no longer a plane but a surface with source variation from the stamping process.

A novel fixture design method, prediction and correction method is proposed for the configuration of direct locators. Based on the prediction and correction method an example is carried out including cases of single short weld, single long weld and two short welds. The simulation results show that if the proper arrangement of weld locations is made the application of multi-short welds is better than single long weld from the viewpoint of reducing tooling cost. The example also shows the proposed methodology is convenient and effective for fixture configuration and is valuable for industrial application.

CHAPTER FOUR

OPTIMIZATION FOR FIXTURE CONFIGURATION DESIGN

4.1 Introduction

The locating scheme obtained by the general fixture configuration design is a feasible locating scheme for the assembly process. But it is not optimal. So in this chapter the optimization of fixturing design is carried out.

Cai, Hu and Yuan(1996) set up principle and algorithm of fixture configuration design for deformable sheet metal with RSW in which the locations of the designed fixtures are regarded as design variables in their optimal model. The fixturing design for sheet metal assembly with RSW is to control the total deformation of Key Process Characteristic (KPC) points when weld force is applied and the nonlinear programming is employed for optimization.

As stated by Rearick, Hu and Wu(1993), Sequential Quadratic Programming(SQP) is one of the most efficient numerical optimization algorithm, however the gradient information of design variables is important for this method. Because it is difficult to get the derivatives of the objective function, an analytical form of which is rather difficult to obtain, a finite difference method is employed to approximately calculate gradient of the objective function by the definition of a perturbation vector of the design variables(Lee and Heynes, 1987), as shown in Eq. (4.1).

$$g_k = \frac{F(X+\Delta X_k)-F(X)}{\Delta X_k} \tag{4.1}$$

where $\boldsymbol{g}=[g_1 \ \cdots \ g_k \ \cdots \ g_N]^T$ and $\Delta X_k=[0 \ \cdots \ \delta_k \ \cdots \ 0]^T$.

A problem arises that locators must be applied on the mesh nodes of the FE model. Because the design space is continuous, if a locator is located between two neighboring nodes, a localized remeshing procedure must be adopted. Each remeshing will correspond to a new run of FEA. Moreover, remeshing also leads to objective function discontinuity. The original mesh shape is shown in Figure 4.1(a). A black dot represents a fixture location. Figure 4.1(b) shows that the black dot is the closest to node 2. In this case the re-meshing procedure will move node 2 to the fixture location. If the fixture location is close to the midpoint between two nodal points, the re-meshing shape is also similar to Figure 4.1(b). After perturbation the fixture location will be closest to nodal point 3. Thus a new re-meshing shape like Figure 4.1(c) appears. This abrupt change of mesh shape will lead to objective function discontinuity. This will directly lead to more iteration required or even lead to divergence.

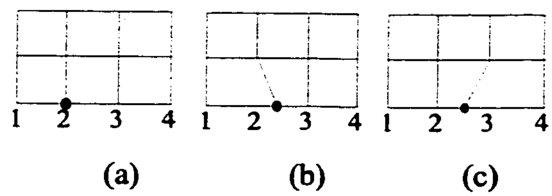


Figure 4.1 Remeshing scheme

The problem of objective function discontinuity has been stated by Rearick Hu and Wu(1993) but no solution was given. Cai, Hu and Yuan(1996) adopted a Multipoint Constraint(MPC) feature of MSC/ NASTRAN software to substitute the remeshing technique. The MPC employs linear interpolation between the two neighboring nodes. This approximate method is feasible based on the assumption of linear small deformation.

For fixture configuration design of sheet metal assembly with laser welding, it is rather different. In Chapter 3 a prediction and correction method with a finite element model under the specified "3-2-1" locating scheme is proposed. The objective of this chapter is to propose an optimal fixture configuration design model and carry out optimal fixturing.

4.2 Genetic Algorithm and Its Application in Optimal Fixturing

4.2.1 Problem Statement

As mentioned before, in optimal fixturing design with RSW, the employment of sequential quadratic programming will lead to remeshing and discontinuity of the objective function. The same will apply in laser welding. Thus sequential quadratic programming cannot be directly applied to fixture design for laser welding. When fixture configuration design is carried out the locator is assumed to be a rigid point contact. However this is impossible. One reason is that in the structure elements of the locator, errors exist from manufacturing and assembly process. Moreover, since not all continuous values are effective in industrial application, it is possible to treat the design variables for configuration of locators as discrete variables, thus the mesh pattern will be kept unchanged. In the discrete design space the designed locators will move on the nodes of the locating area. In this way the corresponding remeshing procedure can be avoided. In order to improve the solution accuracy of the optimization process a local high meshing procedure is desired during geometric modeling and the mesh density should be small enough (say, $L_0 = 1\,\text{mm}$). In brief, when the design space is limited to discrete space the geometric model will be fixed, the changes in the optimal design are only changes of different load sets and constraint sets corresponding to different locating schemes. Thus the updating data file will be much easier than changing the geometric model.

However, another problem arises. Since the design space is discrete the gradient calculation by perturbation method will not work. A simplified treatment for gradient calculation instead of perturbation method can be used. A Taylor's series expansion is shown in Eq. (4.2). By neglecting the higher order terms, the gradient vector can be written as Eq. (4.3) and (4.4). Thus the calculation of gradient vector is only related to the mesh nodes, in this way objective function discontinuity is avoided.

$$y_{i+1} = y_i + \frac{\partial y_{i+1}}{\partial x_{i+1}}(x_{i+1} - x_i) + \frac{\partial^2 y}{2!\partial x^2}(x_{i+1} - x_i)^2 + \cdots \tag{4.2}$$

$$\frac{\partial y_{i+1}}{\partial x_{i+1}} = \frac{y_{i+1} - y_i}{x_{i+1} - x_i} \tag{4.3}$$

$$g_i = \begin{bmatrix} \frac{\partial y_1}{\partial x_1} & \cdots & \frac{\partial y_i}{\partial x_i} & \cdots & \frac{\partial y_N}{\partial x_N} \end{bmatrix} \tag{4.4}$$

The evaluation criterion of metal fit-up is very strict; and the precision requirement for fixture design is high. The derivatives derived from Taylor's series expansion do not have enough precision. After all, the sequential quadratic programming is an optimal algorithm for continuous variables, but here the design variables of the optimal fixturing for laser welding are treated as discrete variables. So a new optimal algorithm with capability of solving discrete variable is desirable.

4.2.2 Genetic Algorithm (GA)

A Genetic Algorithm (GA), based on the principles of natural biological evolution, has received considerable and increasing interests over the past decade. Compared with the traditional optimization method, GA is robust, global and may be applied generally without recourse to domain-specific heuristics(Liu and Wang, 1999). In engineering design problems, the design variables are often zero-one, discrete or continuous. Since most classical optimization techniques are designed to work with continuous variable and these methods deal with mixed variables by adding artificial constraints to penalize infeasible values of variables, this combination increases the complexity of the underlying problem and requires considerable amount of effort in evaluating infeasible solutions (Deb and Goyal, 1998). GA is an ideal optimization algorithm for not only mixed variables but also unconvex or indifferent optimal problems. So GA has been widely used for function optimizing, machine learning, etc. Figure 4.2 is a description of generic GA .

There are basically 6 steps in a simple GA. The first step is encoding, the encoded strings can be used on various alphabets based on the need of actual problem, such as, binary, integer, floating-point, etc. Then an initial population is produced randomly. The third step is to evaluate fitness. Engineering problems generally takes on fitness as the objective function and it is also the basis for selection and evaluation: the higher the fit of individuals, the higher the probability of being selected for reproduction. By applying genetic operators to selected individual pairs with certain probability, a new offspring results. In order to avoid pre-convergence, mutation operator is required. Then fitness of the new offspring will be evaluated. If the convergence criterion is satisfied, the optimal solution is reached. Otherwise the same procedure is continued to select and regroup by genetic operators till convergence is achieved.

```
Procedure Genetic Algorithm
Begin
   k: =0;
   Generate Initial Population p(k) randomly;
   Compute Fitness of population p(k);
   While (convergence criterion=0) do
        Begin
        k: =k+1;
        Select p(k) from p(k-1) by sorting
             and Reproduction Operator;
        Regroup p(k) by
             Crossover Operator
            Mutation Operator
        Compute Fitness of population p(k);
        End
End
```

Figure 4.2 Description of generic GA

4.2.3 Application of GA on Optimal Fixturing

Kumar, Subramaniam and Seom(1999) is the first to use the combination of neutral network and GA for conceptual design of fixtures. GA is an objective function-dependent algorithm. This is one of the advantages in using GA in optimal fixturing since gradient information will not be used in the algorithm. The process of FEA is time-consuming for optimal fixture design; thus the optimization algorithm is required to be highly efficient. In order to improve search efficiency of GA, the Case Control feature of MSC/NASTRAN is employed. By setting sub-cases of the Case Control, one can set different priorities on load sets and constraint sets, this will greatly enhance the search efficiency when the GA is adopted.

To GA, one evolution generation corresponds to one run of FEA, which means evaluation for all individuals of population within one generation will be obtained by only one run of FEA. If we let the evolution generation number of GA be N_g, the evaluation of initial population will also consume one run of FEA, the total run number of FEA is N_g+1. Another problem is when too many evolution generations are used it is also time-consuming. Three methods are used here in order to reduce the number of evolution generation. First, reasonable control parameters for GA are adopted. In particular a relatively big population number which has direct effect on generation number is specified; second, since the locators are located on certain locating areas, the feasible design space only includes these locating areas instead of covering the entire sheet metal; thirdly, in order to avoid the degradation of optimal efficiency, the best locating scheme obtained from each evolution generation is directly appended to the scheme candidates of the next generation.

As stated by Deb and Goyal(1998), binary encoding with length L represents exactly 2^L solutions and binary strings may not be efficient in representing the discrete variable having arbitrary search space because a penalty method with extra constraints are used. In this way it is difficult to improve the optimal efficiency. So in this study, a direct integer-coded procedure is adopted, the crossover operator and the mutation operator are then applied by taking integer values from the real-coded convergence space. An interface for GA and FEA

(MSC/NASTRAN) is given in Figure 4.3. The modifications of load sets and constraint sets are included in the module for updating analysis file.

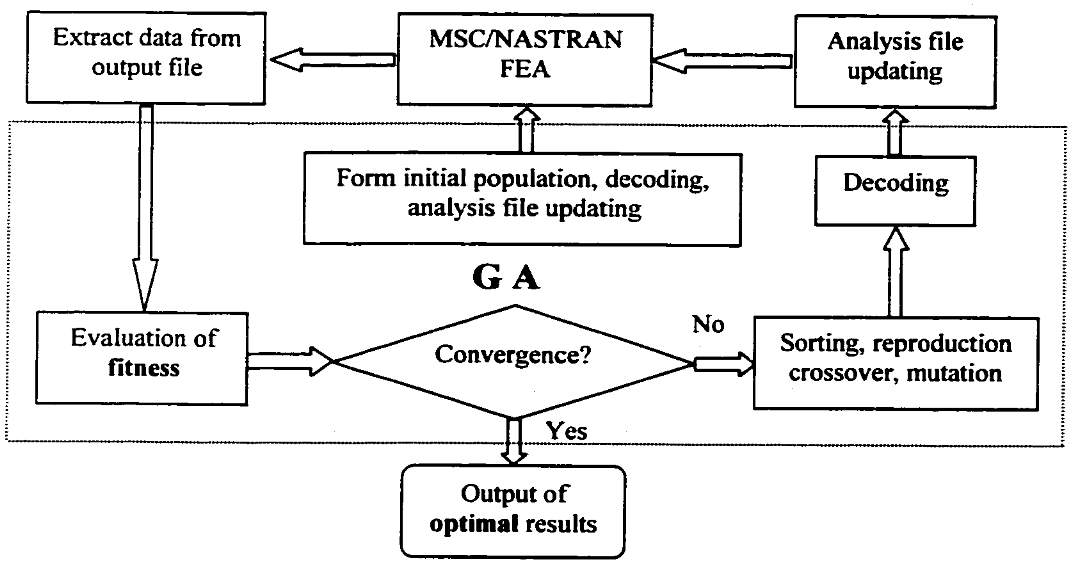


Figure 4.3 Interface structure of GA and FEA

4.3 Optimal Design Model for Fixture Configuration

4.3.1 Basic Strategy for Optimal Fixturing

A new locating scheme with both total locating and direct locating for welds has been proposed in Chapter 3. Based on this new locating scheme a conceptual design model for

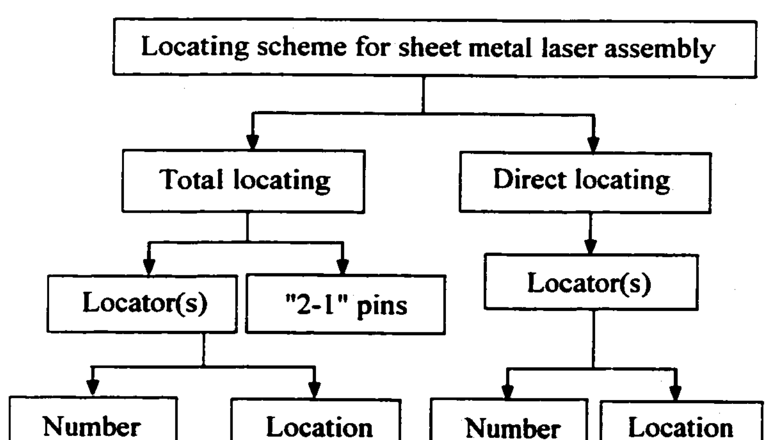


Figure 4.4 A conceptual design model for fixture design

fixture configuration design is shown in Figure 4.4. In the figure it is shown that both the total locating and direct locating are taken into account. In this model both the location and the number of designed locators are taken as objective function for optimal design.

Based on the prediction and correction method, the direct locating area and the minimum number of direct locators required for the metal fit-up can be determined. This number will be directly used in the optimal fixture configuration design. For the total locating scheme the determination of the number and the locating area of total locators are given below.

4.3.1.1 Total locating scheme

Total locating scheme can be described as a "N-2-1" scheme, the elements of the fixture are pins and locators, the "2-1" locating of the total locating scheme is realized by a 4-way pin and a 2-way pin, while "N" is realized by locators. The "2-1" locating scheme is to restrain the in-plane motion which is very small since the orientation of variation in sheet metal assembly is primarily normal to the panel surface. Thus the in-plane variation is neglected. In order to reduce the "2-1" locating error, two pins should be further apart (Cai, Hu and Yuan, 1996). The purpose of the optimal configuration design for total locating is to optimally design the number and the location of "N" total locators.

Firstly a pattern sorting method for determining the number of total locators is proposed and described as follows.

1. *Determination of locating pattern* To a certain sub-assembly, it is always possible to define four areas to apply fixtures. An illustrative example of the "3-2-1" total locating scheme is shown in Figure 4.5. The two pins and locators are distributed on the four specified areas. The labels "12","23"and "3" refer to the restrained DOF of the fixture. In order to reduce the fixture cost, due to the locating effect of direct locators for welds, it is possible to reduce the number of total locators in the "3-2-1" locating scheme. Thus there are four different candidates of the locating scheme: being "3-2-1", "2-2-1", "1-2-1" and "2-

1" locating scheme. The locations of the two pins are relatively fixed. The 4-way pin locates on the bottom-left node of the panel and the 2-way pin locates on the top-

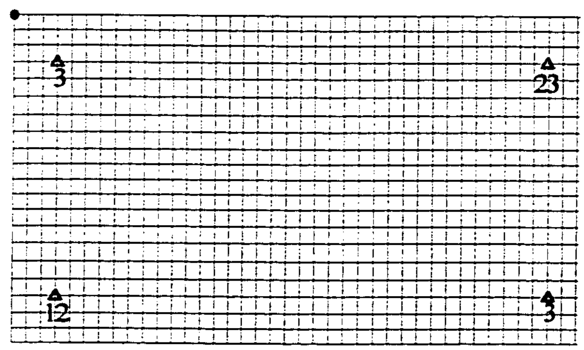


Figure 4.5 Illustrative example of "3-2-1" locating scheme

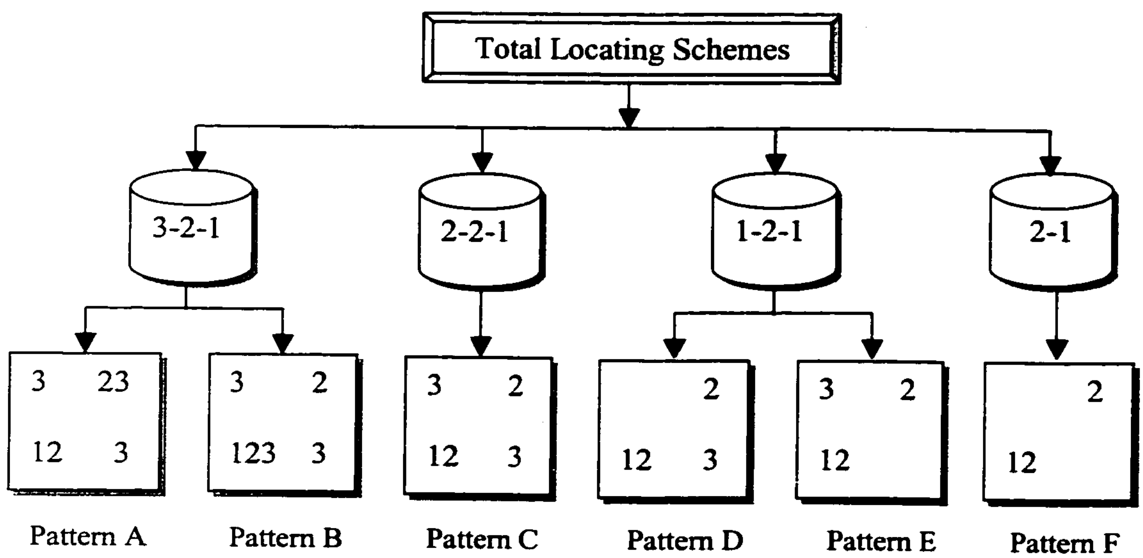


Figure 4.6 Locating pattern diagram for total locating schemes

right node of the panel. Only the location of the locator(s) are considered as being changeable and the four corner locations can be resided by the locator. In this way to some total locating schemes, different patterns can be configured on the four locating areas of the assembly based on the different locations of the locator(s). A two-level locating pattern diagram can be obtained and is shown in Figure 4.6. Level 1 shows the different alternatives of total locating schemes; level 2 shows the different patterns corresponding to the above locating schemes. For instance, there are two locating patterns for the "3-2-1" locating scheme; apart from the two pins, two of the three locators can be located on the top-left node and the bottom-right node of the panel. There are two options for the location of the third locator, if the locator locates on the top-right node this location pattern is called as pattern A; if the locator locates on the bottom-left location the pattern is called pattern B. The same situation will be met in the "1-2-1" locating scheme. There are a total of six patterns for total locating scheme as shown in the figure.

2. *Pattern Sorting* A "3-2-1" locating scheme with pattern A is applied for direct locator configuration by the proposed prediction and correction method. By fixing the configuration of direct locators all the patterns of total locating can be tested by FEA. Thus we can sort all 6 patterns based on the DMF. Then a total locating scheme with the minimum number of fixtures that satisfied the criterion of metal fit-up is obtained. The determined number is the desired number of total locators for optimal fixturing design.

In Figure 4.6, if the optimal total locating scheme is a "2-1" configuration, the number "N" equals zero which means the design variables of the optimal fixture configuration design only include direct locators. Generally speaking, both total locators and direct locators should be considered. Another case should be mentioned here, if the two patterns of one locating scheme are both satisfied with the metal fit-up criterion, the pattern with minimum DMF will be selected as the total locating scheme. Taking the three cases from Chapter 3 as example, a pattern sorting with single short weld, single long weld and double short welds is shown in Table 4.1. From Table 4.1 we can see that based on the criterion of DMF $\leq$ 0.1IMF, the feasible locating schemes for the three cases are Pattern F, Pattern D and Pattern D (represented by boldface). This pattern sorting method is used to determine the number of total locating schemes and also initial total locating scheme for optimization. The location of the total locators and the location of direct locators will be optimally determined by GA.

Table 4.1 Pattern sorting results for two DMF criteria

DMF criterion	Weld type	Number of direct locators	Maximum variation on weld stitch for six patterns(mm)					
			Pattern A	Pattern B	Pattern C	Pattern D	Pattern E	Pattern F
0.1 IMT	Single short weld	3	-0.088	-0.091	0.093	-0.091	0.033	**-0.073**
	Single long weld	10	-0.070	-0.075	-0.071	**-0.075**	0.326	0.321
	Two short welds	7	0.092	0.027	0.108	**-0.042**	0.316	0.354
0.124IMT	Single long weld	5	-0.122	-0.235	-0.263	-0.234	**0.083**	-0.292
	Two short welds	6	-0.123	-0.235	-0.262	-0.243	0.099	**0.119**

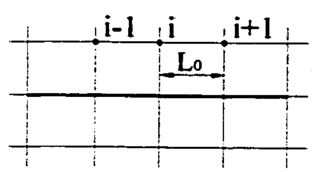
4.3.1.2 Feasible Design Space

Because the "2-1" configuration restrains in-plane movement, these locators have little effect on the movement normal to the panel surface which is controlled by total and direct locating. So the "2-1" locating pins are fixed while let the two pins move further apart. As mentioned before it is not necessary to set feasible design space to cover the whole sheet metal since the locating area is locally distributed. The Feasible Design Spaces(FDS) for direct locators and total locators are described as follows:

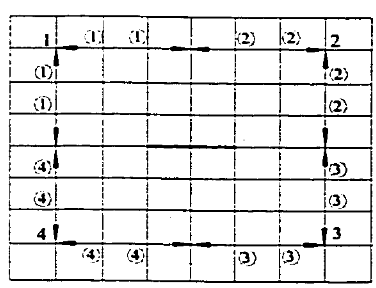
1. *FDS for direct locators* A local design space for direct locators can be set near to the initial design scheme obtained from prediction and correction method. As shown in Figure 4.7(a), a direct locator is applied at node i and the original mesh size is L_0, and the feasible design space for optimal design is the discrete points on the curve between node i-1 to node i+1. A high mesh density is required on locating area(this is not shown in Figure 4.7(a)). Based on this local design space, a local optimal fixture design scheme can be obtained while it may not be a global optimal scheme.

