DIMENSIONAL VARIATION ANALYSIS AND OPTIMAL PROCESS DESIGN FOR NON-RIGID SHEET METAL ASSEMBLIES

BY

XIAOYUN LIAO

A Thesis
Submitted to the Faculty of Graduate Studies
In Partial Fulfillment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY

Department of Mechanical and Manufacturing Engineering
The University of Manitoba
Winnipeg, Manitoba
Canada

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

*****

COPYRIGHT PERMISSION

DIMENSIONAL VARIATION ANALYSIS AND OPTIMAL

PROCESS DESIGN FOR NON-RIGID

SHEET METAL ASSEMBLIES

BY

XIAOYUN LIAO

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of

Manitoba in partial fulfillment of the requirement of the degree

OF

DOCTOR OF PHILOSPOHY

Abstract

Non-rigid sheet metal assembly is widely used in manufacturing industries, such as aerospace and automotive industries. Improving product quality and reducing the cost are main concerned issues for a manufacturing company to achieve higher product competitiveness in current global market. The dimensional quality of a non-rigid sheet metal assembly is a crucial and yet challenging quality indicator due to the non-rigidity of the sheet metal components. Although the product dimensional variation analysis and process design for rigid assembly have been studied for many years, such study for non-rigid assemblies is emerging, and also challenging. There remain many unrecognized and/or unsolved issues in the study of non-rigid assemblies. This thesis presents a number of new, systematical, and generally applicable methods for analyzing and minimizing the non-rigid sheet metal assembly variations.

Firstly, a novel fractal-based method for sheet metal assembly variation analysis is developed to deal with the fractal variations of parts (i.e., component of an assembly). The surface microstructure of part variation is modeled by fractal geometry and its influence on the final assembly variation is studied by modeling the sheet metal assembly process.

Next, a new methodology based on wavelet transform is proposed for analyzing the contribution of variation components with various scales to the final assembly dimensional variation, considering possible sources of variation from both parts and the assembly process. It is more general and advantageous than the approach based on the fractal geometry. The integrated procedure of wavelet transform and Finite Element Method (FEM) for non-rigid assembly variation analysis is developed and implemented. Its effectiveness is demonstrated via an application example.

Thirdly, a simultaneous optimization method for fixture layout and joint positions is developed. The optimization variables from both the product design (assembly joint positions) and the production plan (the fixture layout) are included in the mathematical model. The mode-pursuing sampling method (MPS) is modified and employed to search for the global optimal solution.

Finally, the elastic contact phenomenon in the sheet metal assembly process is studied. A non-linear assembly dimensional variation analysis method is developed by establishing the elastic contact model between the assembly surfaces. The assembly dimensional variation analysis with and without contact modeling is respectively conducted. The corresponding physical experiments are also carried out and used to validate the contact FEM models.

The work enables us to gain more in-depth understanding on the characteristics of the non-rigid sheet metal assembly dimensional variation. It provides not only the fundamental analysis and modeling methodologies, but also the corresponding software tools that can be easily integrated with most current general-purpose commercial FEA packages (such as ANSYS and CATIA). The developed approaches, technologies and tools presented in this thesis can benefit both the academic research and industrial applications on the design and manufacturing of non-rigid sheet metal assemblies.

Acknowledgement

I would like to express my deepest thanks to my advisor, Prof. Gary Wang, for giving me so much freedom to explore and investigate the new areas in non-rigid assemblies and providing valuable guidance, encouragement, and insightful feedback during all stages of my research, journal paper preparation, and thesis writing.

My sincere gratitude goes to my advisory committee members, Profs. R. Jayaraman, N. Rattanawangcharoen, and T. ElMekkawy, for their careful review, comments, and suggestions to my thesis research. I would like to thank Prof. Qingjin Peng for providing the test facilities, and Mr. Paul Krueger for his help in preparing the test workpieces. Thanks also to Prof. D. Xue, the external examiner of the thesis examination committee.

I would like to appreciate Prof. A. Parkinson (Brigham Young University, Utah, USA), Prof. D. Ceglarek (University of Wisconsin at Madison, USA), Mr. D. Baulier (Aliant Machine Ltd., Windsor, Ont.), and Mr. A. Pardasani (IMTI, NRC, London, Ont.) for their help and suggestions at the early stage of my research. I also would like to thank all my friends and colleagues for their support and discussions about the research topics in this thesis.

In addition, I would give my grateful acknowledgement to financial support from the Natural Science and Engineering Research Council of Canada (NSERC) and the University of Manitoba's Graduate Fellowship (UMGF).

Finally, I would like to thank my wife, daughter and parents for their support, love and encouragement.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Motivation of Research

Non-rigid sheet metal parts are often used in aircraft, automobiles, furniture, and home appliances (Hu and Wu 1992, Ceglarek and Shi 1995). For example, an auto body is often composed of hundreds of non-rigid sheet metal panels. These parts are large but relatively thin; they tend deform and comply with the forces experienced during the assembly process, mainly from clamping and joining. The final assembly's dimensional variation control has been recognized as an important factor in product quality assurance (Ceglarek and Shi 1995, Chang and Gossard 1997).

Unsatisfactory dimensional variations of the final product always decrease product performance and increase warrant costs, and cause many problems such as rework, as well as quality rejects and resulting engineering changes (Ceglarek and Shi 1995). For instance, a large vehicle door's variation may lead to the poor sealing, high closing effort, water leaks, excessive wind noise, and so on. It is thus an important and interesting task to predict the effects of part and tooling variations on the final product quality during the early design stage (Camelio *et al.* 2001).

A typical non-rigid sheet metal assembly process is composed of many steps to join two parts, while a product is built through a lot of common assembly operations. During the assembly process, the product variation is influenced by many kinds of variation sources, such as part flexibility, fixture location variation, assembly tools variation, and the propagation of such variations in assembly steps (Hu 1997, Hsieh and Oh 1997). These variation sources can vary and interact with each other, resulting in complex analysis problems.

Methods for analyzing assembly variation have been the subject of considerable amount of research. The primary approaches that have been widely adopted include: the worst case analysis, root sum squares or statistical analysis, and Monte Carlo simulation methods (Greenwood and Chase 1988, Chase and Parkinson 1991, Lee and Woo 1990). However, these methods are not directly applicable to non-rigid assemblies because all of them rely on the assumption that all the parts in assembly are rigid. As discussed by Taezawa (1980), the dimensional variation does not simply "stack up" as predicted by these methods because parts deform in non-rigid assemblies. The dimensional variation analysis and control for non-rigid assemblies are apparently more difficult than that of rigid assemblies.

The variation analysis for non-rigid assemblies is an emerging and challenging area (Hu *et al.* 2003). There are in the literature a number of modeling and analysis approaches for non-rigid assemblies to simulate the assembly processes and to analyze the assembly variation in the past a few years (Hu 1997, Hsieh and Oh 1997, Bihlmaier 1999, Huang and Ceglarek 2002, Camelio *et al.* 2002b, Ceglarek *et al.* 2004, Dahlstrom and Lindkvist 2004). Unfortunately, little investigation has been done for sheet metal assembly to address the detail structure of part variation and its impact on final assembly quality, nonlinear behavior of variation propagation, optimization of fixture layout and joint (welding) positions, and so on.

The aim of this thesis is to develop new, systematical, and generally applicable methods for: identifying and modeling the detailed assembly variations, analyzing the nonlinear behavior of variation propagation, establishing the simulation methods for the variation distribution of non-rigid assemblies, and optimizing fixture layout and joint/welding positions.

1.2 Literature Survey

It is well known that many factors influencing the final dimensional quality are coupled together during the non-rigid sheet metal assembly process. These coupled factors make it a complex and difficult task of modeling and analyzing sheet metal assembly quality. According to the report from Dahlstrom *et al.* (2002), the main variables are divided into three main groups: the design concepts, variation, and process layout.

The design concept group includes parameters that control the sensitivity of the concept to variations, such as geometry of parts, joint type, stiffness, and number of parts.

The variation group consists of two sources: part and process variation. Part variation includes variations that occur in the sheet metal parts during its manufacturing. Process variation is defined as all variations introduced during the assembly process such as fixturing and welding variations.

The process layout controls how variations are introduced to the assembly, including variables such as welding configuration, assembly sequence, fixture design, and clamping layout.

To date, many methods are proposed to study the variation and its propagation during the assembly process, which are reviewed in the following subsections.