The global design space for direct locators is distributed on the whole direct locating area. As shown in Figure 4.8 two finite element models with high mesh density on locating areas will be used for example of this chapter. The single long weld locates on the centering line of the two mating panels as shown in Figure 4.8 (a). The direct locating area refers to the loop area formed by high meshing. In Figure 4.8 (b) the two short welds are located on the center of the panels, and the two-loop area formed by high meshing is to show direct locating area. Actually each of the two FE models includes two panels as is shown in Figure 3.4. In Figure 4.8 the X-Y view of the sheet metal assembly with lap joint is shown, so the two panels of each figure are projected into one plane, but actually they are two mating panels.

2. *FDS for total locators* Similar to the design space for direct locating, the locating area for total locating scheme can be on the whole panel. Total fixture is often applied along the boundary. Considering the dimension of the fixture, the feasible design space is on a curve around the boundary as shown in Figure 4.7(b). From the figure we know 4 locating areas should be specified and each area should be approximately located on as a quarter of the curve. In fact if all the four locating areas are applied with the total locators, it is a "4-2-1" total locating scheme. For the proposed locating scheme, a "3-2-1" scheme is applied. Thus, not all four locating areas are employed in the optimization.

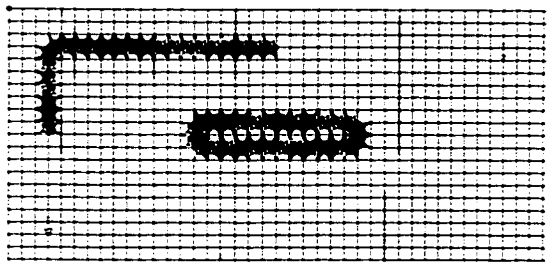


(a) direct locating

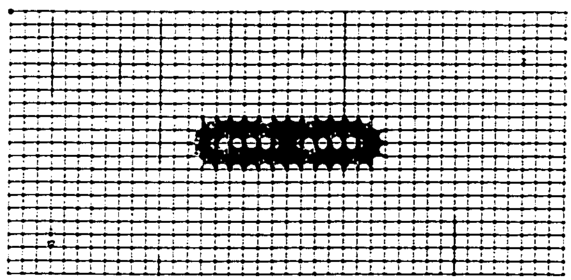


(b) total locating

Figure 4.7 Illustrative feasible design space



(a) single long weld



(b) two short welds

Figure 4.8 Finite element models for the two cases

As shown in Figure 4.7(b), label 1, 2, 3 and 4 show the specified locations for prediction and correction method, while label ①,②,③ and ④ is to show the feasible range of different locating area for optimization. In Figure 4.8(a) only one locator needs to be applied for the total locating, the total locating area is just the "L" shaped high meshing area. While in Figure 4.8(b) no total locator is applied.

4.3.2 Fuzzy Determination of Criterion of DMF

In the fixture configuration design by prediction and correction method a stringent criterion of DMF is employed: DMF$\leq$ 0.1 IMT. The resultant direct locating scheme based on this criterion is used as the initial scheme. After optimization, the DMF can reach a very high accuracy, while DMF with 0.1IMT is sufficient in engineering application. Improving the DMF will require more direct locators. The tooling cost will increase also. In fact, if

DMF is within 0.15IMT the weld process is acceptable (Havrilla, 1996). So a DMF criterion within(0.1~ 0.15) IMT is reasonable. A question arises as to what percentile of the DMF criterion is much more feasible for prediction and correction based on the real status of the workshop facilities.

In this research the desired DMF criterion is examined as a fuzzy quantity and can be expressed as Eq. (4.5). As shown in Figure 4.9, the membership function $\mu_{\tilde{D}}$ of the fuzzy allowable section $\tilde{D}$ can be written as Eq. (4.6).

$$DMF = \delta \cdot IMT \quad \text{and} \quad \tilde{\delta} \subset \tilde{D} \tag{4.5}$$

$$\mu_{\tilde{D}}(\delta) = \begin{cases} 1 & \delta \leq 0.1 \\ 1 - \dfrac{\delta - 0.1}{0.15 - 0.1} & 0.1 \leq \delta \leq 0.15 \\ 0 & \delta \geq 0.15 \end{cases} \tag{4.6}$$

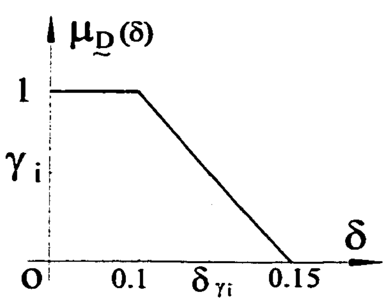


Figure 4.9 Membership function

From the figure we can see, when $\delta \leq 0.1$ the degree of satisfaction is 1 and when $\delta \geq 0.15$ the degree of satisfaction is 0. A straight line is used to show the transition between degree of satisfaction and dissatisfaction. On the straight line different level set γ_i will correspond to different δ_{γ_i}, the key of this issue is to determine an optimal level set γ_0. A fuzzy synthesis evaluation method based on fuzzy set theory (Huang, 1997) is employed to obtain an optimal level set γ_0. The adopted method is described as follows:

(1) *Determination of factor set U* There are a lot of influential factors on DMF in the process of laser welding for a lap joint. The following 4 factors are included in the factor set $U = \{u_1 \quad u_2 \quad u_3 \quad u_4\}$:

u_1 : degree of penetration into the lower layer panel;

u_2 : weld bead width requirement;

u_3 : material type;

u_4 : welding speed.

(2) *Determination of selection set V* The variational range of δ is $(0.1 \sim 0.15)$, if we discretize this range, we can obtain a set $\{0.1 \quad 0.11 \quad 0.12 \quad 0.13 \quad 0.14 \quad 0.15\}$. Corresponding to this set, a selection set reflecting the degree of satisfaction can be written as: $V = \{v_1 \quad v_2 \quad v_3 \quad v_4 \quad v_5 \quad v_6\} = \{1 \quad 0.8 \quad 0.6 \quad 0.4 \quad 0.2 \quad 0\}$.

(3) *Determination of evaluation matrix* $\underset{\sim}{R}$ To each factor in the factor set there will be different degree of satisfaction related to the selection set. Thus each factor can be specified an evaluation vector with the same size as the selection set. Totally an evaluation matrix can be formed. In order to determine this evaluation matrix, we assume that the levels of the 4 factors are in the following status: (a) full penetration is not allowed; (b) weld bead width is moderate; (c) the material type is mild steel; (d) the welding speed is slow. Thus based on the above factor status an expert-based evaluation matrix can be written as follows:

$$\underset{\sim}{R} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} & r_{15} & r_{16} \\ r_{21} & r_{22} & r_{23} & r_{24} & r_{25} & r_{26} \\ r_{31} & r_{32} & r_{33} & r_{34} & r_{35} & r_{36} \\ r_{41} & r_{42} & r_{43} & r_{44} & r_{45} & r_{46} \end{bmatrix} = \begin{bmatrix} 0.2 & 0.5 & 0.8 & 1.0 & 0.5 & 0.0 \\ 0.5 & 0.7 & 1.0 & 0.6 & 0.2 & 0.0 \\ 1 & 0.8 & 0.6 & 0.4 & 0.2 & 0.0 \\ 0 & 0.3 & 0.5 & 0.7 & 0.8 & 1.0 \end{bmatrix}$$

Each row of the matrix shows the degree of satisfaction to the selection set under the specified factor status.

(4) *Determination of factor weight set* $\underset{\sim}{W}$ Different factors will have different effect on DMF. Factor weight is used to evaluate the degree of factor's importance. The weight set of the factors is specified by designers. Factor u_1, u_2 and u_4 are inter-related and equally important while the importance of material type is less than that of the other three, so the following factor weight set is specified: $\underset{\sim}{W} = (0.3 \quad 0.3 \quad 0.1 \quad 0.3)$.

(5) *Determination of evaluation set* $\underset{\sim}{B}$ Based on the above four steps a fuzzy synthesis evaluation process is carried out. There are a lot of composition rules (Huang, 1997). In this research a "multiply and plus" rule $M(\bullet,+)$ is adopted, the operation of this rule is similar to generalized matrix multiplication. The evaluation set is written as shown in Eq.(4.7). By substituting the actual value into the above matrix an evaluation set can be obtained: $\underset{\sim}{B} = (0.31 \quad 0.53 \quad 0.75 \quad 0.73 \quad 0.47 \quad 0.3)$.

$$\begin{aligned} \underset{\sim}{B} = \underset{\sim}{W} \circ \underset{\sim}{R} = (w_1 \quad w_2 \quad w_3 \quad w_4) \circ \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} & r_{15} & r_{16} \\ r_{21} & r_{22} & r_{23} & r_{24} & r_{25} & r_{26} \\ r_{31} & r_{32} & r_{33} & r_{34} & r_{35} & r_{36} \\ r_{41} & r_{42} & r_{43} & r_{44} & r_{45} & r_{46} \end{bmatrix} \\ = (b_1 \quad b_2 \quad b_3 \quad b_4 \quad b_5 \quad b_6) \end{aligned} \tag{4.7}$$

(6) *Determination of optimal level set* γ_0 In order to determine the optimal level set from the evaluation set $\underset{\sim}{B}$, a lot of rules can be employed, i.e. in the simplest way, γ_0 can be either the maximum value or the minimum value of the set $\underset{\sim}{B}$. However the effect of some factors is neglected. Here a weighted average method is adopted, the expression is written as:

$$\gamma_0 = \sum_{i=1}^{6} b_i v_i \Big/ \sum_{i=1}^{6} b_i \tag{4.8}$$

By substituting the actual value where an optimal level set γ_0 is determined, $\gamma_0 = 1.57/3 = 0.523$, then substituting γ_0=0.523 to Eq. (4.6), the fuzzy quantity δ is computed, $\delta = 0.124$. Thus the resultant new criterion of DMF is : DMF =0.124 IMT.

4.3.3 Main Flowchart of Optimal Fixturing Design

Based on the new criterion of DMF determined by fuzzy synthesis evaluation, the number and locating area for direct locators can be determined and the number of total locators can also be determined by the pattern sorting method. Then an optimal fixture configuration design is carried out. The optimal objective function can be written as:

$$\min F\,(\boldsymbol{X}) = \max(x_{ij}) \quad i=1,2,\dots,n_w,\; j=1,2,\dots,n \tag{4.9}$$

$$\text{s.t.} \quad G_i\,(\boldsymbol{X}) \geq 0$$

where x_{ij} represents the DMF of the *i*th mating nodes on the *j*th weld stitch; n_w represents the nodal number on a weld stitch and *n* represents the total number of weld stitches.

An unequal constraint set is given here, the main constraints include three parts: first, the limits of the search space, this constraint is guaranteed by GA; second, the FEA software cannot allow duplicate nodes being applied by locators. On the locating area the mesh density is 1mm and considering the structural dimension of the locator, the neighboring nodes on which locators are applied in one fixturing scheme should be equal or greater than a specified distance(say, 5mm); thirdly, variation requirement on KPC points specified by user. The KPC points must be located on the nodes of FE mesh. The main flowchart of the optimal fixturing is shown in Figure 4.10.

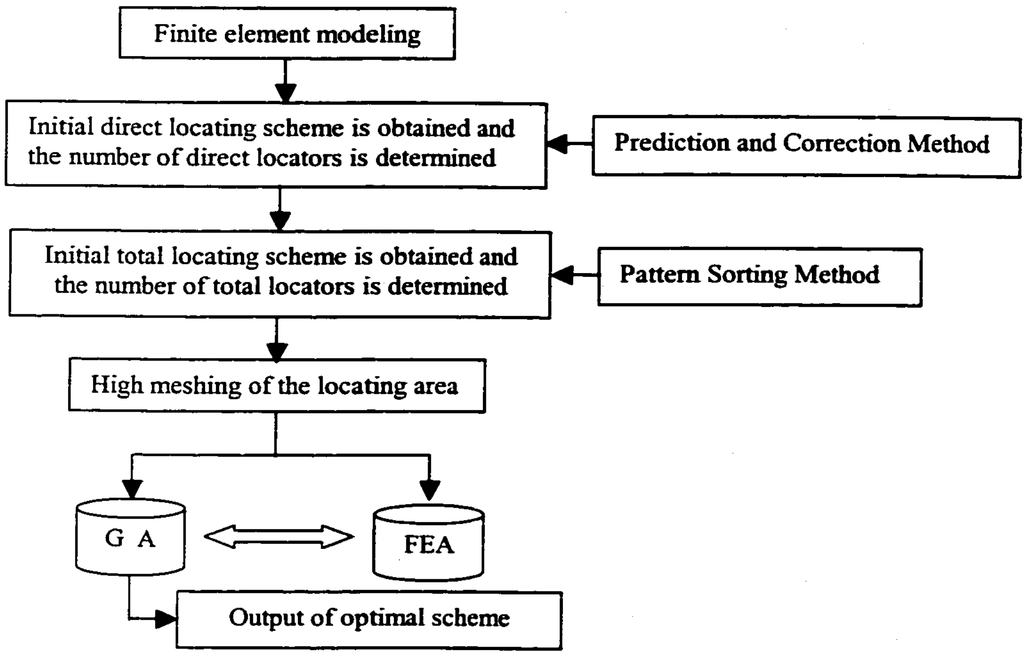


Figure 4.10 Main flowchart for optimal fixturing

4.4 Example

Two study cases are used here for fixturing optimization of sheet metal laser welding. The length, width and thickness of the two panels are 200mm×100mm×1mm. The material of all panels are mild steel with Young's modulus E=20,7000 N/mm^2 and Poisson's ratio ν=0.3. As shown in Figure 4.8 two different FE models with identical weld location are employed in this study: (a) one single long weld with 50mm in length; (b) two short welds with 20mm in length each. For illustration purpose, no variation constraints of KPC points are specified in the optimal models. The origins of the two finite element models are all located on the top-left corner node.

The initial scheme of direct locating is obtained by the prediction and correction method based on the new DMF criterion of 0.124 IMT. The pattern sorting method is used to determine the initial scheme of total locating and the pattern sorting results for the two cases are shown in Table 4.1. From the table we can see that the numbers of direct locators for the two cases are 5 and 6. The total locating patterns corresponding to the two cases (a) and (b) are pattern E and F. In case (a), the locating scheme is "1-2-1" for total locating and 5 direct locators are used for direct locating. In case (b), the locating scheme is "2-1" for total locating and 6 direct locators are used for direct locating. The control parameters of genetic algorithm for this example are given as follows: the number of the population is set at 30, the reproduction probability is 0.15, the probability for crossover and mutation are 0.9 and 0.03 respectively. The convergence criteria include two parts: one is $\|F_{i+1} - F_i\| \leq \varepsilon$, where F_{i+1} and F_i refer to objective functions of adjacent generations; the other is the evolution generations reaching a specified number in order to avoid pre-convergence of the algorithm.

The optimal results for the two cases are shown in Table 4.2. Three objective function values including initial locating scheme and the optimal locating scheme searching in both local design space and global design space are obtained. In the global design space, the most optimal result can be reached. From the table we know by optimal design the degree of metal fit-up(objective function) has obviously been improved. That means the scheme obtained from optimization is better than the scheme obtained from the prediction and correction method. In this way the high quality of laser welding for the assembly process can be obtained.

As shown in Figure 4.8(b) the shape of locating area is a double- rectangle area, a shared edge of the two rectangles is located in the middle of the locating area. From the optimal result based on the global design space we can see that there are three direct locators near the shared area, which will have locating effect on both weld stitches. So this also verifies the conclusion stated in chapter 3 that the designed weld locations including shared locating areas can improve the metal fit-up performance significantly.

Table 4.2 Fixturing design results for the example

<table>
<tr><td rowspan="4">Weld type</td><td colspan="2" rowspan="2">"2-1" pins</td><td>X- and Y-Coord.(mm)</td><td>(15,-85)</td><td>(185,-15)</td></tr>
<tr><td>Restrained direction</td><td>(X, Y)</td><td>(Y)</td></tr>
<tr><td colspan="5">Designed locators(mm)</td></tr>
<tr><td colspan="2">Locator number</td><td>Initial scheme</td><td>Optimal scheme
local</td><td>Optimal scheme
global</td></tr>
<tr><td rowspan="3">Single long weld</td><td>total</td><td>1</td><td>(15,-15)</td><td>(15,-43)</td><td>(62,-15)</td></tr>
<tr><td>direct</td><td>5</td><td>(100,-45)
(105,-45)
(105,-55)
(100,-55)
(95,-55)</td><td>(107,-45)
(100,-55)
(106,-55)
(94,-55)
(95,-45)</td><td>(123,-45)
(70,-51)
(127,-55)
(113,-45)
(115,-55)</td></tr>
<tr><td colspan="2">Objective function(mm)</td><td>0.083</td><td>0.071</td><td>0.058</td></tr>
<tr><td rowspan="3">Two short welds</td><td>total</td><td>0</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>direct</td><td>6</td><td>(95,-45)
(100,-45)
(105,-45)
(105,-55)
(100,-55)
(95,-55)</td><td>(101,-45)
(107,-45)
(102,-55)
(96,-55)
(94,-45)
(108,-55)</td><td>(127,-55)
(104,-55)
(122,-45)
(108,-45)
(93,-45)
(100,-51)</td></tr>
<tr><td colspan="2">Objective function(mm)</td><td>0.119</td><td>0.057</td><td>0.025</td></tr>
</table>

A comparison of the maximum evolution generation between case (a) and case (b) in global design space shows that it requires 7 generations for convergence in the case of (a) while in the case of (b) 9 generations are required. Considering the generation of initial population the total number of evolution generation are 8 and 10 respectively. The amount of time used is reasonable.

4.5 Chapter Summary

A powerful optimization technique, genetic algorithm, is presented, it is not only capable of treating different design variables in engineering problem but also capable of finding global or "near global" solution for optimal fixturing. The logistic interface structure between GA and MSC/NASTRAN is set up. An optimization model for fixture configuration is proposed considering the effects of total locating and direct locating for welds. The design model considers both the number and the location of the fixtures. The number of total locator(s) is determined by the presented pattern sorting method. The proposed prediction and correction method is used to determine the number and the locating area of direct locators. Taking the criterion of Degree of Metal Fit-up as fuzzy quantity and a new criterion of DMF is developed by fuzzy synthesis evaluation method.

The example shows that, based on the new locating scheme, the sheet metal laser assembly does not necessarily take a "3-2-1" total locating scheme due to the influence of direct locating. Moreover, it reveals the importance of weld location design due to the shared locating effect of the shared locators for the case of multi-weld stitches. From the example we can see that by optimization the objective functions can be significantly reduced comparing to that of the initial locating schemes. With improved degree of metal fit-up high weld quality will be obtained. The example shows that the optimal fixturing approach is effective and efficient to meet the metal fit-up requirement for sheet metal assembly with laser welding.

CHAPTER FIVE

ROBUST FIXTURE CONFIGURATION DESIGN

5.1 Introduction

The deterministic optimization problem is to minimize the objective function $f(\mathbf{x})$, whose design vector $\mathbf{x}$ is subject to inequality constraints $g_i(\mathbf{x})$, equality constraints $h_j(\mathbf{x})$, while the upper and lower limits of the design vectors are x_k^U and x_k^L.

$$\text{minimize } f(\mathbf{x}) \qquad (5.1)$$

$$\text{s. t. } g_i(\mathbf{x}) \le 0 \quad i = 1,2,\cdots,I$$

$$h_j(\mathbf{x}) = 0 \quad j = 1,2,\cdots,J$$

$$x_k^L \le x_k \le x_k^U \quad k = 1,2,\cdots,N$$

Generally speaking, the optimal solution is more sensitive to the design variables and is not robust. Assuming that the variation source is design variables, a one-dimensional illustrative example of deterministic and robust design is shown in Figure 5.1, with the same neighboring domain $\pm\Delta x$ of the optimal solution x_{opt} and robust solution x_{robust}. The corresponding response ranges of the performance are quite different. From the figure we can see that the response of robust design has low sensitivity to input.

Recently the application of robust design has covered a wide range of engineering problems. Some researchers carried out robust parametric design by employment of Taguchi method, and some concentrated on robust tolerance design. Some have been reported as applications in linkage synthesis, mechanism balancing, structural shape optimization etc. Cai, Hu and Yuan(1997) developed a robust fixture design for 3-D workpieces by a

In this chapter a robust design model is developed and the quality design for fixturing design of sheet metal laser welding is carried out.