1.2.1 Dimensional Variation Modeling

Because rigid parts have negligible deformation during assembly, the parts and tooling variation can be represented by kinematics relationships: translations and rotations. While non-rigid parts will possibly deform during the assembly process, the variation models should include a force analysis, considering the stiffness of each part and forces exerted from each tool.

Since Takezawa (1980) observed that for non-rigid sheet metal assemblies the traditional addition theorem of variation for rigid part assemblies was no longer valid, several models have been proposed to represent the variation propagation on assembly processes and the relationship among part dimensions and product characteristics. The models for non-rigid assemblies can be divided into two different groups, depending on whether the models are for single station or multi-station analysis. Single station level models treat the assembly process as if it is conducted in one step. In contrast, multi-station models analyze the process recursively as the assembly is moved from one station to the next.

With a single station model, Liu *et al.* (1996) and Liu and Hu (1997b) proposed a model to analyze the effect of deformation and spring-back on assembly variation by applying linear mechanics and statistics. Using finite element methods (FEM), they constructed a sensitivity matrix for compliant parts of complex shapes. The sensitivity matrix establishes the linear relationship between the incoming part variation and the output assembly variation. Long and Hu (1998) extended this model to a unified model for variation simulation considering part variation and fixture variation.

Shui *et al.* (1997) presented a simplified flexible beam representation of auto body structures. The model was applied for dimensional control of assembly process with non-rigid parts for automotive body. They also used this kind of model to optimize tolerance allocation of sheet metal assembly (Shui *et al.* 2003). Ceglarek and Shi (1997) also proposed a variation analysis methodology for the sheet metal assembly based on physical / functional modeling of the fabricated error using a beam-based model. Hu *et al.* (2001) developed a numerical simulation method for the assembly process incorporating compliant non-ideal components. The effects of various variation sources were analyzed.

In addition, Hsieh and Oh (1997) represented a procedure for simulating the combined effects of deformation and dimensional variation in the elastic assembly. Sellem and Riviere (1998) developed a methodology based on influence matrices taking into account three different kinds of variation in the simulation: position, conformity, and shape variability.

Bihlmaier (1999) and Stout (2000) applied spectral analysis and geometric covariance in compliant assembly tolerance analysis, respectively. Camelio and Hu (2002b) presented a method for predicting the variation in compliant assembly by using the covariance matrix of the components. The method replaces the sensitivity matrix with the variation vectors defined for each deformation mode identified from the covariance of the components, thus reducing the number of FEM computations. Huang and Ceglarek (2003) applied the discrete-cosine-transform to analyze the modes of sheet metal part form error.

All of the above methods ignored the contact phenomenon in the sheet metal assembly process. Currently, there are only few reports on the contact behavior in sheet metal assemblies. Dahlstrom *et al.* (2002) indicted that the contact between curved flanges would affect the quality of sheet metal assembly, but they did not further study this issue. Lian *et al.* (2002) investigated the effect of elastic contact on variation transformation by a simple beam structure assembly.

Mattikalli *et al.* (2000) described an approach that involved a model of contact between compliant bodies based on variational inequalities to model the mechanics of assembly. By solving a quadratic programming (QP) problem, the contact situation can be resolved and the mechanics of parts during assembly can be obtained. The assembly variation, however, was not addressed.

Recently, Dahlstrom and Lindkvist (2004) studied the contact modeling in the method of influence coefficient (MIC) for variation simulation of sheet metal assemblies. They described the steps in the contact algorithms and how it was used in MIC.

With a multi-station model, Liu and Hu (1995b) developed a model to evaluate the spot weld sequence in sheet metal assembly. This model considered a process where welding was carried out in multistage. Chang and Gossard (1997) presented a graphic approach for multi-station assembly for non-rigid parts. Hu (1997) set up the "stream of variation" theory for the automotive body assembly variation analysis.

Ceglarek *et al.* (2004) made a detailed review on the "stream of variation" theory in terms of the state space model, characterizing variation propagation in the multistage assembly. Camelio *et al.* (2001) developed a methodology to evaluate the dimensional variation propagation in a multi-station non-rigid assembly system based on linear mechanics and a state space representation. Three sources of variation were analyzed, including part variation, fixture variation, and welding gun variation.

Current methods, either at the single station level or the multi-station level, did not address the detailed microstructure of component variations and its propagation in the assembly process. Little is known about how the detailed microstructure of component variations affects the assembly dimensional quality.

In the meanwhile, the existing studies on the contact problem of the sheet metal assembly are fairly limited. The currently available methods in literature are difficult to utilize in engineering practice, and never validated by physical experiments. The contact modeling method of non-rigid sheet metal assembly towards dimensional variation analysis is still under development.

Those issues regarding the detailed variation microstructure and the contact modeling are very challenging when the high-precision analysis process for the non-rigid sheet metal product design and manufacturing is required. The corresponding applicable modeling and analysis methods regarding the influence of the detailed variation microstructure and/or the assembly surface contact on the final product quality are required for further investigation and validation.

1.2.2 Fixture Layout Design

Fixtures are used to locate and hold work pieces in a manufacturing process. In general, fixture elements can be classified by functionality into locators and clamps. Locators establish the datum reference frame. Clamps provide additional restraint by holding the part in position under the application of external forces.

In general, a 3-2-1 locating scheme is used to uniquely locate rigid bodies (Lee and Haynes 1987). The 3-2-1 scheme constraints the six degrees of freedom of parts. According to this principle three locators are placed in primary plane, two in the secondary plane and one in the tertiary plane. However, Cai and Hu (1996a) and Cai *et al.* (1996b) showed that an N-2-1 principle, i.e., N (more than 3) locators in the primary plane, was to be applied to locate and support non-rigid sheet metal parts because of part flexibility. Fixture design is very important for assembly process (Hu *et al.* 2003). One of the primary concerns of fixture design is determining the layout of the fixture elements such that the spring-back deformation of assemblies after releasing some fixture tools is minimized.

Fixture layout optimization design has been widely studied for machining process of rigid/non-rigid parts (Lee and Haynes 1987, Menassa and DeVries 1991, Kashyap and DeVries 1999). The studies on fixture layout for non-rigid sheet metal assemblies have also gained some successes. Currently, the nonlinear programming methods and genetic algorithms are the two often applied optimization methods.

Rearick *et al.* (1993) proposed an optimization algorithm to obtain the optimal number and location of clamps that minimize the deformation of compliant parts. Cai *et al.* (1996b) proposed the N-2-1 fixture principle for compliant sheet metal assembly. They also presented an optimization algorithm to find the optimal location for N fixtures that minimized work piece deflection under a given force. The work piece deformation was calculated by using FEA. Li *et al.* (2002) and Li *et al.* (2003) investigated the fixture configuration design problem, focusing on the sheet metal laser welding process.

Dahlstrom and Camelio (2003) proposed a general method to predict the effect of fixture design in compliant assembly. It focused on the impact of fixture layout, as well as locator and clamp positions on the dimensional quality of sheet metal assemblies. FEA and design of computer experiments are used to derive the response models. The response models are used to analyze the final assembly sensitivity to fixture, part, and tooling variation for different assembly configurations.

Camelio *et al.* (2002a) presented a new fixture design method for sheet metal assembly processes. The proposed optimization algorithms combined FEM and nonlinear programming methods to find the optimal fixture position such that the assembly variation was minimized.

Liao (2002) proposed a genetic algorithm (GA) – based optimization method to automatically select the optimal number of locators and clamps as well as their optimal positions in sheet metal assembly fixtures. Lai *et al.* (2004) presented a method that directly minimized work piece location errors due to its fixture elastic deformation. They developed a variation of genetic algorithm to solve the fixture layout problem.

Besides the fact that the fixture layout affects the assembly dimensional quality, the joint positions in sheet metal assembly, coupled with the fixture layout, also impact the final assembly variation. For instance, the joint configurations and three kinds of most commonly used joints in sheet metal assembly: lap joints, butt joints, and butt-lap joints were parametrically modeled and evaluated based on the assembly variation levels in Liu and Hu (1997a). Zhang and Taylor (2001) presented the optimization problem of a spot-welded structure, whose optimal position of the spot welds in the structure yielded the maximum stiffness. To date, no literature is found on the study of the simultaneous optimization method for the fixture layout and joint positions of non-rigid sheet metal assemblies, which will be studied in this thesis.