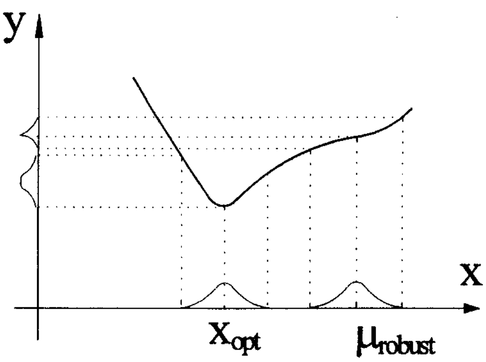


Figure 5.1 Illustration of optimal and robust solutions

5.2 Robust Design Model for Fixture Configuration

5.2.1 Problem Statement

As stated above, the quality of laser welding is directly determined by the degree of metal fit-up on the weld joint, which is quantitatively evaluated by the criterion of DMF. So in the robust fixture configuration design the degree of metal fit-up along the weld joint is set as the performance characteristic of the sheet metal laser welding. The control variables are the locations of the designed locators. The illustration of the two pins for a sheet metal assembly has been shown in Figure 3.6. From the figure we can see that the 4-way pin restrains the movement along x and y directions and the 2-way pin restrains the movement along the y direction, so that the contact point between the 2-way pin and the slot of the panel is movable along the x axis. Actually the minor movement of the 4-way pin along both x and y directions are possible due to the existence of manufacturing error. Assuming tight tolerance is set to the pins and hole/slot on the panels, the only noise variable in this study is set as the movement of the 2-way pin along the x direction. Other movements can be considered as being controllable.

The sheet metal is a flexible part. It is difficult to obtain the explicit relationship between control variables and performance characteristic in the fixture configuration design. FEA is used for evaluation of the performance characteristic for the metal fit-up. It should be mentioned that there exist interactions between control variables and also between control and noise variables. The two main disadvantages of Taguchi's method are as follows(Tsui, 1992): a large amount of runs is required and the method is based on the assumption that the control variables are independent. Response Surface Methodology(RSM) is capable of overcoming these disadvantages, so in this study the RSM is employed as the robust design approach. However, when using RSM there is a premise that the design variables must change within a relatively small region of interest in the independent variable space (Montgomery, 1995), otherwise the fitting response function may not be a suitable approximation of the real-life situation. However, based on the fixture configuration design principle, the design space of the designed locators will cover a wide range. There is a problem that it is not proper to apply RSM directly. So an improved RSM is required.

5.2.2 A Two-stage Response Surface Methodology

In this section a two-stage response surface methodology is proposed, which will well solve the above-mentioned problem. The first stage is to find the relevant small region where the robust space of the design variables is covered. In this stage it is assumed that the design variables are independent. Then in the second stage a response surface model is set up based on the small region determined in the first step. The developed method can be used for dealing with the kind of engineering problems that the explicit relation between variables and performance characteristic is difficult to obtain. In the following part a detailed description about this model is given.

5.2.2.1 Determination of the Robust Design Space

A definition of *Robust Design Space*(RDS) is given first: *Robust Design Space* refers to the relative less-sensitive region("flat region") over the entire feasible design space where the robust solutions reside.

The purpose of determining RDS is to find the "small regions" in which the robust design solutions are situated. In order to find RDS a robust optimization approach is required in this step. Then a small region around the vicinity of the robust solution can be determined. In this step we assume that the design variables are independent. The objective function of the robust optimization based on sensitivity analysis is determined below.

1. *Quality loss function* Taguchi(Clarke and Kempson,1997) introduced the concept of loss function to achieve better quality, the typical quadratic loss function is defined as:

$$L(f) = k(f - \tau)^2 \tag{5.2}$$

where f represents the performance characteristic evaluated at a particular parameter setting; τ represents the nominal value(target) of the performance characteristic; k is a quality loss coefficient, which is determined by the designer.

2. *Formulation of objective function* Let the expected mean and variance of the performance characteristic be μ_f and σ_f. Then the expected mean of the quality loss function can be written as:

$$E[L(f)] = kE\{f - E(f)\}^2 = k\{(\mu_f - \tau)^2 + \sigma_f^2\} \tag{5.3}$$

By simplifying Eq. (5.3) the objective can be defined as minimizing the expected quality loss function:

$$\text{minimize} \quad E[L(f)] = k\sigma_f^2 \tag{5.4}$$

In order to do exact evaluation of the above variance, the computationally expensive integration with joint probability function of control variables is often required. So a Taylor expansion approximation up to and including the second-order term is employed. The objective and the mean of the performance characteristic can be written as:

$$f(x)=f(M)+\sum_{i=1}^{n}\left(\partial f/\partial x_i\Big|_M\right)(x_i-\mu_i)+\frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n}\left(\partial^2 f/\partial x_i\partial x_j\Big|_M\right)(x_i-\mu_i)(x_j-\mu_j) \quad (5.5)$$

$$E(f)=f(M)+\frac{1}{2}\sum_{i=1}^{n}\left(\partial^2 f/\partial x_i^2\Big|_M\right)\mathrm{Var}(x_i)+\sum_{j>i}^{n}\sum_{i=1}^{n}\left(\partial^2 f/\partial x_i\partial x_j\Big|_M\right)\mathrm{Cov}(x_i,x_j) \quad (5.6)$$

Where M refers to the means of the control variables; $\mathrm{Var}(x_i)$ is the variance of x_i; $\mathrm{Cov}(x_i,x_j)$is the covariance of x_i and x_j. It has been assumed that the control variables are independent; thus substituting Eq.(5.5) and Eq.(5.6) into Eq.(5.4) with simplification, we can obtain the simplified expression:

$$\text{minimize } E[L(f)]\approx k\sum_{i=1}^{n}\left(\partial f/\partial x_i\Big|_M\right)^2\mathrm{Var}(x_i) \quad (5.7)$$

Since in this study the design variables are all the locations of the designed locators, so they can be looked as having the same values of variance,

$$\mathrm{Var}(x_1)=\mathrm{Var}(x_2)=\cdots=\mathrm{Var}(x_n)=\sigma^2 \quad (5.8)$$

then Eq.(5.7) can be written as:

$$\text{minimize } E[L(f)]\approx k\sum_{i=1}^{n}\left(\partial f/\partial x_i\Big|_M\right)^2\sigma^2=K\sum_{i=1}^{n}\left(\partial f/\partial x_i\Big|_M\right)^2 \quad (5.9)$$

where K is a resultant coefficient, $K=k\sigma^2$

Since equality constraints can be treated as inequality constraints by setting a tolerance, we can only consider inequality constraints in the optimal process. In this study the modification of the feasible region which is suggested by Parkinson(1993) is taken as constraints. The first-order Taylor's approximation is used to accommodate the "propagating variation" in the constraints:

$$g_i(x)+\sum_{j=1}^{n}\left|\frac{\partial g_i}{\partial x_j}\Delta x_j\right|\leq 0 \quad i=1,2,\ldots,n \tag{5.10}$$

3. *Global finite difference method* From the minimized objective we know the calculation of the sensitivity contributes a large percentage to the determination of the RDS. There are two groups of sensitivity calculating methods(Sienz and Hinton,1997). One is called discrete method, which mainly includes global finite difference method, semi-analytical method and analytical method; the other group is called variational method, which mainly includes direct method and adjoint variable method. The discrete method is simpler to implement than the variational method, and is more suitable for implicit functions and highly nonlinear functions of the parameters or design variables.

A global finite difference method is employed in this study. The advantage of it is that it can be implemented with less effort and there is no need to access the interior structure of the FE code. Note that in Eq.(5.9) the design variables are the mean locations of the designed locators, so the employment of a central finite difference scheme is appropriate, as shown in Eq.(5.11).

$$\nabla f(x)=\frac{f\left(x+\frac{\Delta x}{2}\right)-f\left(x-\frac{\Delta x}{2}\right)}{\Delta x} \tag{5.11}$$

By taking the norm of Eq.(5.11) a bounded relation can be obtained as follows,

$$\left\|f\left(x+\frac{\Delta x}{2}\right)-f\left(x-\frac{\Delta x}{2}\right)\right\|=\|\nabla f(x)\Delta x\|\leq\|\nabla f(x)\|\|\Delta x\| \tag{5.12}$$

The upper bound can reach a maximum at $\Delta x=\varepsilon_x$. We can rewrite Eq.(5.12) as:

$$\frac{\partial f(x)}{\partial x_i}\geq\frac{1}{\|\varepsilon_x\|}\left\|f\left(x_i+\frac{\varepsilon_x}{2}\right)-f\left(x_i-\frac{\varepsilon_x}{2}\right)\right\| \quad i=1,2,\ldots,N_{TD} \tag{5.13}$$

Where N_{TD} refers to the number of the design locators including both total locators and direct locators. Substituting Eq.(5.13) into Eq.(5.9), by taking the minimum estimation of the sensitivity a new minimum objective can be obtained as shown in Eq.(5.14).

$$\text{minimize} \quad F(x) = K \sum_{i=1}^{N_{TD}} \left[\frac{1}{\|2\varepsilon_x\|} \| f(x_i + \varepsilon_x) - f(x_i - \varepsilon_x) \| \right]^2 \tag{5.14}$$

From Eq.(5.14) the perturbation magnitude ε_x is a parameter that the designer can select. It should also be noted that too small a perturbation can not produce sufficient change in the responses for the detection of round-off errors while too big a step-size will cause inaccuracy due to the truncation errors of the Taylor's series expansion (Sienz and Hinton, 1997). In the context of the fixture configuration design, the above perturbation ε_x can be set as a certain fluctuation α, say, 1%, 0.5% or even smaller percent, around the center nodes on the locating area where the design locators move along.

When evaluating Eq.(5.14) by using finite difference method, the perturbed point must be on the finite element node, so a remeshing procedure must be carried out after each perturbation. In order to avoid objective function discontinuity corresponding to remeshing as mentioned in Chapter 4, we set the design variables as discrete variables. Thus the design locators will move along a discrete design space. However, ε_x is a very small quantity. If one takes the value of ε_x as mesh size, it will be too demanding on the computer hardware for FEA. To deal with this situation some kind of approximation is desired. Cai, Hu and Yuan(1996) have verified it is feasible to use linear interpolation for approximation of perturbed objective function when they use sequential quadratic programming for sheet metal fixture design with resistance spot weld. In order to adopt linear interpolation for finite difference calculation and also guarantee the accuracy of approximation, in the locating area of the FE model, a fine mesh is required.

By linear interpolation approximation the minimized objective can be reformed as shown below: assuming that when the interested design locator is located on node *i*, and the perturbed objective functions $f(x_i + \varepsilon_x)$and $f(x_i - \varepsilon_x)$ are denoted by f^+ and f^-, the values of f^+ and f^-can be obtained by linear interpolation of objective functions among the neighbor nodes of node *i*. An illustration of the direct locating area is shown as curve *abcd* in Figure 3.7(a). Let the location and objective function of the node *i* and its two neighboring nodes be x_i, x_{i-1}, x_{i+1} and f_i, f_{i-1}, f_{i+1}. The perturbed variables are denoted as $x^+$and x^-. Then by linear interpolation the objective function of f^+ and f^- can be written as:

$$f^+ = f_i + \frac{f_{i+1} - f_i}{x_{i+1} - x_i}\left(x^+ - x_i\right) \tag{5.15}$$

$$f^- = f_i + \frac{f_{i-1} - f_i}{x_{i-1} - x_i}\left(x^- - x_i\right) \tag{5.16}$$

Assuming the mesh size is h, then as defined above, the perturbed magnitude is given by $\varepsilon_x = \alpha h$, where α is specified by the designer, α can be taken within the range of 0~1. The perturbed variables are written as: $x^+ = x_i + \varepsilon_x$ and $x^- = x_i - \varepsilon_x$. Substituting these quantities together with Eq.(5.15) and Eq.(5.16) into Eq.(5.14), the minimized objective can be reformed as:

$$\text{minimize } F(x) = \frac{K}{\|h\|^2} \sum_{i=1}^{N_{TD}} \|f_{i+1} - f_{i-1}\|^2 \tag{5.17}$$

In Eq.(5.17) coefficient K can be used to balance the power of the objective term. Actually the resultant optimal scheme by Eq.(5.17) is relatively the most robust locating scheme in the design space since we only take the degree of robustness as objective. However, the optimal result may not correspond to good performance characteristic. Sometimes the performance characteristic will cause big deviation from the target. There are two ways for solving this problem.

(a) A series of constraints related to performance characteristic are fed into the optimal model, as shown below,

$$f_i + \sum_{j=1}^{n} \left| \frac{\partial f_i}{\partial x_j} \Delta x_j \right| - \tau \le 0 \tag{5.18}$$

where τ refers to the target value of the quality performance and f_i refers to the performance characteristic when all designed locators lie in the mean locations.

(b) A combined objective function $F_c(x)$ is used, including the robustness and the performance characteristic with weighted factors ω_1 and ω_2, as shown below,

$$\text{minimize} \qquad F_c(x) = \omega_1 F(x) + \omega_2 (f_i - \tau) \tag{5.19}$$

where $F(x)$ is the robustness objective as shown in Eq.(5.17). The designer can assign different values of ω_1 and ω_2 to set the preference of robustness and performance.

In this study the combined objective is adopted to consider both robustness and performance characteristic. The only performance characteristic is the degree of metal fit-up on the weld joints. The target value of the performance characteristic is strictly set as $\tau = 0.1IMT$. The minimized objective is shown in Eq.(5.20). When carrying out optimization, the two components of the combined objective are required to be normalized for avoiding " the dimensionally unmatchable" problem which easily leads to failure of optimization.

$$\text{minimize} \qquad F_c(x) = \omega_1 \left(\frac{K}{\|h\|^2} \sum_{i=1}^{N_{TD}} \|f_{i+1} - f_{i-1}\|^2 \right) + \omega_2 (f_i - 0.1IMT) \tag{5.20}$$

The weld stitch on the assembled panels is generally a straight line. The locating area will be composed of several connected lines. As shown in Figure 3.7(a) the design space for direct locators is illustratively shown as curve *abcd* around the weld stitch. Except the four corner nodes a, b, c and d, all other in-line nodes can be applied with central finite difference as a good approximation. To corner node, say, node c, its two neighboring nodes *i-1* and *i+1* are not collinear. So in order to guarantee the accuracy of approximation a fine mesh size is required, say, h=1mm.

4. *Optimal algorithm* In this optimal stage, GA is used in the optimization as well as in the deterministic optimization. In the deterministic optimization the number of FE runs corresponding to each evolutionary generation is just the number of population (PO) of GA. However, in this stage a different scenario appears. As can be seen from Eq.(5.17) the total number of FE runs is equal to the previous number of runs (PO) multiplied by three times of the number of total design locators. For example, let the total number of design locators be 5, the number of population PO is 30, then the total number of running FEA is 450. So in order to reduce the running time, PO should be set as small as possible. The interface between GA and FEA is shown in Figure 5.2. The control parameters of GA in this optimal stage are as follows: the number of population is 20, the reproduction probability is 0.15, the crossover probability is 0.9, the mutation probability is 0.01, and the convergence criterion is $\|F_{i+1} - F_i\| \leq \xi$. When the mean optimal solution is reached, the robust design space can be obtained by setting a certain fluctuation around the mean location of the designed locators.

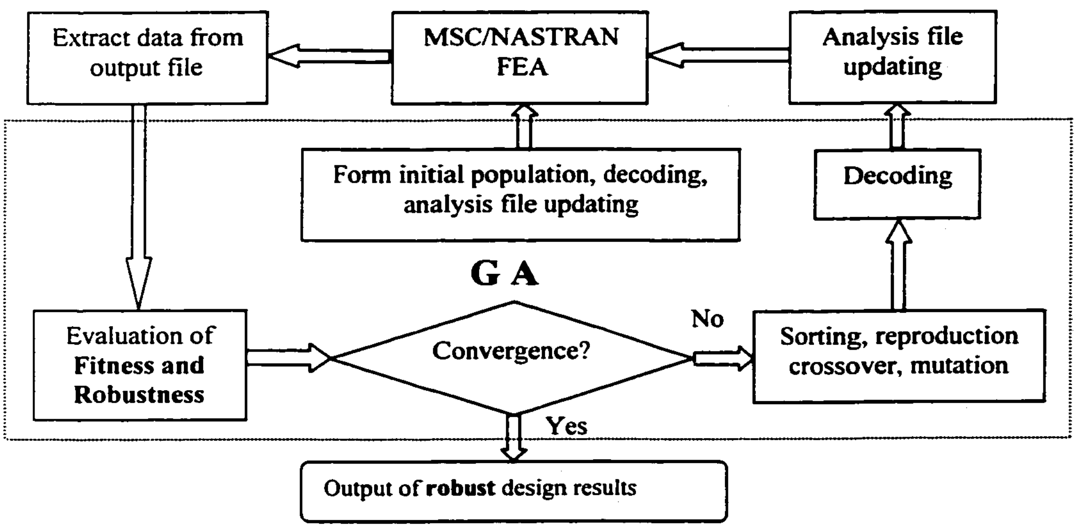


Figure 5.2 Interface structure between FEA and GA for robust design

5.2.2.2 Response Surface Methodology

The fluctuation of the design variables(controllable factors) and noise variables (uncontrollable factors) widely exists in engineering processes. However, the relationship between the dependent and the independent variables is very complex, or unknown. The advantage of RSM is that the procedure can help engineers and designers identify the predominant variables and obtain a better understanding of the overall system.

The response surface methodology includes a set of techniques (Montgomery, 1995): first, the design of a set of experiments that will yield adequate and reliable measurements of the response of interest; second, determination of a mathematical model that best fits the data collected from the designed experiments, by conducting appropriate tests of hypotheses concerning the model's parameters; the optimal settings of the experimental factors that produce minimum(or maximum) value of the response are then determined.

Assuming that the input variables are $x_i (i = 1,2,\cdots,n)$, which include both design and noise variables. The predicted response function can be either a first-order or a second-order polynomial approximation. The two kinds of fitted response model can be written as Eq.(5.21) and Eq.(5.22).

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n \tag{5.21}$$

$$y = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n-1} \sum_{j>i}^{n} \beta_{ij} x_{ij} + \sum_{i=1}^{n} \beta_{ii} x_i^2 \tag{5.22}$$

where β_i, β_{ij} and β_{ii} are estimated parameters; n is the number of input variables; y is the response function. Since the second-order model can reflect the nonlinear influence, its application is more popular.

The designs for response surface analysis are usually based on 2- or 3- level factorials according to whether a first-order or second-order surface is to be fitted(Clarke and Kempson,1997). So if we take a second-order fitting surface, at least 3 levels of each variables are required for estimating all the coefficients in Eq.(5.21) and Eq.(5.22). In this study a 3^k fractional factorial design is used for fitting a second-order model of the response surfaces. Two experimental options, the Central Composite Design(CCD) and Box-Behnken Design(BBD), can be used as the fraction of the 3^k factorial design considering the design as being rotatable or near-rotatable.

After a fitted polynomial model is set up, a response surface analysis is necessary to determine whether the model reflects the true relationship of the problem. For example, test of lack-of-fit, visual examination of the contour plot, etc. Based on the analysis the influential variables that are important information for designer will be also found. In this study a spherical design BBD that can give a complete estimation of the coefficients is employed in the response model. The response value is the degree of metal fit-up.

5.3 Example

Two rectangular sheet metals assembled with laser welding are used here. A single lap joint is located at the centering line of the sheet metals. The length of the weld joint is 50mm. The geometric model here is a surface with normal-distributed source variation. The direction of the source variation is normal to the panel. By generating normal distributed random number with zero mean and 1.5mm as 6σ values the statistical data are simulated. The length, width and thickness of the two panels are 200mm, 100mm and 1mm respectively. The material of the two panels are mild steel with Young's modulus E=20,7000 N/mm^2 and Poisson's ratio ν=0.3. Since the thickness of the panel is 1mm(IMT=1mm), quantitatively the metal fit-up criterion for the whole design process can be classified into two parts: DMF=0.124mm is used for the determination of the number of designed locators, while DMF=0.1mm is the target value of the performance characteristic in the robust design.

5.3.1 Deterministic Optimization

First, a prediction and correction method is adopted for the determination of the number of direct locators with a "3-2-1" total locating scheme. As shown in Table 5.1, 5 direct locators are required and the degree of metal fit-up is -0.122mm under the "3-2-1" total locating scheme with Pattern A.

Second, a minimum number of the total locators is determined based on a pattern sorting method, a "1-2-1" locating scheme for total locating is obtained due to the effect of direct locators. In the optimal fixture configuration design the number for designed direct locators is 5 and the number for designed total locators is 1. Then a discretization of the design space is carried out. The discrete total design space is a quarter of the rectangle since only one locator is enough for total locating. A fine mesh with 1mm mesh size is used, the finite element model for the fixture configuration optimal design is shown in Figure 4.8(a), the optimal results are shown in Table 5.1.

5.3.2 Robust Design

The proposed two-stage response surface methodology is used for robust fixture configuration optimization. The first stage is to optimally determine the mean locating scheme of the Robust Design Space. A comparison is carried out by using two different objectives: one objective, which is expressed by Eq.(5.17), considers only the robustness, while the other objective which is expressed by Eq.(5.20) takes both robustness and performance characteristic into account. The weighting factors ω_1 and ω_2 for the latter case are specified as 0.7 and 0.3.

By optimization with GA the mean locating schemes of the RDS can be obtained. The objective function values corresponding to the two objectives are also listed in Table 5.1. To the case of single robustness objective, the objective function has obvious deviation from the metal fit-up requirement of 0.124IMT. While by using Eq.(5.20) the quality performance influence is fed into the optimal process, the degree of metal fit-up is around the target value τ which is set as 0.1IMT. The result shows that the use of combined objective for optimization of RDS is reasonable.