On the other hand, the simultaneous optimization problem for fixture layout and joint positions of non-rigid sheet metal assemblies is non-linear. The objective function is like a "black-box" function and its properties are unknown. It is known that the conventional gradient-based methods always give a local optimum for non-linear problems and the gradient calculated from FEA is usually noisy and not reliable (Haftka *et al.* 1998). For the Genetic Algorithms (GA), however, its application would be too computation intensive since GA needs a large number of function evaluations and one FEA process is required for each objective function evaluation. Therefore, a fast and applicable global optimization algorithm needs to be identified and / or developed.

1.3 Objectives and Scope of This Thesis

Due to the complexity of non-rigid sheet metal assemblies, there are many interesting topics needed to be investigated. The research in this thesis focuses on three fundamental areas, shown in Figure1.1.

The first objective is to apply some new mathematical tools: fractal geometry (Mandelbrot 1983, Falconer 1990) and wavelet analysis theory (Chui 1992, Mallat 1998) to model and identify the part manufacturing variation. The sheet metal assembly process is simplified and modeled at first. The detailed structure of part variation and its influence on the final assembly quality are analyzed.

The second objective is to develop a simultaneous optimization method for fixture layout and joint positions. Firstly, the simultaneous optimization mathematical model for fixture/joint position is established, and then the FEA method is utilized to compute the assembly variation under the part variations and fixture variations. A global optimization algorithm is identified to search the optimal positions of fixtures and joints (in this work the *Mode- Pursuing Sampling* (MPS) method developed by Wang *et al.* (2004) is used).

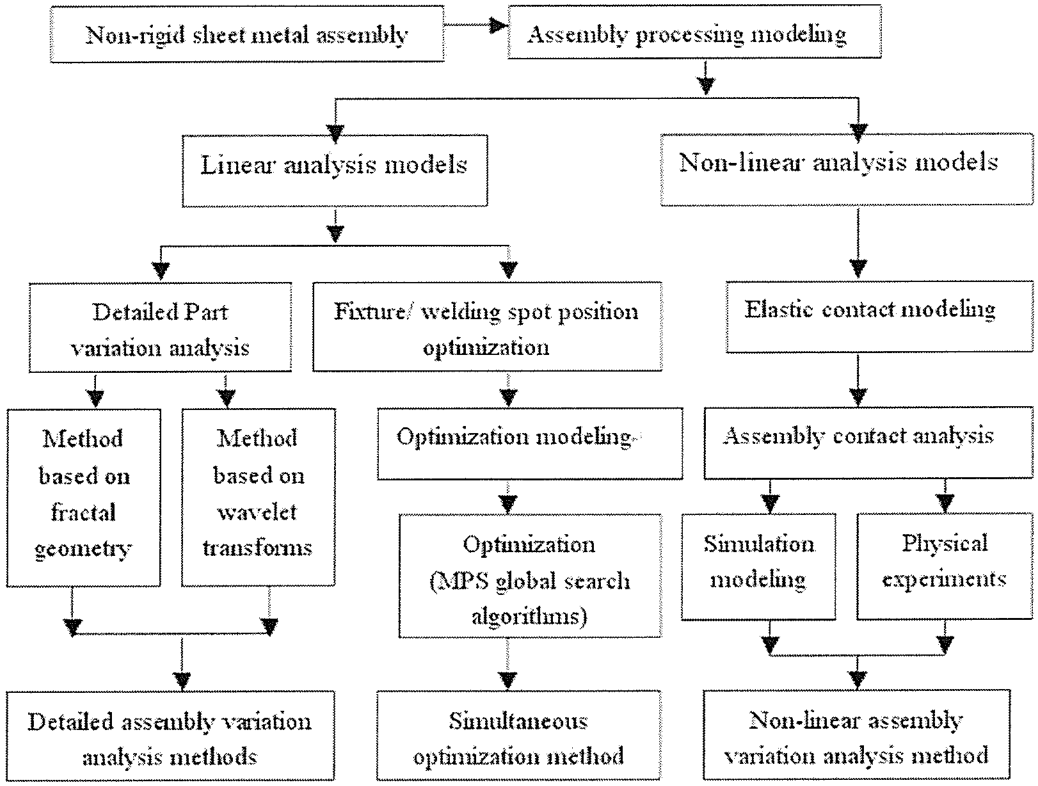


Figure 1.1 The research objectives and scope

The third objective of the research is to extensively study the contact problem related to the sheet metal assembly variation analysis by applying both numerical FEA modeling and physically experiments, and to develop the non-linear dimensional variation analysis method for sheet metal assemblies by establishing an elastic contact model (Hills 1992) between the assembly surfaces. In order to make comparisons with the linear (non-contacting) model, an example of an assembly of two sheet metal parts is applied to conduct, respectively, assembly dimensional variation analysis with and without contact modeling. The physical tests are performed to validate the contact FEA models.