Table 5.1 Fixture configuration results for the example

<table>
<tr><td colspan="2">Number of direct locators</td><td colspan="4">5</td></tr>
<tr><td colspan="6">Six scheme patterns of the total locating(mm)</td></tr>
<tr><td colspan="2">Pattern A</td><td colspan="2">Pattern B</td><td colspan="2">Pattern C</td></tr>
<tr><td colspan="2">-0.122</td><td colspan="2">-0.235</td><td colspan="2">-0.263</td></tr>
<tr><td colspan="2">Pattern D</td><td colspan="2">Pattern E</td><td colspan="2">Pattern F</td></tr>
<tr><td colspan="2">-0.234</td><td colspan="2">0.083</td><td colspan="2">-0.292</td></tr>
<tr><td colspan="6">"2-1"locating pins</td></tr>
<tr><td colspan="2">Coordinate
(mm)</td><td>(15,-85)
(185,-15)</td><td colspan="2">Restrained
direction</td><td>X , Y</td></tr>
<tr><td colspan="6">Designed locators (mm)</td></tr>
<tr><td colspan="2" rowspan="2">Locator number</td><td rowspan="2">Initial
scheme</td><td colspan="3">Optimal scheme</td></tr>
<tr><td>deterministic</td><td>Mean of RDS
$\begin{pmatrix}\omega_1 = 0.7\\ \omega_2 = 0.3\end{pmatrix}$
(by Eq.(20))</td><td>Mean of
RDS
(by Eq.(17))</td></tr>
<tr><td>total</td><td>1</td><td>(15,-15)</td><td>(15,-32)</td><td>(31,-15)</td><td>(84,-15)</td></tr>
<tr><td>direct</td><td>5</td><td>(100,-45)
(105,-45)
(105,-55)
(100,-55)
(95,-55)</td><td>(92,-45)
(100,-45)
(130,-48)
(104,-55)
(90,-55)</td><td>(96,-45)
(117,-45)
(130,-55)
(111,-55)
(101,-55)</td><td>(110,-45)
(130,-48)
(123,-55)
(95,-55)
(83,-55)</td></tr>
<tr><td colspan="2">Metal Fit-up (mm)</td><td>0.083</td><td>0.058</td><td>0.099</td><td>0.378</td></tr>
</table>

After the mean locating scheme of the RDS is obtained, the minimal mesh size h = 1mm in the discrete design space is used as fluctuation forward and backward. The determined RDS in the case of fixture configuration design can be simply written as the limits of the x and y coordinates. The design variables are the locations of 6 locators on the two metals. Let the notation T1 be the design total locator, and notations D1,D2,...,D5 be the design direct locators. The resultant RDS can be written as 6 groups and the unit of the expression below is millimeter.

$T1:\{(30-32),-15\}$ $D1:\{(95-97),-45\}$ $D2:\{(116-118),-45\}$
$D3:\{(129-130),(54-55)\}$ $D4:\{(110-112),-55\}$ $D5:\{(100-102),-55\}$

The second stage of the robust optimization is to set up a second-order response model. In this stage the control variables are the locations of 6 designed locators; the noise variable(P1) is the location of the two-way pin, so totally there are 7 input variables. To carry out experimental design the location limits of the 7 input variables need to be set at 3 levels, representing the 3 possible moving directions due to uncertainty: forward, backward or in the mean location. However, the design domain of the input variables cannot be used directly in the fitted response model since the location information include both x and y coordinates. As a substituted quantity, the distance from different design locations to the origin can reflect the nature of the location of the design locators. Since the determined RDS is a small region, the distance intervals between upper limit to the mean location and from low limit to the mean location are approximately equal, thus coded variables +1, 0 and –1 can be used as the 3 levels in the Box-Behnken design.

The low, mean and upper location limits and the corresponding coded representations for 7 input variables are shown in Table 5.2. In the table, 7 columns represent 7 input variables. Totally there are 56 experimental runs and 4 center runs. The experimental runs and the corresponding response values are shown in Appendix 1. Table 5.3 is the analysis of variance for the fitted response surface model. The test on individual regression coefficients of the full-term second-order response surface model is shown in Table 5.4. From the table, by the use of t-test on individual regression coefficients with a 0.95 confidence interval, we can see that not all terms are significant to the fitted model. All the influential terms are labeled with "+" in the table. The effective terms can also be detected from the bar diagram as shown in Figure 5.3. With the deletion of the less-effective terms the meaningful response surface model can be obtained below:

$$y = 0.097369 - 0.010804*X2 + 0.004649*X6 + 0.0051305*X2*X2 + 0.0045699*X3*X3 + 0.0045356*X4*X4 - 0.003889*X2*X3 - 0.007933*X2*X6 \quad (5.23)$$

The optimal solutions for Eq.(5.23) within the ±1 limits of the four variables are: X2=1.0, X3=0.423, X4=0.030, X6=1.0. The response at the optimal solutions is 0.088mm. The other three variables can be set at mean values in the RDS. The coded coordinate expressions and natural coordinate expressions of the optimal solution and corresponding X and Y coordinate expressions are listed in Table 5.5. From the application of RSM, it shows that eight response terms have significant effect on the performance characteristic of the assembly process. As an illustrative example, the response surface and contour plot for designed locator D1 and designed locator D2 are shown in Figure 5.4. From this figure one can see that when X2=1 and X3=0.4231, a minimum point of the fitted response surface can be obtained. The response surface and contour plot for designed locators D1 and D5 are shown in Figure 5.5. From this figure one can see that when X2=1 and X6=1.0, a minimum point of the fitted response surface can be obtained.

Table 5.2 Three location levels and the coded representations

Input variable	Low limit (mm)	Mean (mm)	Upper limit (mm)
T1(X1)	33.541(-1)	34.438(0)	35.341(+1)
D1(X2)	105.119(-1)	106.024(0)	106.930(+1)
D2(X3)	124.423(-1)	125.355(0)	126.289(+1)
D3(X4)	140.420(-1)	140.769(0)	141.156(+1)
D4(X5)	122.984(-1)	123.879(0)	124.776(+1)
D5(X6)	114.127(-1)	115.004(0)	115.884(+1)
P1(X7)	184.610(-1)	185.607(0)	186.604(+1)

Table 5.3 Analysis of variance for the response surface model

Source of variance	Sum of Squares	D. O. F	Mean Square	F-ratio	$F_{0.05,n1,n2}$
Regression	0.0061	35	1.742e-004	6.358	1.915
Residual	6.575e-004	24	2.740e-005		
Lack of Fit	5.651e-004	21	2.691e-005	0.874	8.655
Pure Error	9.241e-005	3	3.080e-005		
Total	0.0068	59			
Response mean : 0.1009			Root MSE: 0.0052		

Table 5.4 Test on individual regression coefficients of full-term second-order response model

Variable	Coefficient Estimate	Standard Error	t for H_0 (coeff.=0)	$t_{0.025,24}$: 2.064
intercept	0.974E-01	0.262E-02	37.205	+
X1	-0.239E-03	0.114E-02	-0.209	-
X2	-0.108E-01	0.116E-02	-9.312	+
X3	-0.139E-02	0.107E-02	-1.301	-
X4	-0.402E-03	0.107E-02	-0.376	-
X5	0.825E-03	0.108E-02	0.762	-
X6	0.465E-02	0.107E-02	4.351	+
X7	-0.217E-03	0.108E-02	-0.200	-
X1*X1	-0.232E-02	0.151E-02	-1.532	-
X2*X2	0.513E-02	0.152E-02	3.372	+
X3*X3	0.457E-02	0.151E-02	3.019	+
X4*X4	0.454E-02	0.151E-02	2.997	+
X5*X5	-0.197E-02	0.152E-02	-1.292	-
X6*X6	-0.126E-02	0.151E-02	-0.835	-
X7*X7	0.810E-05	0.152E-02	0.005	-
X1*X2	0.628E-03	0.185E-02	0.340	-
X1*X3	-0.380E-05	0.185E-02	-0.002	-
X1*X4	-0.144E-02	0.243E-02	-0.593	-
X1*X5	-0.113E-04	0.185E-02	-0.006	-
X1*X6	-0.493E-04	0.185E-02	-0.027	-
X1*X7	0	0.185E-02	0	-
X2*X3	-0.389E-02	0.185E-02	-2.102	+
X2*X4	0.974E-03	0.221E-02	0.440	-
X2*X5	-0.260E-02	0.214E-02	-1.216	-
X2*X6	-0.793E-02	0.185E-02	-4.287	+
X2*X7	0.651E-03	0.193E-02	0.338	-
X3*X4	0.250E-05	0.185E-02	0.001	-
X3*X5	-0.199E-03	0.185E-02	-0.107	-
X3*X6	0.587E-03	0.185E-02	0.317	-
X3*X7	0	0.185E-02	0	-
X4*X5	0.168E-03	0.185E-02	0.091	-
X4*X6	0.245E-03	0.185E-02	0.132	-
X4*X7	0	0.185E-02	0	-
X5*X6	0.368E-03	0.185E-02	0.199	-
X5*X7	0.651E-03	0.193E-02	0.338	-
X6*X7	0	0.185E-02	0	-

Table 5.5 Optimal solutions by the fitted model

Coded Coord.		Designed Fixture		
		Fixture code	Natural Coord. (mm)	X-Y Coord. (mm)
X1	0.0	T1	34.438	(31,-15)
X2	1.0	D1	106.930	(97,-45)
X3	0.4231	D2	125.750	(117.423,-45)
X4	0.0297	D3	140.780	(130,-54.028)
X5	0.0	D4	123.879	(111,-55)
X6	1.0	D5	115.884	(102,-55)
X7	0.0	P1	185.607	(185,-15)

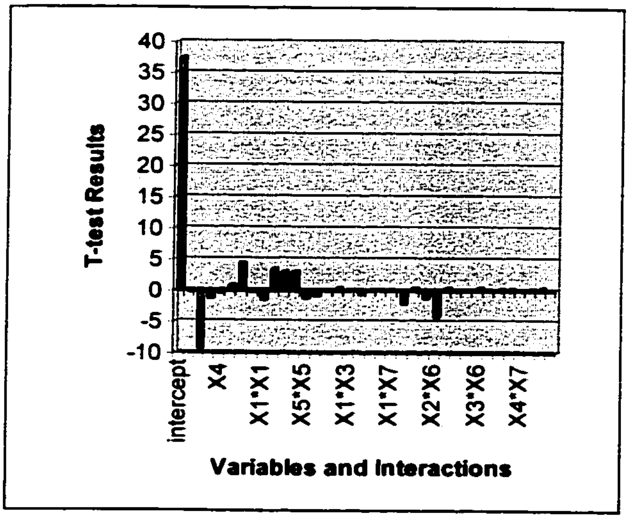


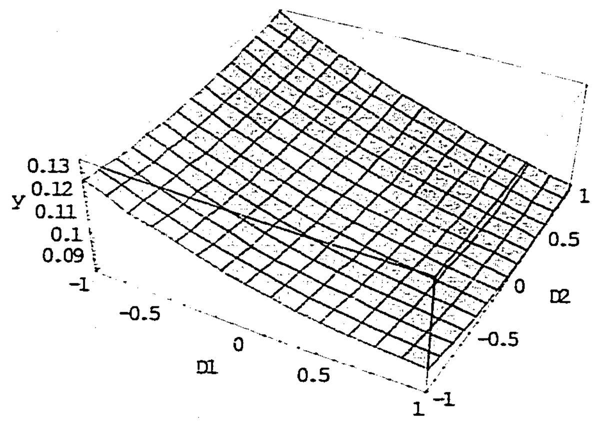
Figure 5.3 Bar diagram for detecting effective terms

Comparing the results between deterministic and robust optimal design we can see the performance characteristic of the deterministic optimization is better than that of robust design. On the other hand, the robust design can lead to not only a less-sensitive locating scheme but also to a scheme close to the target of the performance.

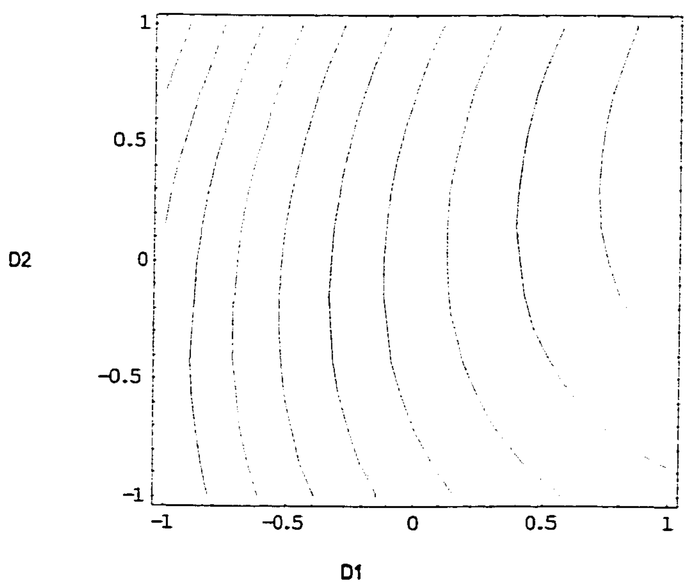
5.4 Chapter Summary

To reduce the sensitivity of the performance characteristic of DMF about the location fluctuation, a robust fixturing design is carried out. In order to consider the interaction of different designed locators and also the interaction between control and noise variables, a response surface methodology is employed. Due to the wide variety of the input variables, the appropriate response surface model cannot be formed easily. Thus a two-stage response surface methodology is then developed in this study. The first step is to optimally find the Robust Design Space. A combined objective including both robustness and performance characteristic is derived. Then within the small region RDS a second-order response surface model is fitted by 3^k fractional factorial design. By analysis of variance of the experimental data, a fitted response model is finally obtained. Based on this model a robust locating scheme can be formed.

The illustrative example shows that the optimal value of the traditional optimization problem is smaller than the values in the robust optimization. The robust fixture configuration design scheme is less sensitive to the location uncertainty of the input variables due to manufacturing and assembly error. The influential response terms are found by tests on individual regression coefficients of the fitted response model. This information is important for manufacturing and quality engineers when the location adjustment of the locators is desired. This method is generally suitable for the kind of engineering problems in which the analytical expression is difficult to obtain but the approximate first-order derivative is available.

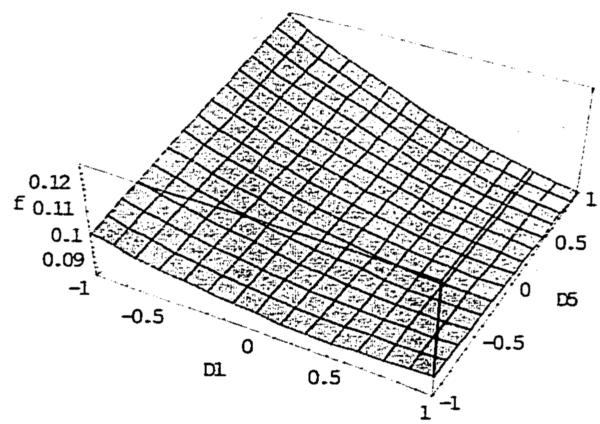


(a) response surface

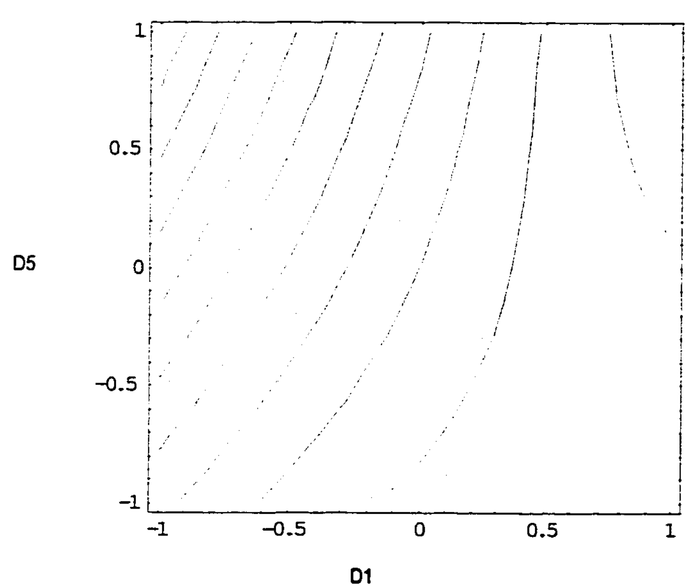


(b) contour plot

Figure 5.4 Response surface and contour plot for D1 and D2



(a) response surface



(b) contour plot

Figure 5.5 **Response surface and contour plot for D1 and D5**

CHAPTER SIX

WELD PATTERN DESIGN FOR SHEET METAL LASER WELDING

6.1 Introduction

In sheet metal assembly the weld pattern is the critical process specification that must be established prior to initiation of an in-depth tooling design. Thus, product structural problems can be resolved early in the design phase by modifying the weld pattern with minimal cost. Weld length and weld location are two main weld patterns.

In RSW, the weld gun can cause heat and high local weld tip pressure during the welding process, this guarantees the proper welding quality. So the design issue of the assembly weld patterns with RSW is not very important. However, when laser welding is applied to the assembly process, metal fit-up becomes crucial in ensuring the implementation of laser welding and in improving weld quality(Havrilla,1996). Thus the weld patterns have great influence on the feasibility of laser processing. In the workshop for automotive body assembly the weld pattern, weld location in particular, is basically determined based on the engineer's experience. There are many factors that need to be considered by manufacturing engineers when specifying weld location. They must pay much attention to anticipate the poor metal fit-up conditions on the flange area of the assembly parts. Then they have to evaluate the manufacturing feasibility of the product and whether or not the fixtures are capable of overcoming the dimensional limitations. This experience-based pattern determination makes the elements of the weld pattern negotiable. So in order to improve weld quality, the specified weld pattern should be feasible enough in order to cope with problems related to structural requirements of the product. If the stamping quality of the flange area is too poor, a combined method adopting both RSW and laser welding can be used in actual application, by which the poor flange areas can be joined by RSW. However, the drawbacks caused by using RSW cannot be avoided. This experience-based weld pattern determination is generally carried out manually, so a computer aided new design approach is urgently required. So the objective of this chapter is to set up a scientific new approach for determining the assembly weld pattern.

6.2 A New Design Approach of Assembly Weld Pattern

An assembly weld pattern design primarily includes the design of weld length, weld location candidates and the selection of weld locations. The selection of the weld location can be influenced by a number of factors. Sometimes it requires compromises between strength and cost, equipment available and welder skill or even between any two, three or more variables, etc (Jeffus, 1993). Therefore, in typical assemblies, weld test is necessary before selecting the final joint configuration. This chapter will focus on developing a systematic approach for designing assembly weld patterns.

6.2.1 Weld Length Requirement

The strength analysis for the selected metal gauges with lap-joint laser welding was developed by Wang (1993). The weld length for laser welding which gives the equivalent fatigue resistance was predicted using the developed analytical model. The preference of short welds was exhibited. This result is useful for forming laser welding length specifications. Some companies apply multiple short welds(say, less than 25mm) instead of the single long weld in their weld pattern design. Short weld has some other advantages: for example, it can enhance the ability to maintain intimate metal contact by fixtures; it can also minimize the zipper effect when using intermittent stitch. If a fixture is configured properly the number of locators applied in the assembly process of multi-short welds can be reduced. However, this does not mean long weld is not applicable. By applying long weld the possibility of missed welds can be reduced and the keyhole process is also easy to maintain. So in the actual assembly design, the weld length can be short or long or a mixture of the above two. The decision of the weld length pattern can be different based on the quality level of the stamping process for different assemblies or different workshops. So before carrying out weld pattern design the weld length pattern can be set first. This does not mean the weld length is fixed: the actual weld length will be re-determined in the subsequent design process and is described as follows.

6.2.2 Determination of Weld Location Candidates

In the fixture configuration design for sheet metal assembly, the two important design quantities are the number and the location of the designed fixtures. The design for the two quantities is directly related to the weld pattern design. In particular, the weld location is more important in the fixture design process. However, as described above there is a big possibility of deviation in detecting poor metal fit-up area based on the engineer's observation. So a scientific approach for selecting weld location candidates from weld area is desired. In this section a computer aided weld location determination approach is developed. It should be mentioned that in a workshop of automotive body assembly, when the stamping process is completed the stamping sheet metal parts will be inspected by using checking fixtures. Any discrepancy from the allowed tolerance of the parts will require an operation of manual correction. In this way the stamping quality can be controlled under a certain level, such as 6 σ value of 2 millimeter. Thus, the variation of the panels can be regarded as being stable. Even so there may be different degrees of metal fit-up on different areas of the mating edge. The aim of the proposed approach is to find the relatively good metal fit-up area on the weld area of the two panels.

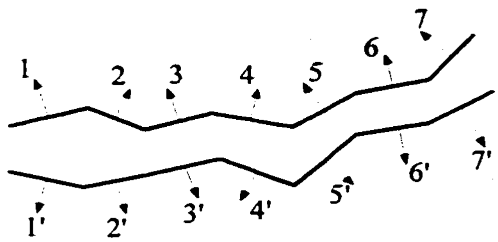


Figure 6.1 Two mating panels with illustrative variation

In a complicated 3D sheet metal assembly, we can assume that the 3D panel is composed of many small planar patches. The side view of two mating panels with illustrative variation is shown in Figure 6.1. From the figure we can see each panel comprises 7 planar patches, the arrow lines represent the average normal vectors of the different patches. To the upper panel, the patch vectors are labeled with 1,2,...,7 and the patch vectors on the lower panel are labeled with 1',2', ..., 7'. Totally there are 7 mating patches, being 1-1', 2-2',..., 7-7'. Obviously, among them only two mating patches 3-3' and 6-6' are approximately parallel, thus when fixtures are applied on the two mating patches, the degree of metal fit-up can be easily satisfied. In this illustrative example the mating patches 3-3' and 6-6' are the good metal fit-up areas we want. The centering line of the interested patches can be set as weld locations.

The ideal evaluation criterion for good fit-up area can be defined as the two patches being parallel, in most common cases the mating patches may not be parallel. Thus a general evaluation criterion is desired. Assuming the total number of the patches is N, in the *i* th mating patch, the corresponding normal vectors are $\mathbf{P}_i$ and $\mathbf{P}_i'$. The angle θ_i between the two normal vectors of the mating patches can be obtained and then a lower limit of the allowable angle θ_0 can be specified as shown in Eq.(6.1).

$$\theta_i \le \theta_0, \quad i=1,2,\ldots,N \qquad \text{where} \quad \theta_i = \cos^{-1}\left(\mathbf{P_i} \cdot \mathbf{P_i'}\right) \tag{6.1}$$

If Eq.(6.1) is satisfied we can regard the *i* th patch as good fit-up area where the weld can be located. In this way the allowable angle limit must be set properly so as to ensure that there are enough weld location candidates.

The number of patches is determined by the mesh density of the FE model on the mating area of the part. If too high a mesh density is used there may be too many patches satisfying Eq.(6.1). On the other hand, if too low a mesh density is used there may be few patches satisfying Eq.(6.1). If short weld is used, fixed weld length can be set as being less than or equal to 25mm. For a workshop with good stamping quality, there can be more patches that satisfy the requirements. In this case as well as in cases where the parts for assembly are rather flat, long weld will be more efficient.

There are two ways to carry out design of weld location candidates for the assembly. One way is called "patch-to-assembly" method, which is to compare the angles of normal vectors between the mating patches of the two parts. After the comparison the weld location candidates for the assembly can be obtained based on the angle information. Since each weld joint generally includes several patches, the adjoined patch information of each part is not considered in this method. This method has been shown in Figure 6.1. The other method is called "patch-to-part-to-assembly" method. This method includes two steps, first, to setup the weld location configurations of each panel; then by comparing the angles of normal vectors between the neighboring patches of each weld configuration, the weld location candidates for the two parts can be obtained separately. Hence the weld location candidates for the assembly can subsequently be extracted. The latter method sufficiently considers the influence of neighboring patches and so is a reasonable method. The procedure for the determination of the weld location candidates by the second method is described below.

Assuming that the required length of the weld is L, let the mesh density be M_d ; thus the number of the patches N_p included in the weld stitch can be obtained by the truncation of the ratio of L over M_d. For the two mating parts, part *a* and part *b*, the normal vectors of the N_p patches of one weld can be written as:

$$\begin{cases} P^a_{i+1}, & \cdots, & P^a_{i+N_p}, & \text{for part } a \\ P^b_{i+1}, & \cdots, & P^b_{i+N_p}, & \text{for part } b \end{cases}$$

The weld location candidate can be determined as shown in Figure 6.2. Let the number of all patches of one panel be N. Since the weld stitch includes N_p patches, the total number of the weld location candidates on one panel is $N-N_p+1$. First, we have to find the maximum angles of the normal vectors between the *i* th patch and the other neighboring N_p-1 patches within one weld candidate. Totally there are $N-N_p+1$ resultant angles. After this step a comparison between these angles and the allowable angle limit θ_0 is carried out. If a certain resultant angle is less than the allowable angle limit, the weld location number corresponding to this resultant angle will be saved into a number set {a} by recording the starting patch number of this weld configuration. Then this location will be regarded as weld location candidate for part *a*. In the same way we can obtain set {b} as weld location candidate for

For $i=1:N-N_p+1$

  For $j=1:N_p$

    $\theta^a_{i,j}=\cos^{-1}\left(P^a_i, P^a_{i+j}\right);\quad \theta^b_{i,j}=\cos^{-1}\left(P^b_i, P^b_{i+j}\right)$

    $\theta^a_i=\mathrm{Max}\left(\theta^a_{i,j}\right)\quad \theta^b_i=\mathrm{Max}\left(\theta^b_{i,j}\right)$

  End j

  if $\theta^a_i \le \theta_0$, save patch number i to set {a}

  if $\theta^b_i \le \theta_0$, save patch number i to set {b}

End i

Candidate weld location set: $\{C_w\}=\mathrm{set}\{a\}\cap\mathrm{set}\{b\}$

Figure 6.2 Description for determination of weld location candidates part *b*. The intersection set {C_w} between set {a} and set {b} will be the weld location candidates for the assembly.

In this way instead of the fixed weld length, the new length of the weld will be obtained from the interaction set. As shown in Table 6.1, there are ten patches (p1,p2,…,p10) included in the weld design area. First we set a weld length, assuming each weld include 5 patches, there are a total of 6 possible weld location configurations for each part, which are labeled with 1,2,...,6 for part *a* and labeled with 1',2',…,6' for part *b*. If location No.1 of part *a* and location No. 1' of part *b* both satisfy the requirement of allowable angle limit, then 1 and 1' will be saved into set {a} and set {b} respectively. Thus the weld location candidates for the assembly can be obtained. The included patch numbers of this weld location in set {C_w} are {p1, p2, p3, p4, p5}. The weld length in this case is just the weld length we set. There is the second case, assuming that location No.3 of part *a* and location No. 4' of part *b* satisfy the allowable angle limit requirement; thus the patch numbers included in the weld location candidates of the two part are: {p3, p4, p5, p6, p7} for part *a* and {p4, p5, p6, p7, p8} for part *b*. Thus the weld location candidate for the assembly can be obtained from the intersection of the above two sets, being {p4, p5, p6, p7}. From this example we know the actual length of designed weld is shorter than the weld length L we set.

Table 6.1 Illustration of weld location configurations

Config. No. for part *a*	Weld design area(10 patches)										Config. No. for part *b*
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	
1	■	■	■	■	■						1'
2		■	■	■	■	■					2'
3			■	■	■	■	■				3'
4				■	■	■	■	■			4'
5					■	■	■	■	■		5'
6						■	■	■	■	■	6'

From the method for determination of weld location candidates we know, the weld location candidate for a single part may not be weld location candidate for the assembly.

Comparing to the fixed weld length, the weld length derived by considering the quality of the two mating parts is more scientific and reasonable. In the design process the magnitude of the allowable boundary angle θ_0 should be set properly. Since the mating two parts may have different manufacturing quality, the angle θ_0 can be set separately. A slightly larger value of θ_0 is required to be set for the case of poor stamping quality in order to avoid design failure. By this approach the weld location candidates for the assembly can be obtained.

6.2.3 Determination of Normal Vectors of the Patches

For weld location design, normal vectors of the patches are important data for determining weld location candidates. However, in most of the cases the CAD model of the part may not be useful for the design here since the CAD model is only a nominal model without tolerance. Thus only discrete points of the part's surface can be obtained by measurement. In this study the normal vector will be obtained from the measuring points by the optimization approach. One patch will be taken as illustrative example to show the approach for determining the normal vector.

An illustrative flange edge(weld area) is shown in Figure 6.3: the total number of patches on the flange area is 15; the interested patch net on the weld area which are shown by the hatched area is 3 in row by 16 in column. In each patch, there are 6(3×2) measuring points. Based on the theorem of "three points form a plane", the combined patch number of selecting 3 different points from 6 can be denoted as ${}_6C_3 = \frac{6!}{3!(6-3)!}$. Apart from two cases in which three co-linear points cannot form a plane, the total number of normal vectors from combined patches is $N_v = {}_6C_3 - 2 = 18$. The illustrative 18 combined patch configurations are shown in Figure 6.4. In order to find the best approximation of the patch's normal vector

$$\min \quad f(n_x, n_y, n_z) = \sqrt{(n_x - n_x^i)^2 + (n_y - n_y^i)^2 + (n_z - n_z^i)^2} \qquad i = 1,2,\ldots,N_v \qquad (6.2)$$

where n_x, n_y, n_z represent three components of the required normal vector, and n_x^i, n_y^i, n_z^i represent normal vector of the *i*th patch configuration. In the same way the normal vectors of other patches can also be obtained.

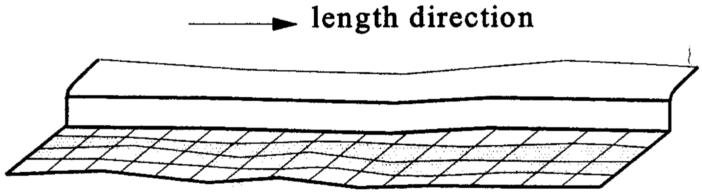


Figure 6.3 Example of patch division for a flange edge

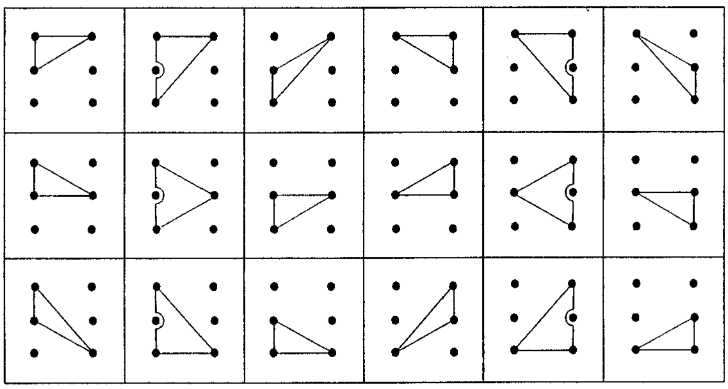


Figure 6.4 18 combined patch configurations

6.2.4 Selection of Weld Locations

Actually the selection of weld locations from the weld location candidates is not only a design process but also a synthesized decision-making process where a lot of factors are involved. From the perspective of the designer, some design considerations are necessary for making right decisions on weld locations.

The strength requirement is the first requirement that has to be met in the welding process. The related strengths include tension and compression, bending, shear, torsion and fatigue etc. At the beginning of the selection an analysis must be carried out to estimate the loading status of this assembly. Then one can approximately determine

The strength requirement is the first requirement that has to be met in the welding process. The related strengths include tension and compression, bending, shear, torsion and fatigue etc. At the beginning of the selection an analysis must be carried out to estimate the loading status of this assembly. Then one can approximately determine which stress is the influential stress for consideration. The stresses involved can be one, two or more. By equating the working stress to the allowed stress limit that can be obtained from material handbook, the minimum requirement of the total weld length corresponding to each stress can be obtained. If more stresses need to be considered, the longest weld length obtained from different strength factors is what we want in this step. Subsequently the resulting total weld length is allocated to different weld location candidates. In this way the weld locations can be determined. The main factors to consider in the allocation of weld locations are described below: first, when the two assembled parts are put into position while the fixtures are not applied, the original degree of metal fit-up can be obtained. The weld location candidate areas with good original metal fit-up are recommended to be weld locations since in this case the metal fit-up requirement is easily satisfied. Second, the weld location is distributed evenly on the good fit-up area of the parts. For safety consideration the actual length of weld should be greater than the resultant total weld length.

In sheet metal assembly there are some important points called Key Product Characteristic (KPC) points that define the functional requirements of the whole assembly. All the welding process must ensure the after-assembly variation of the KPC points are satisfied with required specifications. If the resulting statistical variation cannot meet the specification of KPC points, the selected weld locations have to be changed. By this trial-and-error method the feasible weld location scheme can be obtained. To the typical assemblies the selection of weld joint will involve more factors. The final decision of the weld locations is practically determined by weld test. The flowchart of the assembly weld pattern design is shown in Figure 6.5. The first step in the figure, CAD model representation with measuring data, will be described in the subsequent chapter. From the figure we can see that the weld pattern design is a part of fixture planning. After the weld pattern design the fixture configuration design will follow.

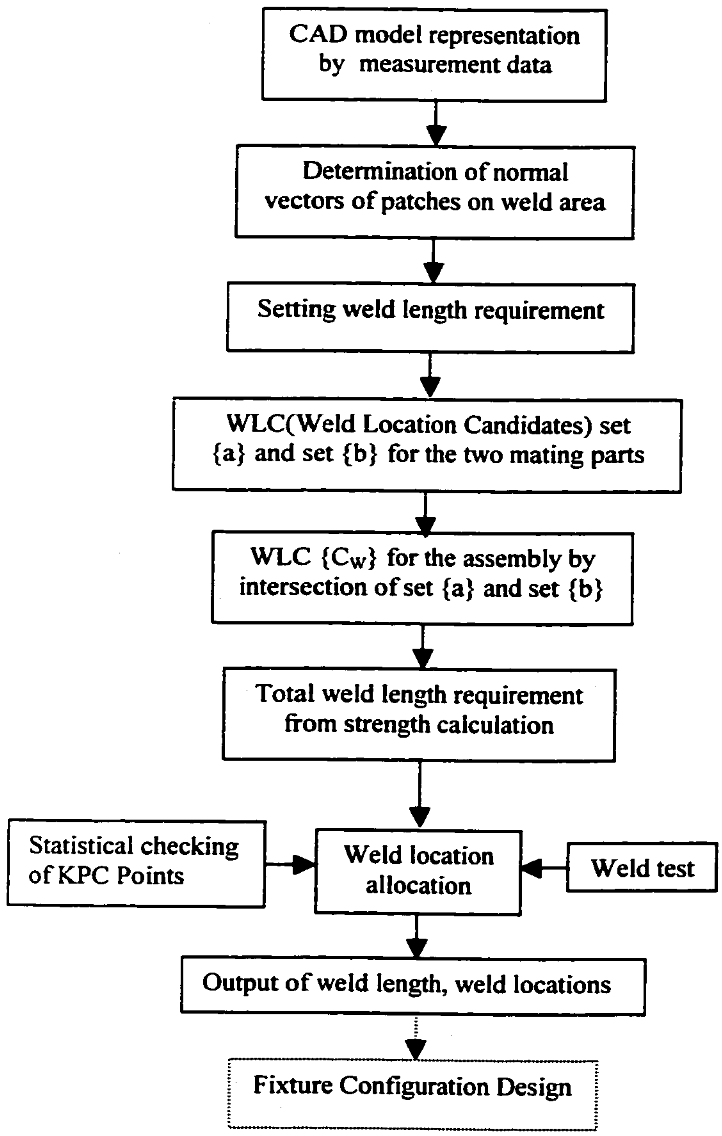


Figure 6.5 Flowchart of the assembly weld pattern design

6.3 Example

An example is used to demonstrate the developed design approach. For illustration purpose no weld test is carried out. Two simple sheet metals are to be assembled together.

On the weld area different variations with 6σ values of 2mm and 3mm are simulated for the two parts respectively. The length and width of the mating edge of the two panels are 140mm and 30mm. The material of the two panels are mild steel with Young's modulus $E=20,7000\ N/mm^2$ and Poisson's ratio $v=0.3$. The finite element mesh is shown in Figure 6.6. In this figure the density of the measured modeling data is 10mm and the density of the finite element mesh is 5mm. Thus there are a total of 28 patches on the weld area of each panel.

Assuming that the weld length of 30mm is specified, thus the total patch number of each weld is 6. There are altogether 23 weld location configurations to each panel. Based on the calculation described in Figure 6.2, the maximum angle of the patches' normal vectors in each weld location configuration can be obtained from the 15 angle candidates. As shown in Figure 6.7(a) there are 23 angles corresponding to 23 weld location configurations based on the "patch-to-part-to-assembly" method. And there are 28 angles corresponding to 28 mating patches based on the "patch-to-assembly" method as shown in Figure 6.7(b). The optimal normal vectors of the two panels are listed in Appendix 2. The design results of the weld location candidates for the assembly are shown in Table 6.2. In order to indicate different manufacturing levels 6.0° and 4.0° are set as allowable angle limits of the two parts, thus the acceptable angles with "good area" configurations can be screened and shown with boldface in Table 6.2. Thus the weld location candidates are obtained as shown in the table. The design results of the assembly weld location candidates by "patch-to-assembly" method are also shown in this table.

From the results we can see there are 13 patches included in the weld location candidates by "patch-to-part-to-assembly" method, while by "patch-to-assembly" method there are 23 patches or 26 patches included in the weld location candidates corresponding to two different

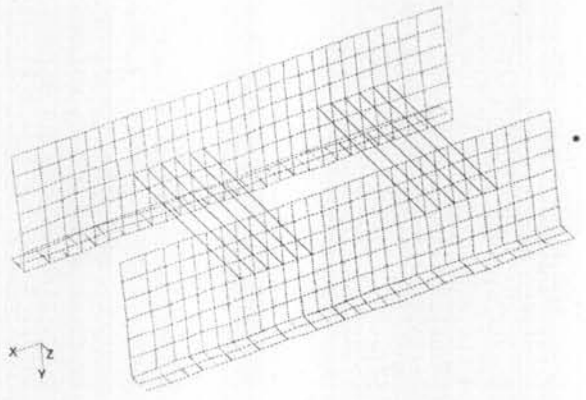
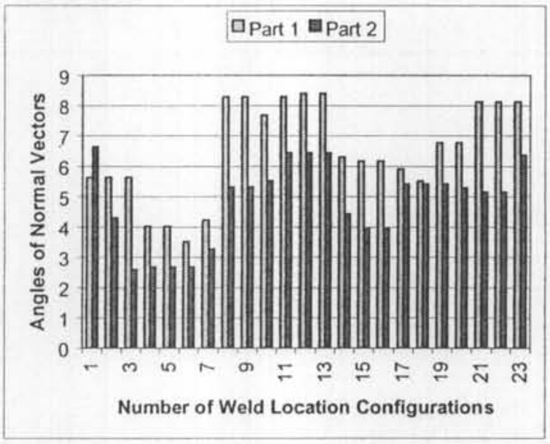
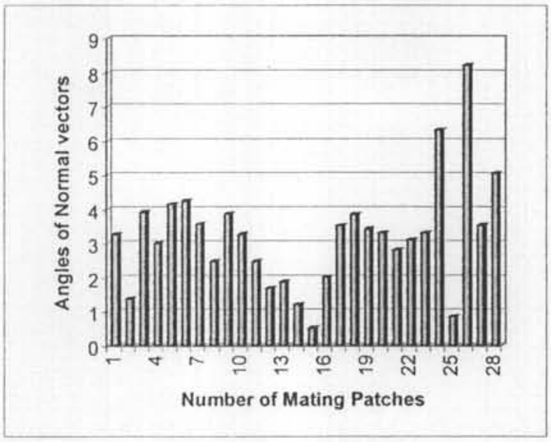


Figure 6.6 Illustrative finite-element mesh



(a) patch-to-part-to-assembly



(b) patch-to-assembly

Figure 6.7 Determination of weld location candidates

Assuming that the shear strength is the main factor to be considered, let the average shear load F_e be 1.2 kN. The shear stress τ_e applied on the weld area can be written as:

$$\tau_e = F_e / (L_T \cdot t) \leq [\tau_e] \quad (6.3)$$

Assuming that the shear strength is the main factor to be considered, let the average shear load F_e be 1.2 kN. The shear stress τ_e applied on the weld area can be written as:

$$\tau_e = F_e / (L_T \cdot t) \leq [\tau_e] \tag{6.3}$$

where L_T represents the required total weld length, t refers to the width of the weld bead, $[\tau_e]$ is the allowable stress limit. Let the working stress be equal to the allowable stress limit, the minimum total weld length can be obtained as shown in Eq. (6.4). If the width of the

$$L_T = F_e / (t \cdot [\tau_e]) \tag{6.4}$$

Table 6.2 Design results for Weld Locations

"patch-to-part-to-assembly" method						
WL Config. No.	Boundary angle θ_0 (°) Part 1: 6.0 Part 2: 4.0 Maximum angles(°)		WL candidates Part 1:18 patches Part 2:17 patches		WL candidates for assembly (13 patches)	Designed Weld Locations
	Part 1	Part 2	Part 1	Part 2		
1	**5.62**	6.64	P1			
2	**5.62**	4.31	P2			
3	**5.62**	**2.59**	P3	P3	P3	
4	**4.01**	**2.68**	P4	P4	P4	P4
5	**4.01**	**2.68**	P5	P5	P5	P5
6	**3.51**	**2.68**	P6	P6	P6	P6
7	**4.24**	**3.27**	P7	P7	P7	P7
8	8.29	5.32	P8	P8	P8	P8
9	8.29	5.32	P9	P9	P9	
10	7.68	5.53	P10	P10	P10	
11	8.29	6.44	P11	P11	P11	
12	8.40	6.44		P12		
13	8.40	6.44				
14	6.29	4.43				
15	6.16	**3.94**		P15		
16	6.16	**3.94**		P16		
17	**5.90**	5.41	P17	P17	P17	P17
18	**5.51**	5.41	P18	P18	P18	P18
19	6.78	5.41	P19	P19	P19	P19
20	6.78	5.29	P20	P20	P20	P20
21	8.13	5.15	P21	P21	P21	P21
22	8.13	5.15	P22			
23	8.13	6.37	P23			
Weld length			90mm	85mm	65mm	50mm

WL candidates for assembly by "patch-to-assembly" method		
Boundary angle	Patch number	Weld length
$\theta_0 = 6.0°$ (26 patches)	P1 to P23, P25, P27, P28	130mm
$\theta_0 = 4.0°$ (23 patches)	P1 to P4, P7 to P23, P25, P27	115mm

weld bead is 1mm and $[\tau_e]$ is 30 MPa, the minimum requirement of the total weld length can be obtained by Eq.(6.4), being 40 mm. Based on this result we can select two 25mm long welds (P4 to P8 and P17 to P21) from two weld location candidates as weld locations. The two selected weld locations are modeled by linear element in the finite element mesh as shown in Figure 6.6, the FE model based on this figure will be used for the subsequent fixture configuration design.