The significance of the above studies can be foreseen as follows:

(1) The research will establish novel methods on assembly variation analysis and

fixture/joint position optimization for non-rigid sheet metal assemblies by employing fractal geometry, wavelet transform, contact analysis, and global optimization. The investigation will contribute to the deep understanding of the coupling influence of component flexibility, detailed part variation, and assembly tool variations on the final assembly geometry quality, and the non-linear behaviour of assembly variation propagation in assembly process. This knowledge as well as the methods and tools to be developed in this thesis will basically enhance the study of integrated design and manufacture of non-rigid sheet metal assemblies.

(2) Results and software tools from the studies in this thesis can be directly transferred to the industry. Quality of some industrial products, such as aircraft, automobiles, cell phones, and furniture is expected to substantially improve by using the results from this study. Market competitiveness of related enterprises will be increased.

1.4 Thesis Organization

The remainder of this thesis is as follows.

Chapter 2 develops two different novel methods to investigate the propagation of the detailed part variation and the influence of the component variation microstructure on the assembly dimensional variation by integrating the finite element method with fractal geometry or wavelet transform, respectively. The proposed methods are implemented by using ANSYS and Matlab, and are respectively illustrated through the case study on the assembly of two flat sheet metal components.

Chapter 3 considers the influence of the fixture layout and the joint positions on the assembly variation. The mathematical model of the fixture and joint position optimization problem is first developed, and then the Mode-pursuing sampling method (MPS), one of the powerful global optimization algorithms, is identified and proposed to solve this optimization problem.

Chapter 4 focuses on the contact problem of the non-rigid sheet metal assemblies. A systematic procedure of the non-linear dimensional variation analysis for the sheet metal assemblies is developed by using the contact finite element method. The conclusions and recommended future work are outlined in Chapter 5.

Chapter 2

Assembly Variation Analysis by Fractals and Wavelet Transform

2.1 Introduction

Dimensional quality is one of the most important issues in the assembly of non-rigid components, which is widely seen in aerospace and automobile industries such as the assembly of auto bodies and airfoils. Many factors involved in the assembly process have impact on the assembly dimension variation, including the component variation, tool variation, fixture layout, and assembly sequence. All types of variation accumulate and propagate along with the assembly process (Hu and Wu 1992, Hu 1997, Dalstrom *et al.* 2002).

In general, the component variation is recognized as a major problem in elastic assembly processes. Its research and application issues have attracted many researchers. A number of methods and tools have been developed to simulate the assembly processes and to analyze the assembly variation. For example, the influence coefficients method to analyze the effect of component variation and assembly spring-back on the assembly variation by applying linear mechanics and statistics was proposed and studied in Liu and Hu (1997b). This approach was extended to model the product variation in multi-station assembly systems by Camelio *et al.* (2001). The "stream of variation" theory for the automotive body assembly variation analysis was proposed in Hu (1997).

Ceglarek and Shi (1997) used a beam-based model for the sheet metal assembly variation analysis based on physical / functional modeling of the fabricated error. Hsieh and Oh (1997) represented a procedure for simulating the combined effects of deformation and dimensional variation in the elastic assembly. The fixture schemes in sheet metal assembly modeling was discussed in Cai *et al.* (1996b) and it was demonstrated that the N-2-1 fixture scheme was better than the 3-2-1 scheme for non-rigid assemblies.

Moreover, a method of using the covariance matrix of the components to predict the variation in compliant assembly was presented in Camelio and Hu (2002b). The method replaces the sensitivity matrix with the variation vectors defined for each deformation mode identified from the covariance of the components, thus reducing the number of FEM computations. In Huang and Ceglarek (2002), the discrete-cosine-transform was applied to analyze the modes of sheet metal part form error.

However, the current methods did not address the detailed microstructure of component variations and its propagation in the assembly process. Little is known about how the detailed microstructure of component variations affects the assembly dimensional quality.