6.4 Chapter Summary

An assembly weld pattern design is one of the important phases of fixture design. The traditional experience-based weld location determination approach often has difficulty in detecting good metal fit-up area on the flange edge of the parts. A new design approach for the assembly weld pattern is proposed.

Two design methods for determination of the assembly weld location candidates are described in this study. The "patch-to-assembly" method is carried out by directly comparing the angles of normal vectors of the mating patches. This method neglects the weld length information, so the resultant assembly weld candidate areas are not very reliable, and may sometimes include bad metal fit-up areas. By "patch-to-part-to-assembly" method the good metal fit-up areas for the two parts can be obtained first; then by comparison of the weld candidate areas of the parts, the assembly weld location candidates and also the actual weld lengths can be obtained. By strength analysis the minimum requirement of total weld length can be derived, thus the weld location can be selected by allocating the total weld length to the weld location candidates.

The illustrative example shows that the presented computer aided design approach is more scientific and reasonable. This work is especially suitable for the initial stage of the fixture design cycle.

CHAPTER SEVEN

A CASE STUDY

7.1 Introduction

The computer-aided fixture design has been rapidly developed to reduce the leading time involved in manufacturing planning. As shown in Figure 7.1, the fixture design cycle of a typical manufacturing system includes three major aspects: set-up planning, fixture planning and fixture configuration design (Ma, Li and Rong, 1999). Set-up planning is aiming at determining the number of set-ups and the position and orientation of the workpiece in each set-up. The flange edges or the weld areas in each set-up of sheet metal assembly are determined within this stage. Fixture planning mainly determines the locating and clamping points on workpiece surfaces. The objective of the fixturing design is to select fixture components and place them into a final configuration to fulfill the

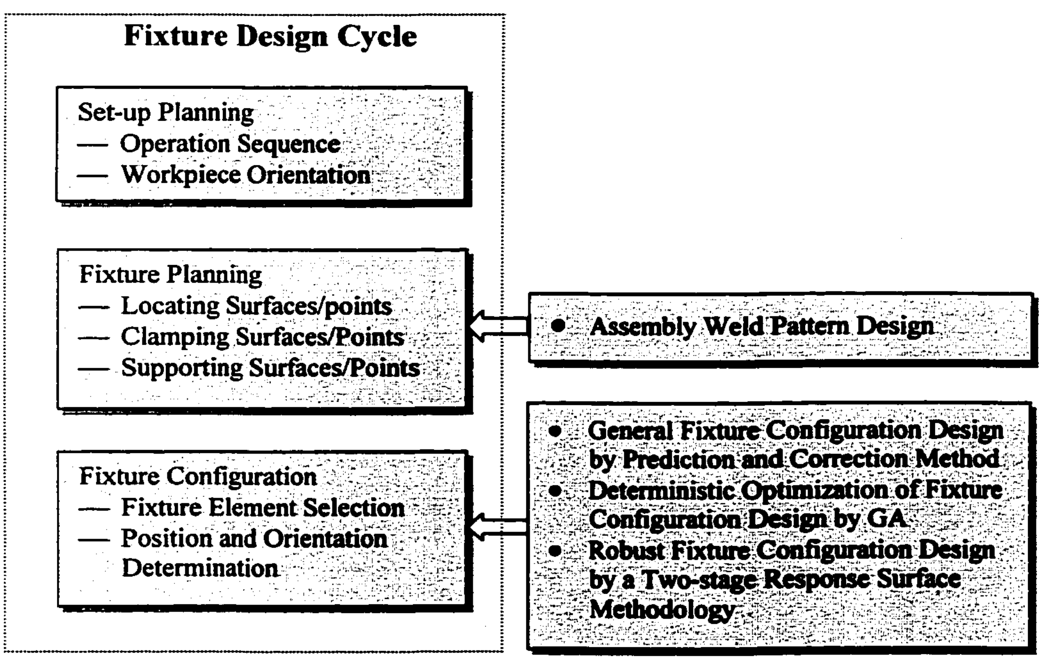


Figure 7.1 A general fixture design cycle

function of locating and clamping the workpiece. In sheet metal laser welding, the assembly fixtures are also configured to satisfy the metal fit-up requirements. The related work stated in chapter 3, 4, 5 and 6 is shown in Figure 7.1. The objective of this chapter is to carry out a case study in which the proposed fixturing principles are applied to actual automotive body assembly. To realize this objective, measurement is necessary to implement the CAD modeling for the experimental case study. Based on the measuring data the finite element modeling is set up and then the fixture configuration design is followed.

7.2 CMM -based Finite Element Modeling

7.2.1 Selection of Experimental Assembly

There are several potential production applications for sheet metal laser welding in automotive industry. Included are door inners, motor compartment rails, A-pillars, body sides, bumpers, B-pillars, floor pans, lift gates and wheelhouse. In North America, such other applications as seat reinforcements, cross-beam members, dash panels and seat risers are being examined(Irving,1994). The selection of the experimental assembly depends mainly on two factors: first, the parts must be suitable for laser welding; second, the dimension of the parts should be relatively small for ease of shipping to laboratory and also ease of measurement under laboratory conditions. In this study the cross member assembly of BIW(Body-In-White) is used in the measuring experiment. As shown in Figure 7.2, the assembly includes two parts, one big part with the dimensions of 1200×180×120mm and the small part with the dimensions of 360×180×80mm. The material of the two panels are mild steel with Young's modulus E=20,7000 N/mm^2 and Poisson's ratio ν=0.3. In this experiment one selected set of the cross member assembly with good manufacturing quality is used.

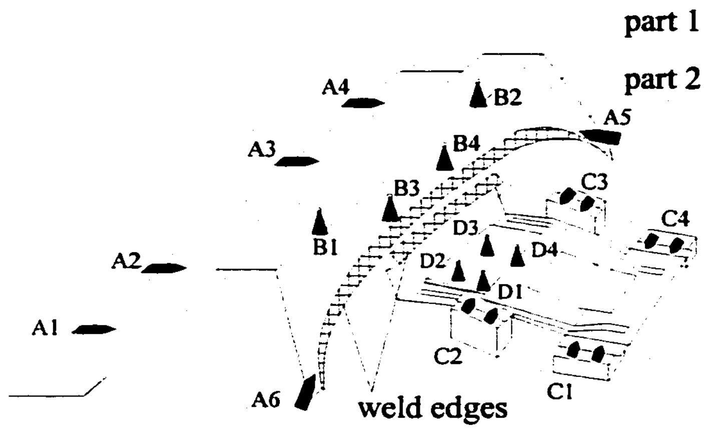


Figure 7.2 Measuring fixture scheme for cross member assembly

7.2.2 CAD Model Representation Based on Measuring Data

In the study of weld pattern design and fixture configuration design, both are carried out based on the finite element model. In order to obtain the finite element model, geometric modeling must be carried out first. The experimental parts in this study are obtained from automotive workshop and the CAD models of the parts are not available. Actually even if the CAD models are available, it is still impossible to directly apply them for fixture design since what we need is the model with tolerances, while the designed CAD model is only a nominal model. So it is necessary to create a CAD representation from the actual model. In this context reverse engineering methodology is employed to solve this problem. Reverse engineering is based on techniques for measuring the shape of physical models and data processing techniques for constructing CAD models from the measured data. Currently, there are many different kinds of digitizing technologies available, ranging from manual touch-probe devices and Coordinate Measuring Machines(CMMs) to laser scanning systems and industrial CT scanners. Each technology comes with its own set of strength and limitations. In the proposed adaptive laser assembly system, Optical CMM is employed for measurement of the physical model. Considering the focus of this study is the fixturing design methodology and based on the laboratory condition, a CMM is employed here to measure the auto-body parts and the measuring data will be used for finite element modeling. In this measuring experiment a "CONTURA" CMM with moving bridge configuration is employed and the corresponding supporting softwares are Calypso and Holos. Calypso software is used for probe calibration and the definition of base alignment of the measurement system. Holos software is used to digitize the physical surfaces of the parts.

The first step of the measurement is division of the digitized surface. Based on the geometrical features of the digitized surface, the workpiece surface will be divided into more patches. In order to make it easier to probe the boundaries of the surface, the division mesh is marked with a marker pen. Since in this case the weld areas are distributed on the flange area of the assembly, the measuring points with high density are set on the flange area. The other important factor that needs to be considered in this step is that the design of the surface division should be convenient for constructing the surface.

The second step is the setup of the measuring fixtures. The fixture requirements for measurement purpose are quite different from those for welding. The main role of the measuring fixtures is to keep the dimension of the parts stable. The fixturing scheme in this case is not necessarily limited to "3-2-1" or "4-2-1" locating scheme. Additional clamps and supporting poles are required. In industrial application the popular checking fixture is often a die base with some clamps applied. However, in laboratory the use of die base is not cost-justifiable, so clamps and supporting poles are employed. The automotive parts are free-form parts; the measuring fixture elements are used to clamp the sheet metal parts onto the worktable of the CMM. If necessary the measuring datum is provided for base alignment. In the fixture configuration design what we are concerned with is whether the DMF of weld can meet the laser welding specification. It is very important that the finite element model, in particular, the weld area on the model, can reflect the real-life manufacturing quality. So the best measurement operation is one based on the actual assembled location of the two parts.

However, in this way the measuring fixture will be very complicated in order to keep the two flange edges of the assembly in intimate fit-up since we do not have any physical information available at this stage. Considering there exists some manufacturing data for each part, if these data are set as measuring data, the fixture for measurement will be greatly simplified. So in this study we measure the two assembled parts separately. In order to connect the two parts in the MSC/NASTRAN software, three mating points on each part need to be recognized. Then based on the point information the alignment and rotation operation in MSC/NASTRAN are carried out.

The illustrative diagram of the fixturing scheme for measurement has been shown in Figure 7.2. Clamps A1, A2,..., A6 and supporting poles B1, B2, B3, B4 are used to locate part 1; locating blocks C1, C2, C3, C4 and the supporting poles D1,D2,D3,D4 are used to locate part 2. The base alignment is defined on part 1, a 2-D line connecting the center points of the locating hole and locating slot, and a point on the side plane of part 1 is defined. Subsequent to the measuring operation based on the division mesh, the approximation of the surface segments can be obtained. Then constructing surfaces from the measuring patches, the CAD representation of the two parts can be obtained. The digitized measurement by CMM is shown in Figure 7.3.

7.2.3 Finite Element Modeling

The digitized surface model obtained from CMM can be imported to the MSC/NASTRAN software. In order to carry out finite element modeling, the imported surface needs to be cleaned-up and some small features that are not important to the FEA need to be deleted for the improvement of analysis efficiency. Then the finite element model can be generated. Based on this finite element model the weld pattern design and the fixture configuration design can be carried out.

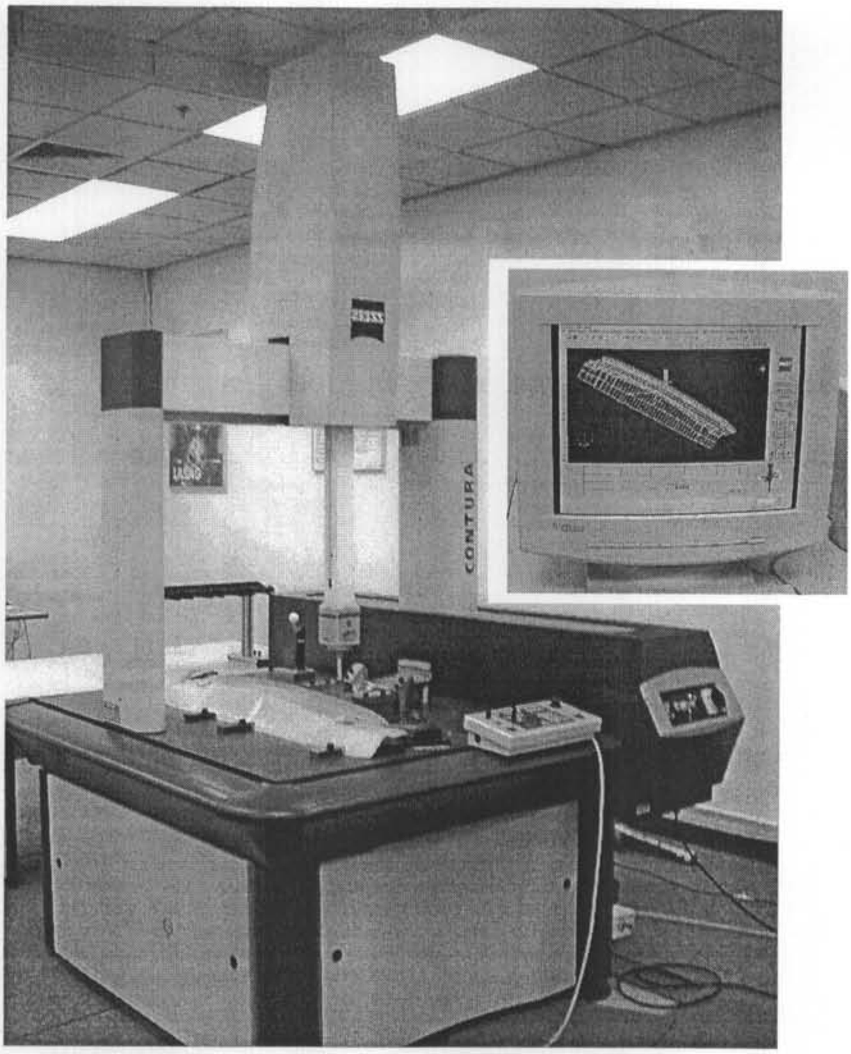


Figure 7.3 Digitized measurement by CMM

Thus the weld area of interest can be set as 3 rows by N+1 columns. Note that the probe stylus will touch the outer surface of the panel, while the FE modeling is along the mid-plane of the panel. In this study there is one approximation that the measured surface is treated as the required mid-plane. For the complicated 3D sheet metals, the DMF is calculated in the following way. Assuming the nodal coordinates of two mating weld joint nodes by CMM are (x_1, y_1, z_1) and (x_2, y_2, z_2), and when a certain fixture scheme is set on position, the corresponding deformations after FEA are $(\Delta x_1, \Delta y_1, \Delta z_1)$ and $(\Delta x_2, \Delta y_2, \Delta z_2)$; thus the DMF is evaluated by the distance between the two mating corresponding deformations after FEA are $(\Delta x_1, \Delta y_1, \Delta z_1)$ and $(\Delta x_2, \Delta y_2, \Delta z_2)$; thus the DMF is evaluated by the distance between the two mating nodes on weld area as shown in Eq.(7.1).

$$DMF = \sqrt{[(x_2 + \Delta x_2) - (x_1 + \Delta x_1)]^2 + [(y_2 + \Delta y_2) - (y_1 + \Delta y_1)]^2 + [(z_2 + \Delta z_2) - (z_1 + \Delta z_1)]^2} \quad (7.1)$$

Similar to the finite element modeling described in Chapter 3, the locator is set as enforced displacement, two pins of each assembled parts are set as constraints. The weld location of the two parts is connected by gap element. High mesh is modeled on the locating area as shown in Figure 7.5(b). The designed locator is treated as rigid point contact and without thermal influence.

7.3 Design Results

The first aspect of fixturing design is weld pattern design. The weld areas in this assembly are the flange edge of the small part and the corresponding mating area of the long part. The assembly weld pattern design shown in Chapter 6 is carried out and the weld location candidates are listed in Table 7.1. The loading status of this assembly when being assembled into BIW frame is very complicated. Assuming the average shear load applied in this assembly is 1.8KN. The width of the weld bead is 1mm and the allowed boundary strength $[\tau_e]$ is 30 Mpa. Thus the minimum total length of the weld can be obtained, being 60mm. From the consideration of the distribution of the original DMF, two welds each 35mm can be determined. The patch number of the two welds is listed in Table 7.1. Then the fixture configuration design is followed. Based on the "4-2-1" locating scheme on the two assembled parts, general fixture design is carried out. The nodal variation graph and the hierarchy level chart for general fixture design are shown in Figure 7.4 and Table 7.2. By the prediction and correction method, 9 direct locators are needed to reach the DMF of

0.103mm(the allowed DMF limit is set at 0.124mm). By testing with different total locating schemes from "4-2-1" to "2-1", the DMFs are almost unchanged, this is because the weld type of this assembly is butt weld, so the total locating direction is different from variational direction of the weld lines. Moreover, the part dimension is rather big. Thus in the optimal and robust fixture design only direct locators are taken as designed locators with "2-1" total locating scheme applied. The finite element model of this case study is shown in Figure 7.5.

The fixture design results of this case study are presented in Table 7.3. In the optimization of fixture design, the number of locators is treated as a design variable and is optimized first based on the coarse mesh size; the optimal results show that 7 direct locators is enough to reach the DMF of 0.092 mm. The optimization process is shown in Figure 7.6. The optimal result based on the fine mesh with 7 locators shows that the DMF in this case can reach 0.085 mm. Regarding the result of the determination of robust design space as center point and ±1 mm as fluctuation the robust design space is determined. The control variables are designed locators(*D1,D2,...,D7*) and a 3^k fractional factorial BBD is carried out. The experimental run and the response values are listed in Appendix 3. The analysis of variance and the test for independent variables of the response model are shown in Table 7.4. From the table we can see that ten influential terms of the response model are detected. The approximate response function with influential terms is shown in Eq.(7.2). The optimal results are: X1= -1, X3= -1, X4= 1, X5= 1, X6= -1 and X7= -1. The response at the optimal solutions is 0.118mm. Thus the locator D2 can be set on the mean location of X2=0. The four response surfaces for locator D1 and D7, D3 and D7, D4 and D7, D3 and D4 are shown in Figure 7.7. The robust design results are also listed in Table 7.3.

$$\begin{aligned} R(X) = {} & 0.1257725 - 0.00049778 \cdot X1 + 0.00092008 \cdot X4 - 0.00089274 \cdot X5 \\ & + 0.00139358 \cdot X6 + 0.00202291 \cdot X7 - 0.00085275 \cdot X1 \cdot X7 \\ & + 0.00112188 \cdot X3 \cdot X4 - 0.00094463 \cdot X3 \cdot X7 - 0.00189833 \cdot X4^2 \end{aligned} \quad (7.2)$$

Table 7.1 Weld location design results for case study

Total Patch No. On Weld Area	28	Included Patch No. Per Weld	7	Total No. of WL Configuration	22

WL Configuration No.	Maximum angles(°)		WL candidates	
	Part 1	Part 2	Part 1	Part 2
1	**0.94**	1.55	P1	
2	**0.00**	1.76	P2	
3	**0.77**	1.79	P3	
4	**0.00**	1.71	P4	
5	**0.00**	1.19	P5	
6	**0.00**	**0.90**	P6	P6
7	**0.67**	**0.64**	P7	P7
8	**0.00**	**0.64**	P8	P8
9	**0.00**	**0.81**	P9	P9
10	**0.00**	**0.80**	P10	P10
11	**0.98**	**0.96**	P11	P11
12	**1.00**	**0.96**	P12	P12
13	**1.30**	**1.00**	P13	P13
14	1.66	**0.76**	P14	P14
15	**1.48**	**0.85**	P15	P15
16	1.97	1.17	P16	P16
17	2.46	1.55	P17	P17
18	2.34	1.66	P18	P18
19	2.90	2.11	P19	P19
20	2.58	1.89	P20	P20
21	1.75	1.73	P21	P21
22	1.57	1.34		
Boundary angle	$\theta_0 = 1.5°$	$\theta_0 = 1.0°$	21 patches	16 patches

WL candidates for assembly (Weld length: 80mm)		
Patch number	P6, P7, P8, P9, P10, P11, P12, P13,P14, P15, P16, P17, P18, P19, P20, P21	
Designed two welds	P6, P7, P8, P9, P10, P11, P12	Weld length: 35mm
	P15, P16, P17, P18, P19, P20, P21	Weld length: 35mm

Table 7.2 HLC for general fixturing design

Level i	V_i(mm)	No. of Applied Locators	Nodal ID No.
1	0.54	3	5,6,30
2	0.5	6	5,6,30,3,13,15
3	0.42	9	5,6,30,3,13,15,9,18,29
4	0.37	11	5,6,30,3,13,15,9,18,29,1,17
5	0.36	14	5,6,30,3,13,15,9,18,29,1,17,8,19,28
6	0.34	16	5,6,30,3,13,15,9,18,29,1,17,8,19,28,12,38
7	0.30	19	5,6,30,3,13,15,9,18,29,1,17,8,19,2812,38,10,20,31
8	0.26	22	5,6,30,3,13,15,9,18,29,1,17,8,19,28,12,38,10,20,31,4,14,36
9	0.2	25	5,6,30,3,13,15,9,18,29,1,17,8,19,28,12,38,10,20,31,4,14, 36,2,25,32
10	0.16	28	5,6,30,3,13,15,9,18,29,1,17,8,19,28,12,38,10,20,31,4,14, 36,2,25,32,33,35,40
11	0.11	31	5,6,30,3,13,15,9,18,29,1,17,8,19,28,12,38,10,20,31,4,14, 36,2,25,32,33,35,40,26,27,37
12	0.08	33	5,6,30,3,13,15,9,18,29,1,17,8,19,28,12,38,10,20,31,4,14, 36,2,25,32,33,35,40,26,27,37,7,41
13	0.06	36	5,6,30,3,13,15,9,18,29,1,17,8,19,28,12,38,10,20,31,4,14, 36,2,25,32,33,35,40,26,27,37,7,41,22,23,24
14	0.04	39	5,6,30,3,13,15,9,18,29,1,17,8,19,28,12,38,10,20,31,4,14, 36,2,25,32,33,35,40,26,27,37,7,41,22,23,24,16,21,24
15	0	41	5,6,30,3,13,15,9,18,29,1,17,8,19,28,12,38,10,20,31,4,14, 36,2,25,32,33,35,40,26,27,37,7,41,22,23,24,16,21,24,11,39

Table 7.3 Design results for case study

"2-1" pins		Node number Restrained direction			Part 1: 1257 Part 2: 2422 (*X*,*Y*)		Part 1: 1100 Part 2: 2655 (*X*)	
Total locating scheme DMF(mm)	Part 1: "4-2-1" Part 2: "4-2-1" 0.103				Part 1: "2-1" Part 2: "2-1" 0.104			
Num. of direct locators	General fixture design: 9				Optimal design: 7			
Designed locators with "2-1" total locating scheme								
	Initial Scheme		Optimal Scheme		Robust Design			
					Mean of RDS (ω_1=0.7, ω_2=0.3)		Robust Scheme	
	Part 1	Part 2	Part 1	Part 2	Part 1	Part 2	Part 1	Part 2
Node number	2115	2748	2863	3241	2848	3220	2847	3221
	2118	2745	2932	3315	2119	2744	2119	2744
	2112	2741	3648	3388	3017	3443	3016	3444
	2129	2734	3101	3540	3052	3480	2127	2736
	2155	2764	3061	3489	3156	3559	3155	3558
	2156	2763	3010	3432	3061	3489	2152	2765
	2104	2774	2960	3344	2970	3380	2100	2762
DMF(mm)	0.092		0.085		0.125		0.118	

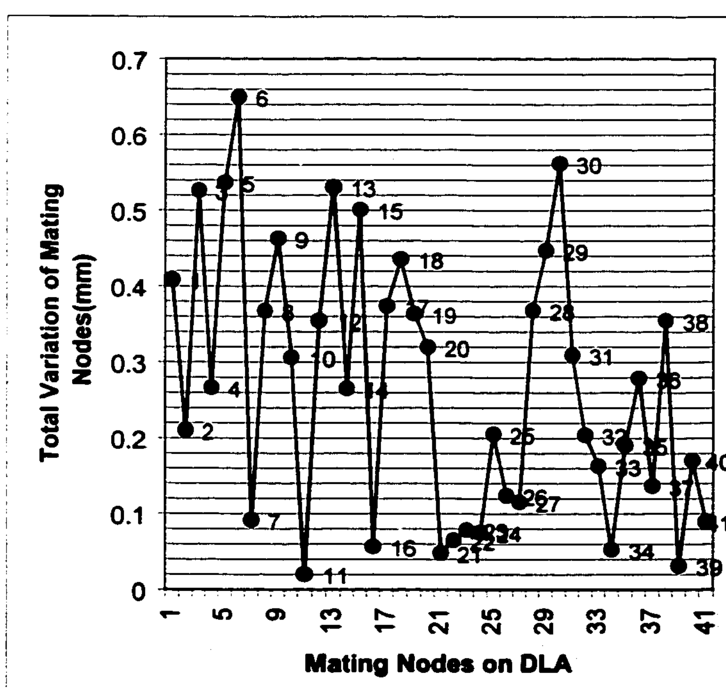
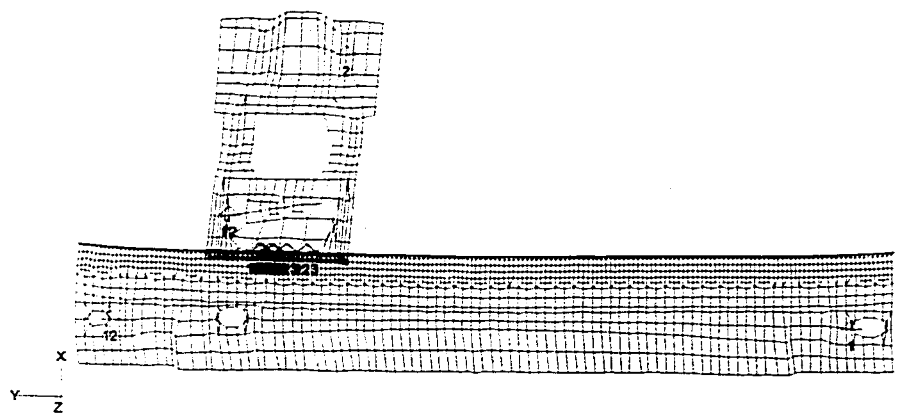
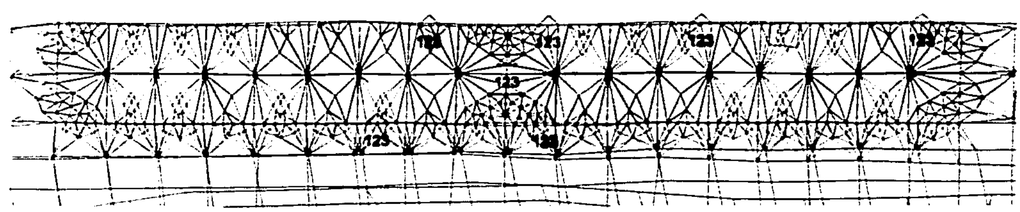


Figure 7.4 NVG for general fixture design



(a) whole model



(b) local fine mesh on weld location

Figure 7.5 Finite element model

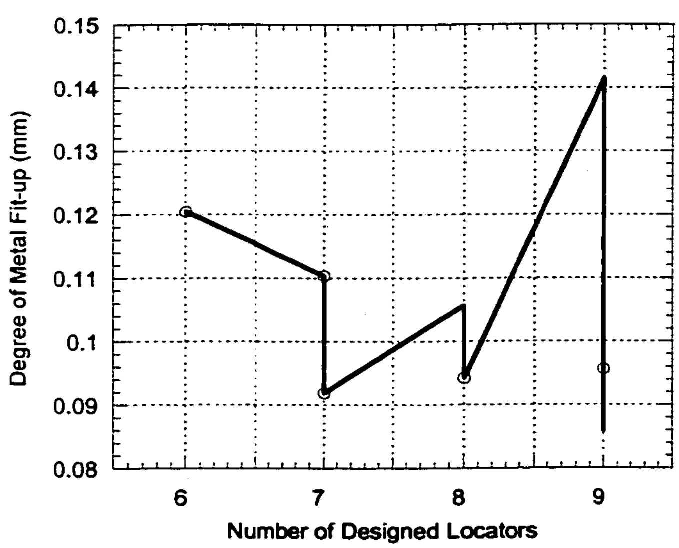
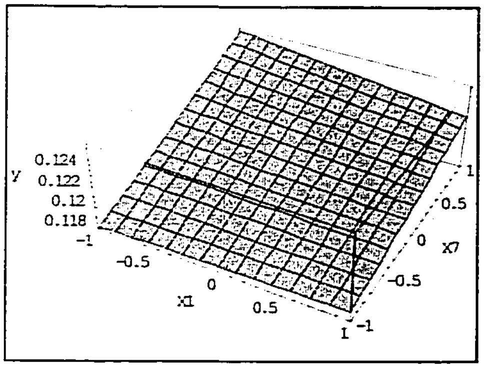


Figure 7.6 Optimization for the number of designed locators

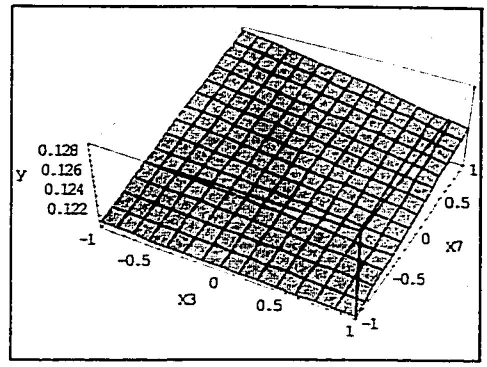
Table 7.4 **Analysis and test of the second-order response model**

Analysis of Variance					
Source of variance	Sum of Squares	DOF	Mean Square	F-ratio	$F_{0.05,n1,n2}$
Regression	3.067e-04	35	8.763e-06	7.512	1.915
Residual	2.800e-05	24	1.167e-06		
Lack of Fit	2.386e-05	21	1.136e-06	0.823	8.655
Pure Error	4.141e-06	3	1.380e-06		
Total	3.347e-04	59	R-square=0.909		
Mean Response:	0.125		RootMSE:		0.001

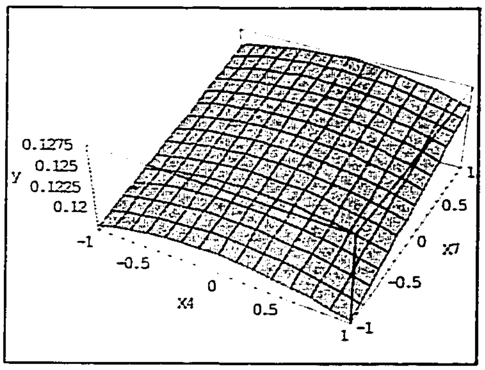
Test on individual regression coefficients			
Variable	Coefficient Estimate	t for H_0 (coeff.=0)	$t_{0.025,24}$: 2.064
intercept	0.126	232.896	+
X1	-0.498E-03	-2.111	+
X2	0.281E-04	0.117	-
X3	-0.108E-04	-0.049	-
X4	0.920E-03	4.173	+
X5	-0.893E-03	-3.994	+
X6	0.139E-02	6.321	+
X7	0.202E-02	9.050	+
X1*X1	0.178E-03	0.569	-
X2*X2	-0.640E-03	-2.038	-
X3*X3	-0.584E-03	-1.870	-
X4*X4	-0.190E-02	-6.078	+
X5*X5	-0.318E-04	-0.101	-
X6*X6	0.162E-03	0.518	-
X7*X7	-0.201E-03	-0.641	-
X1*X2	-0.174E-04	-0.046	-
X1*X3	0.321E-04	0.084	-
X1*X4	0.257E-03	0.514	-
X1*X5	0.250E-03	0.656	-
X1*X6	-0.243E-03	-0.636	-
X1*X7	-0.853E-03	-2.233	+
X2*X3	-0.275E-05	-0.007	-
X2*X4	-0.112E-03	-0.246	-
X2*X5	-0.117E-03	-0.264	-
X2*X6	-0.125E-05	-0.003	-
X2*X7	0.234E-04	0.059	-
X3*X4	0.112E-02	2.938	+
X3*X5	0.179E-04	0.047	-
X3*X6	-0.178E-04	-0.046	-
X3*X7	-0.945E-03	-2.474	+
X4*X5	-0.148E-03	-0.388	-
X4*X6	0.267E-03	0.698	-
X4*X7	0.464E-03	1.216	-
X5*X6	-0.270E-03	-0.706	-
X5*X7	-0.279E-03	-0.701	-
X6*X7	0.331E-03	0.867	-



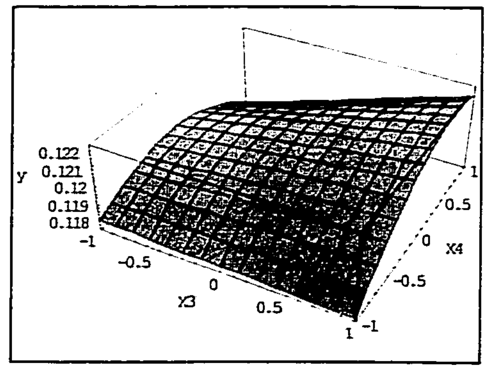
(a) locators D1 and D7



(b) locators D3 and D7



(c) locators D4 and D7



(d) locators D3 and D4

Figure 7.7 Response surfaces for the main designed locators

7.4 Chapter Summary

In this chapter a case study of automotive laser assembly by applying the developed fixture configuration design methodologies is carried out. A selected cross member assembly of BIW is taken as the study object. In order to get the physical model of the car body parts with actual tolerances, CMM is employed for measurement of the assembled parts. A CMM-based finite element model is generated. In this case study the degree of metal fit-up is no longer a one-dimensional variation but a 3D variation. Thus the distance between the mating nodes on weld area in 3D space is regarded as performance characteristic of this design.

By weld pattern design two 35-mm long welds on the flange edges are determined and so the locating area are determined. By general fixture design additional direct locators are required. In chapter 4 this number would have been directly used in the optimal design part, while in this case study the number of direct locators is treated as a design variable. The optimal process is a dynamic design process. First, the number of designed locators is optimized on the locating area with coarse mesh; then the global optimization is carried out using a fine mesh for the locating area. Robust design is then followed up with the developed two-stage response surface methodology. The influential terms of the response model are detected and the robust fixturing scheme is obtained.

From the results listed in Table 7.3 we can see that the optimal design scheme has better performance characteristic while the robust design scheme has less sensitivity to the location fluctuation. By this case study we can see that the proposed fixture configuration methodologies can effectively meet the requirement of industrial applications.

CHAPTER EIGHT

CONCLUSIONS AND FUTURE WORK

8.1 Conclusions

This dissertation initiates systematic research on fixturing design for sheet metal assembly with laser welding, with the following contributions.

A new adaptive assembly system with the application of OCMM and flexible fixtures for sheet metal assembly with laser welding is proposed, and a detailed assembly system with distributed measuring scheme is also proposed. In the proposed assembly system, OCMM is used to provide variation information of the assembly parts for fixturing configuration design. Different cycles of the same assembly will result in different fixturing schemes which can be accommodated by the adjustments of flexible fixtures. The in-process fixturing design module is a key module in the assembly system and is also the main focus of this thesis.

A new locating scheme with both total locating and direct locating for welds is proposed. The total locating scheme is used to locate the overall assembly and the direct locating scheme is used to locate the weld location, which is critical for ensuring metal fit-up. In the new locating scheme both total variation and local variation on weld area are considered. Based on the presented new locating scheme the fixturing designs for sheet metal laser welding are carried out.

A finite element model with the consideration of characteristic of sheet metal laser welding is set up, where gap elements are used to model the weld joint and enforced displacements are used to model the locators. A nonlinear static FEA is carried out.

A general fixture configuration design for sheet metal assembly with laser welding is proposed. A prediction and correction method for the configuration of direct locators is developed. By setting the weld nodes to nominal values the nodal variation of the locating area can be obtained. Then the locating nodes can be grouped by setting different variational values which are obtained from FEA. Thus the feasible fixturing scheme can be obtained from applying the right group of direct locators.

An optimal fixture configuration design model is then proposed based on the new locating scheme. In this model both the number and the location of the concerned locators are considered as research objectives. The degree of metal fit-up is taken as the objective function. The proposed prediction and correction method is used for determining the number of direct locators and a pattern sorting method is developed for determining the number of total locators. Considering the DMF to be a fuzzy quantity, a feasible evaluation criterion about DMF is also developed using a fuzzy synthesis evaluation method. Genetic algorithm is employed as the optimization procedure.

A quality design, robust fixture configuration design for sheet metal laser welding is then developed. By robust design the sensitivity of the performance characteristic to the location fluctuation of designed locators is reduced. A two-stage response surface methodology is developed for the robust design. In the new robust design methodology the first stage is to optimally find the Robust Design Space (RDS) where a relatively insensitive area can be obtained. Within RDS a second-order response surface model is fitted by a 3^k fractional factorial design in the second stage. Based on the two-stage response surface methodology the robust fixture configuration scheme can be obtained. The developed robust design method is a generic method for engineering design.

The design for assembly weld pattern is a critical phase for a fixture design cycle. Traditionally the determination of the weld pattern is based on designer's experience. In this way it is quite easy to cause unexpected discrepancy from the assembly weld quality requirements. *A new design method of the assembly weld pattern is developed*, where the source variation on the weld areas of the parts are considered in detail. By this method the resultant weld location and the weld length are much more reasonable.

An industrial case study with the cross member subassembly is presented in order to demonstrate the feasibility of the proposed fixture design principles in industrial application. In order to obtain the physical model with actual tolerance, reverse engineering technologies are employed for geometric modeling of the assembled parts. Considering the requirement of modeling accuracy a CMM -based finite element modeling is carried out and the performance characteristic with 3D feature is obtained. In the case study the assembly weld patterns are designed first so as to determine the weld locations. Then the general design, the deterministic optimization and the robust design of the fixture configuration are carried out respectively. The results of case study show that the proposed fixturing principles are reasonable and effective for meeting the requirements of sheet metal laser welding in practical application.

8.2 Future Work

In the future the following aspects need to be further investigated as follows:

The proposed new assembly system for sheet metal assembly with laser welding includes many aspects. This thesis only focuses on in-process fixture configuration design module. Other aspects are still under investigation.

A quality monitoring system for sheet metal laser welding system and the modeling of reliability for the assembly system are still desired.

In this thesis fixturing issues for the implementation of laser welding are the primary concerns. The after-weld variation control that directly affects the product quality needs to be further investigated.

It is very important to carry out research on enhancing the quality of the stamping process. Poor stamping quality may cause the proposed new locating scheme to encounter difficulty in overcoming the problem of distorted edges.

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1. **B. Li**, B. W. Shiu and K. J. Lau, 2001, Principle and Simulation of Fixture Configuration Design for Sheet Metal Assembly with Laser Welding, Part I: Finite Element Modeling and A Prediction and Correction Method, *International Journal of Advanced Manufacturing Technology*, Vol.18 (will appear in Issue 4).

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APPENDICES

Appendix 1 Experimental Runs and Response Values

No	X1	X2	X3	X4	X5	X6	X7	Response(mm)
1	0	0	0	+1	+1	+1	0	0.107
2	0	0	0	+1	+1	-1	0	0.092
3	0	0	0	+1	-1	+1	0	0.104
4	0	0	0	+1	-1	-1	0	0.090
5	0	0	0	-1	+1	+1	0	0.107
6	0	0	0	-1	+1	-1	0	0.093
7	0	0	0	-1	-1	+1	0	0.104
8	0	0	0	-1	-1	-1	0	0.092
9	+1	0	0	0	0	+1	+1	0.101
10	+1	0	0	0	0	+1	-1	0.101
11	+1	0	0	0	0	-1	+1	0.086
12	+1	0	0	0	0	-1	-1	0.086
13	-1	0	0	0	0	+1	+1	0.102
14	-1	0	0	0	0	+1	-1	0.102
15	-1	0	0	0	0	-1	+1	0.086
16	-1	0	0	0	0	-1	-1	0.086
17	0	+1	0	0	+1	0	+1	0.086
18	0	+1	0	0	+1	0	-1	0.086
19	0	+1	0	0	-1	0	+1	0.090
20	0	+1	0	0	-1	0	-1	0.090
21	0	-1	0	0	+1	0	+1	0.115
22	0	-1	0	0	+1	0	-1	0.115
23	0	-1	0	0	-1	0	+1	0.113
24	0	-1	0	0	-1	0	-1	0.113
25	+1	+1	0	+1	0	0	0	0.094
26	+1	+1	0	-1	0	0	0	0.092
27	+1	-1	0	+1	0	0	0	0.117
28	+1	-1	0	-1	0	0	0	0.118
29	-1	+1	0	+1	0	0	0	0.090
30	-1	+1	0	-1	0	0	0	0.092
31	-1	-1	0	+1	0	0	0	0.117
32	-1	-1	0	-1	0	0	0	0.118
33	0	0	+1	+1	0	0	+1	0.102
34	0	0	+1	+1	0	0	-1	0.102
35	0	0	+1	-1	0	0	+1	0.103
36	0	0	+1	-1	0	0	-1	0.103
37	0	0	-1	+1	0	0	+1	0.110
38	0	0	-1	+1	0	0	-1	0.110
39	0	0	-1	-1	0	0	+1	0.111
40	0	0	-1	-1	0	0	-1	0.111
41	+1	0	+1	0	+1	0	0	0.100
42	+1	0	+1	0	-1	0	0	0.098
43	+1	0	-1	0	+1	0	0	0.097
44	+1	0	-1	0	-1	0	0	0.095
45	-1	0	+1	0	+1	0	0	0.100
46	-1	0	+1	0	-1	0	0	0.098
47	-1	0	-1	0	+1	0	0	0.098
48	-1	0	-1	0	-1	0	0	0.095
49	0	+1	+1	0	0	+1	0	0.085
50	0	+1	+1	0	0	-1	0	0.100
51	0	+1	-1	0	0	+1	0	0.094
52	0	+1	-1	0	0	-1	0	0.112
53	0	-1	+1	0	0	+1	0	0.124
54	0	-1	+1	0	0	-1	0	0.108
55	0	-1	-1	0	0	+1	0	0.118
56	0	-1	-1	0	0	-1	0	0.104
57	0	0	0	0	0	0	0	0.091
58	0	0	0	0	0	0	0	0.095
59	0	0	0	0	0	0	0	0.100
60	0	0	0	0	0	0	0	0.104

Appendix 2 Optimal Normal Vectors of the Two Panels

Patch No.	Part 1			Part 2		
	X-dir	Y-dir	Z-dir	X-dir	Y-dir	Z-dir
P1	-0.0112	0.0056	0.9999	-0.0316	0.0320	-0.9990
P2	0.0360	0.0233	0.9991	0.0197	0.0080	0.9997
P3	0.0682	0.0195	0.9975	0.0021	0.0380	0.9993
P4	-0.0123	-0.0070	-0.9999	0.0002	0.0579	0.9983
P5	0.0298	-0.0070	-0.9996	-0.0022	0.0738	0.9972
P6	0.0208	-0.0157	-0.9997	0.0106	0.0817	0.9966
P7	0.0074	-0.0180	-0.9998	0.0152	0.0758	0.9970
P8	0.0180	0.0154	0.9997	-0.0001	0.0539	0.9985
P9	0.0410	0.0122	0.9991	0.0170	-0.0460	-0.9988
P10	0.0306	0.0090	0.9995	-0.0043	0.0539	0.9985
P11	-0.0094	-0.0066	-0.9999	0.0106	0.0499	0.9987
P12	0.0333	-0.0050	-0.9994	0.0143	-0.0280	-0.9995
P13	0.1032	0.0022	-0.9947	0.0699	-0.0040	-0.9976
P14	0.0650	0.0178	-0.9977	0.0439	0.0220	-0.9988
P15	0.0032	-0.0280	0.9996	-0.0060	0.0419	-0.9991
P16	0.0404	-0.0191	0.9998	0.0279	-0.0519	0.9983
P17	0.0432	-0.0012	0.9990	-0.0125	0.0539	-0.9985
P18	0.0178	0.0158	0.9997	0.0080	0.0460	-0.9989
P19	0.0345	-0.0280	-0.9990	0.0349	0.0320	-0.9989
P20	0.0543	-0.0316	-0.9980	0.0340	0.0220	-0.9992
P21	0.0200	-0.0255	-0.9995	0.0080	-0.0160	0.9999
P22	0.0250	0.0320	0.9991	0.0574	-0.0100	0.9983
P23	0.0411	0.0467	0.9981	0.0120	-0.0040	0.9999
P24	0.0618	0.0523	0.9967	0.0325	0.0040	-0.9995
P25	0.0048	-0.0028	-0.9999	0.0020	-0.0001	0.9999
P26	0.0796	-0.0506	-0.9956	0.0559	0.0040	0.9984
P27	0.0383	-0.0559	-0.9977	0.0100	0.0180	0.9998
p28	0.0319	0.0293	0.9991	0.0549	-0.0120	-0.9984

Appendix 3 Experimental Runs and Response Values for Case Study

No	X1	X2	X3	X4	X5	X6	X7	Response(mm)
1	0	0	0	+1	+1	+1	0	0.125
2	0	0	0	+1	+1	-1	0	0.122
3	0	0	0	+1	-1	+1	0	0.128
4	0	0	0	+1	-1	-1	0	0.124
5	0	0	0	-1	+1	+1	0	0.123
6	0	0	0	-1	+1	-1	0	0.122
7	0	0	0	-1	-1	+1	0	0.126
8	0	0	0	-1	-1	-1	0	0.123
9	+1	0	0	0	0	+1	+1	0.128
10	+1	0	0	0	0	+1	-1	0.126
11	+1	0	0	0	0	-1	+1	0.125
12	+1	0	0	0	0	-1	-1	0.125
13	-1	0	0	0	0	+1	+1	0.129
14	-1	0	0	0	0	+1	-1	0.125
15	-1	0	0	0	0	-1	+1	0.127
16	-1	0	0	0	0	-1	-1	0.122
17	0	+1	0	0	+1	0	+1	0.126
18	0	+1	0	0	+1	0	-1	0.122
19	0	+1	0	0	-1	0	+1	0.129
20	0	+1	0	0	-1	0	-1	0.123
21	0	-1	0	0	+1	0	+1	0.126
22	0	-1	0	0	+1	0	-1	0.122
23	0	-1	0	0	-1	0	+1	0.128
24	0	-1	0	0	-1	0	-1	0.123
25	+1	+1	0	+1	0	0	0	0.123
26	+1	+1	0	-1	0	0	0	0.122
27	+1	-1	0	+1	0	0	0	0.123
28	+1	-1	0	-1	0	0	0	0.122
29	-1	+1	0	+1	0	0	0	0.125
30	-1	+1	0	-1	0	0	0	0.124
31	-1	-1	0	+1	0	0	0	0.125
32	-1	-1	0	-1	0	0	0	0.124
33	0	0	+1	+1	0	0	+1	0.127
34	0	0	+1	+1	0	0	-1	0.123
35	0	0	+1	-1	0	0	+1	0.119
36	0	0	+1	-1	0	0	-1	0.120
37	0	0	-1	+1	0	0	+1	0.127
38	0	0	-1	+1	0	0	-1	0.122
39	0	0	-1	-1	0	0	+1	0.127
40	0	0	-1	-1	0	0	-1	0.120
41	+1	0	+1	0	+1	0	0	0.124
42	+1	0	+1	0	-1	0	0	0.126
43	+1	0	-1	0	+1	0	0	0.123
44	+1	0	-1	0	-1	0	0	0.125
45	-1	0	+1	0	+1	0	0	0.125
46	-1	0	+1	0	-1	0	0	0.128
47	-1	0	-1	0	+1	0	0	0.125
48	-1	0	-1	0	-1	0	0	0.127
49	0	+1	+1	0	0	+1	0	0.127
50	0	+1	+1	0	0	-1	0	0.124
51	0	+1	-1	0	0	+1	0	0.126
52	0	+1	-1	0	0	-1	0	0.123
53	0	-1	+1	0	0	+1	0	0.126
54	0	-1	+1	0	0	-1	0	0.123
55	0	-1	-1	0	0	+1	0	0.126
56	0	-1	-1	0	0	-1	0	0.123
57	0	0	0	0	0	0	0	0.125
58	0	0	0	0	0	0	0	0.125
59	0	0	0	0	0	0	0	0.127
60	0	0	0	0	0	0	0	0.126

Appendix 4 Some Interface Programs for Optimization

A4.1 Initial population generation

```
#include "stdio.h"
#include "stdlib.h"
#include "math.h"
#include "string.h"
#define DLS 7
#define D_data_number 193
#define PO 30

int ddn[PO+1][DLS+1] , p1DLAid[194], p2DLAid[194];
double DLTDLAp1[194][3], DLTDLAp2[194][3];

void init_pop()
{
 FILE *fp,*fp1;
 int i,j,k;

 if((fp=fopen("Pop_data.dat","w+"))==NULL)
          {printf("cannot open file\n");exit(1);}
 if((fp1=fopen("interpop.dat","w+"))==NULL)
          {printf("cannot open file\n");exit(1);}

 randomize();

 ddn[1][1]=13;
 ddn[1][2]=34;
 ddn[1][3]=48;
 ddn[1][4]=82;
 ddn[1][5]=122;
 ddn[1][6]=137;
 ddn[1][7]=153;

 for (i=2;i<=PO;i++) {
    for (j=1;j<=DLS;j++) {
       ddn[i][j]=random(D_data_number)+1;
L10:   if(j>1){
          for (k=1;k<=j-1;k++)
             if(fabs((double)(ddn[i][j]-ddn[i][k]))<5.0)
             {ddn[i][j]=random(D_data_number-2)+1; goto L10;}
             }
                   }
             }
```

```
 for (i=1;i<=PO;i++) {
     for (j=1;j<=DLS;j++) {
         fprintf(fp1,"%-6d\n",ddn[i][j]);
                         }
                     }
 fclose(fp1);

 for (i=1;i<=PO;i++){
    for (j=1;j<=DLS;j++){
       fprintf(fp,"%-6d",ddn[i][j]);
       if(j==DLS) fprintf(fp,"\n");
                         }
                   }
 fclose(fp);
}
```

A4.2 Updating data file for FEA

```
void format_nas()
{
 FILE *fp1,*fp2;
 int i,j;

   if((fp2=fopen("subloadc.dat","w+"))==NULL)
     {printf("cannot open file\n");exit(1);}
   if((fp1=fopen("subcases.dat","w+"))==NULL)
     {printf("cannot open file\n");exit(1);}

for(i=1;i<=PO;i++){
   fprintf(fp1,"SUBCASE %d\n",i);
   if(i==1)
   {
    fprintf(fp1,"  ECHO = NONE\n");}
    fprintf(fp1,"  TITLE = sub%d\n",i);
    fprintf(fp1,"  DISPLACEMENT = ALL\n");
    fprintf(fp1,"  SPC  = %d\n",i);
    fprintf(fp1,"  LOAD = %d\n",i);
  }
 fclose(fp1);

 for(i=1;i<=PO;i++){
   fprintf(fp2,"$ MSC/NASTRAN for Windows Load Set %d : NASTRAN %d\n",i,i);
   for(j=1;j<=DLS;j++){
    fprintf(fp2,"SPCD%12d%8d       1%8.4f\n",i,p1DLAid[ddn[i][j]],
         DLTDLAp1[ddn[i][j]][0]);
```

```
    fprintf(fp2,"SPCD%12d%8d      2%8.4f\n",i,p1DLAid[ddn[i][j]],
        DLTDLAp1[ddn[i][j]][1]);
    fprintf(fp2,"SPCD%12d%8d      3%8.4f\n",i,p1DLAid[ddn[i][j]],
        DLTDLAp1[ddn[i][j]][2]);
    fprintf(fp2,"SPCD%12d%8d      1%8.4f\n",i,p2DLAid[ddn[i][j]],
        DLTDLAp2[ddn[i][j]][0]);
    fprintf(fp2,"SPCD%12d%8d      2%8.4f\n",i,p2DLAid[ddn[i][j]],
        DLTDLAp2[ddn[i][j]][1]);
    fprintf(fp2,"SPCD%12d%8d      3%8.4f\n",i,p2DLAid[ddn[i][j]],
        DLTDLAp2[ddn[i][j]][2]);
            }
        }

 for(i=1;i<=PO;i++){
 fprintf(fp2,"$ MSC/NASTRAN for Windows Constraint Set %d:  SPC %d\n",i,i);
 fprintf(fp2,"SPC%13d   1100      1     0.\n",i);
 fprintf(fp2,"SPC%13d   1257     12     0.\n",i);
 fprintf(fp2,"SPC%13d   2422     12     0.\n",i);
 fprintf(fp2,"SPC%13d   2655      1     0.\n",i);

 for(j=1;j<=DLS;j++){
 fprintf(fp2,"SPC%13d%8d     123      0.\n",i,p1DLAid[ddn[i][j]]);
 fprintf(fp2,"SPC%13d%8d     123      0.\n",i,p2DLAid[ddn[i][j]]);
                        }
                      }
 fclose(fp2);
}
```

A4.3 Evaluation of performance characteristic

```
 #include "string.h"
 #define PO  30
 #define SUBCASE 30
 #define NODES 32
 #define N_LINE NODES*SUBCASE*10+NODES
 #define M_BITE 57
 #define N_DATA (N_LINE-NODES)/10
 #define DLS  7
 #define D_data_number 193
 #define RM  9
 #define STA_CROSS 95
 #define STA_MUTU  2

int      p1WLDid[17],p2WLDid[17],p1DLAid[194],p2DLAid[194];
double  p1WLDcood[17][3], p2WLDcood[17][3], DLTDLAp1[194][3],
        DLTDLAp2[194][3],  fitness[SUBCASE+1][NODES/2+1],
        dis_x1[SUBCASE+1][NODES/2+1],
        Data_Matrix_x1[SUBCASE+1][NODES/2+1],
```

```
        dis_y1[SUBCASE+1][NODES/2+1],
        Data_Matrix_y1[SUBCASE+1][NODES/2+1],
        dis_z1[SUBCASE+1][NODES/2+1],

       Data_Matrix_z1[SUBCASE+1][NODES/2+1],
       dis_x2[SUBCASE+1][NODES/2+1],
       Data_Matrix_x2[SUBCASE+1][NODES/2+1],
       dis_y2[SUBCASE+1][NODES/2+1],
       Data_Matrix_y2[SUBCASE+1][NODES/2+1],
       dis_z2[SUBCASE+1][NODES/2+1],
       Data_Matrix_z2[SUBCASE+1][NODES/2+1], Extr_x[N_DATA+1]={0},
       Extr_y[N_DATA+1]={0},Extr_z[N_DATA+1]={0};

void fitness()

{
 FILE *fp1,*fp2,*fp3,*fp4,*fp;
 long i,k,j,p;
 char *Data_LINE={""},*LINE={""};
 if((fp=fopen("Pop_data.dat","r"))==NULL)
   {printf("cannot open file\n");exit(1);}
 if((fp3=fopen("out01.lst","r"))==NULL)
   {printf("cannot open file\n");exit(1);}
 if((fp2=fopen("out01.lst","r"))==NULL)
   {printf("cannot open file\n");exit(1);}
 if((fp1=fopen("out01.lst","r"))==NULL)
   {printf("cannot open file\n");exit(1);}

 j=0,k=0,p=0;

 for(i=0;i<N_LINE;i++) {
      fgets(LINE,256,fp1);
      k=k+1;
      if(strcmp(LINE,"\n")==0) {k=0;p=p+1;}
      if(k==SUBCASE*10+1) {k=0;p=p+1;}
      if(k==(4+10*j-(p-1)*SUBCASE*10)) {
            j=j+1;
            strcpy(Data_LINE,(LINE+M_BITE));
            Extr_x[j]=(double)atof(Data_LINE);
                                              }
                              }
  fclose(fp1);
  j=0,k=0,p=0;
  for(i=0;i<N_LINE;i++) {
      fgets(LINE,256,fp2);
      k=k+1;
    if(strcmp(LINE,"\n")==0) {k=0;p=p+1;}
    if(k==SUBCASE*10+1) {k=0;p=p+1;}
    if(k==(5+10*j-(p-1)*SUBCASE*10)) {
          j=j+1;
```

```
        strcpy(Data_LINE,(LINE+M_BITE));
        Extr_y[j]=(double)atof(Data_LINE);
                                    }
                        }
 fclose(fp2);
 j=0,k=0,p=0;

for(i=0;i<N_LINE;i++)  {
    fgets(LINE,256,fp3);
    k=k+1;
   if(strcmp(LINE,"\n")==0) {k=0;p=p+1;}
   if(k==SUBCASE*10+1) {k=0;p=p+1;}
   if(k==(6+10*j-(p-1)*SUBCASE*10)) {
        j=j+1;
        strcpy(Data_LINE,(LINE+M_BITE));
        Extr_z[j]=(double)atof(Data_LINE);
                                    }
                        }
 fclose(fp3);

 for(i=1;i<=NODES;i++){
  for(j=1;j<=SUBCASE;j++){
        if (i<=NODES/2)  {
           Data_Matrix_x1[j][i]=Extr_x[j+(i-1)*SUBCASE];
           Data_Matrix_y1[j][i]=Extr_y[j+(i-1)*SUBCASE];
           Data_Matrix_z1[j][i]=Extr_z[j+(i-1)*SUBCASE];
                          }
     else{
           Data_Matrix_x2[j][i-NODES/2]=Extr_x[j+(i-1)*SUBCASE];
           Data_Matrix_y2[j][i-NODES/2]=Extr_y[j+(i-1)*SUBCASE];
           Data_Matrix_z2[j][i-NODES/2]=Extr_z[j+(i-1)*SUBCASE];
         }
                          }
                        }

 for(i=1;i<=SUBCASE;i++){
     for(j=1;j<=NODES/2;j++){
              dis_x1[i][j]=Data_Matrix_x1[i][j]+p1WLDcood[j][0];
              dis_y1[i][j]=Data_Matrix_y1[i][j]+p1WLDcood[j][1];
              dis_z1[i][j]=Data_Matrix_z1[i][j]+p1WLDcood[j][2];
              dis_x2[i][j]=Data_Matrix_x2[i][j]+p2WLDcood[j][0];
              dis_y2[i][j]=Data_Matrix_y2[i][j]+p2WLDcood[j][1];
              dis_z2[i][j]=Data_Matrix_z2[i][j]+p2WLDcood[j][2];
                                  }
                         }

 for(i=1;i<=SUBCASE;i++){
       for(j=1;j<=NODES/2;j++){
       fitness[i][j]=sqrt(pow(dis_x2[i][j]-dis_x1[i][j],2.0) +pow(dis_y2[i][j]-
                    dis_y1[i][j],2.0)+pow(dis_z2[i][j]-dis_z1[i][j],2.0));
```

```
        if((dis_x2[i][j]-dis_x1[i][j])<=1e-8) fitness[i][j]=0;
                                    }
                                }
```

A4.4 Genetic algorithm

```
Void G_A(double fitness[][SUBCASE/2+1])
{
 FILE *fp1;
 int     mmd,ccc[DLS],med,Popu[PO][DLS],Popu_new[PO+1][DLS+1], aaa,aaaa;
 double coef_Popu[PO][DLS];
 char    *LINE={""};
 long    i,k,j,p;
 double arfa ,Max_each_fittt[SUBCASE+1],Max_each_fit[PO],mid,comp,mediat;

 for(i=1;i<=SUBCASE;i++){
     Max_each_fittt[i]=fitness[i][1];
 for(j=2;j<=NODES/2;j++) {
     if (fitness[i][j]>Max_each_fittt[i]) Max_each_fittt[i]=fitness[i][j];
                                }
                                }
 for(i=0;i<SUBCASE;i++)
 Max_each_fit[i]=Max_each_fittt[i+1];
     for(i=0;i<PO;i++)
        {num[i]=i;}
     for(i=0;i<PO-1;i++)  {
        for(j=0;j<PO-1-i;j++) {
          if(Max_each_fit[j]>Max_each_fit[j+1])
           {
           mid=Max_each_fit[j+1];
           med=num[j+1];
           Max_each_fit[j+1]=Max_each_fit[j];
           num[j+1]=num[j];
           Max_each_fit[j]=mid;
           num[j]=med;
           }
                                  }
                             }

 bbb=num[0];
    for(i=0;i<=num[0];i++)
       {fgets(LINE,256,fp);}
 output(Max_each_fit,LINE);
 printf("selection for convergence check(1-yes,0-no):\n");
 scanf("%d",&aaa);
    if(aaa==1){
    if((fp4=fopen("interout.dat","r"))==NULL)
```

```
 {printf("cannot open file\n");exit(1);}
  fgets(LINE,256,fp4);
  comp=(double)atof(LINE);
  fclose(fp4);
  mediat=fabs(comp-Max_each_fit[0]);

  if(mediat<=1e-8)
  {printf("Objective function has converged!\n");
   printf("The End? (1-yes, 0-no)\n");
   scanf("%d",&aaaa);
   if(aaaa==1) exit(1);
   if(aaaa==0) goto L100;
  }
 else {printf("Go ahead for next generation!\n");}
                }
L100: inter_output(Max_each_fit);
 fclose(fp);
 if ((fp1=fopen("interpop.dat","r"))==NULL)
   {printf("cannot open file\n");exit(1);}

 for(i=0;i<PO;i++)  {
     for(j=0;j<DLS;j++) {
       fgets(LINE,256,fp1);
       Popu[i][j]=atoi(LINE);
                             }
                       }
 for(i=0;i<DLS;i++)
     {ccc[i]=Popu[bbb][i];}
 fclose(fp1);

 randomize();

 for(k=0;k<RM;k++)
     for(i=0;i<DLS;i++)
     Popu[num[PO-k-1]][i]=Popu[num[k]][i];

 for(i=0;i<PO;i++) {
    for(j=0;j<DLS;j++) {
        coef_Popu[i][j]=(double)Popu[i][j]/(double)(D_data_number);
                             }
                       }
 for(i=0;i<PO;i=i+2) {
    med=random(PO-1-i)+1;
    mmd=num[i+1];
    num[i+1]=num[med];
    num[med]=mmd;

 if(random(100)<STA_CROSS) {

    for(j=0;j<DLS;j++){
```

```
            arfa=random(10000)*0.0001;

            coef_Popu[num[i+1]][j]=(1.0-arfa)*coef_Popu[num[i+1]][j]
                                   +arfa*coef_Popu[num[i]][j];
            coef_Popu[num[i]][j]=(1.0-arfa)*coef_Popu[num[i]][j]
                                   +arfa*coef_Popu[num[i+1]][j];

            if( coef_Popu[num[i]][j]<0.0) coef_Popu[num[i]][j]=0.0;
            if( coef_Popu[num[i]][j]>1.0) coef_Popu[num[i]][j]=1.0;
            if( coef_Popu[num[i+1]][j]<0.0) coef_Popu[num[i+1]][j]=0.0;
            if( coef_Popu[num[i+1]][j]>1.0) coef_Popu[num[i+1]][j]=1.0;
            }
            }
            }
    for(i=0;i<PO;i++){
        for(j=0;j<(DLS);j++) {

           if(random(100)<STA_MUTU){

       med=random(2);
        if(med){
                coef_Popu[i][j]=coef_Popu[i][j]+random(10000)*0.00001*
                                (1-coef_Popu[i][j])*0.4;
               }
        else{
                coef_Popu[i][j]=coef_Popu[i][j]-random(10000)*0.00001*
                                (coef_Popu[i][j]-0.0)*0.4;
           }
                          }
                  }
       }

    for (i=0;i<PO;i++)  {
    for (j=0;j<DLS;j++)    {
      Popu[i][j]=(int)(coef_Popu[i][j]*(D_data_number));
                          }
                       }
    for (i=0;i<PO;i++)  {
    for (j=0;j<DLS;j++)  {
        if (Popu[i][j]<=0) Popu[i][j]=1;
        else     {if(Popu[i][j]>D_data_number) Popu[i][j]=D_data_number;
                  if(Popu[i][j]<1) Popu[i][j]=1; }
                        }
                     }

    for (i=0;i<PO;i++) {
    for (j=0;j<DLS;j++)
     {
L1000:  if(j>0)
```

```
        {
           for(k=0;k<=j-1;k++) {
           if(fabs((double)(Popu[i][j]-Popu[i][k]))<5.0)
        {
           Popu[i][j]=random(D_data_number-2)+1;
           goto L1000;
        }
        }
         }
      }
   }

    for(i=0;i<DLS;i++)
        Popu[0][i]=ccc[i];

    for(i=1;i<=PO;i++){
     for(j=1;j<=DLS;j++){
       Popu_new[i][j]=Popu[i-1][j-1];
                               }
                           }
    reform_pop(Popu_new);
    format_nas(Popu_new);
}
```