The main objective of this chapter is to firstly develop a method for investigating the detailed microstructure of the part variation with fractal characteristics and its influence on the final assembly dimensional variation by applying the finite element method and fractal geometry. Furthermore, another new analysis method based on the wavelet transform is developed to handle part variations with more general complex microstructure.

The fractal function, named Weierstrass-Mandelbrot (W-M) function (Majumdar and Tien 1990, Liao and Lei 1999) and wavelet transform (Chui 1992, Mallat 1998) are introduced in Section 2.2. The assembly process modeling of sheet metal components and subassemblies in a typical assembly station is described in Section 2.3. The assembly variation simulation procedure by fractals is proposed to deal with fractal part variations in

Section 2.4. In Section 2.5, the method of applying wavelet transform to assembly variation analysis for general part variations is developed and discussed. The approaches developed in this chapter provide the applicable tools to analyze the impacts of the detailed microstructure of component variations on the assembly dimensional quality.

2.2 Outlining Fractals and Wavelet Transform

2.2.1 Introduction of Fractals

It was the Polish mathematician Benoit B. Mandelbrot who first introduced the term 'fractal' (from the latin *fractus*, meaning 'broken') in 1975 to characterize spatial or temporal phenomena that are continuous but not differentiable (Mandelbrot 1983). Unlike more familiar Euclidean constructs, splitting a fractal into smaller pieces shall result in the resolution of more structures (Mandelbrot 1983, Falconer 1990). Self-similarity is the property that fractal objects and processes inherit.

Fractal properties include scale independence, self-similarity, complexity, and infinite length / detail. It is well known that fractal structures do not have a single length scale, while a single time scale cannot characterize fractal processes (time series). Nonetheless, the necessary and sufficient conditions for an object (or process) to possess fractal properties have not been formally defined (Falconer 1990).

Fractal theory provides methods to describe the inherent irregularity of natural objects. In fractal analysis, a constant parameter D, known as the fractal (or fractional) dimension, is treated as a relative measure of complexity, or as an index of the scale-dependency of a pattern. Excellent summaries of basic concepts of fractal geometry can be found in Falconer (1990).

The fractal dimension is a statistical overall 'complexity' measurement. A mathematical fractal is formally defined as any series for which the Hausdorff dimension (a continuous function) exceeds the discrete topological dimension (Mandelbrot 1983). Currently there are several kinds of methods, such as box counting, pair counting, and power spectrum method to compute the fractal dimension for a given data set. Topologically, a line is one-dimensional, that is D=1; the fractal dimension of a plane is D=2; and the dimension of a fractal curve is $1 < D < 2$, shown in Figure 2.1.

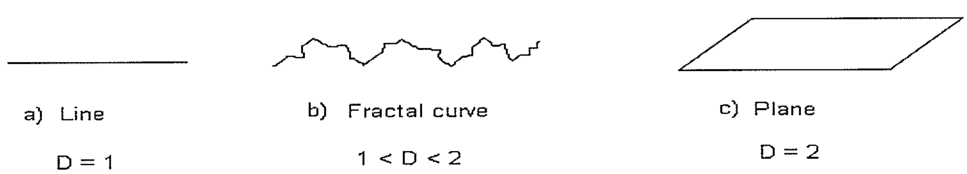


Figure 2.1 Fractal dimensions of typical geometry entities

Nowadays, fractal geometry has been widely applied to study the non-linearity and complexity of physical, chemical, biological, and engineering systems. For example, the property of "seashore" can be modeled using fractals. On the other hand, some complex patterns can be constructed by using iterative procedures. Figure 2.2 shows one example of the process for the construction of the Koch Curve (Falconer 1990).

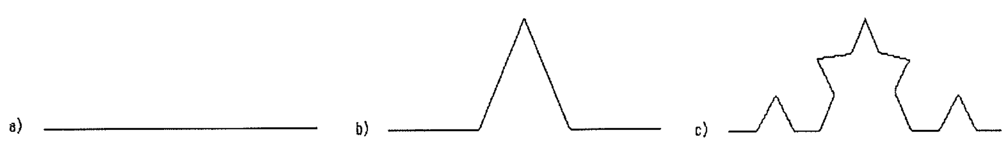


Figure 2.2 An example of the Koch Curve iterated twice (Falconer 1990). (a) A line of unit length. (b) The line increases in length by 4/3. (c) The length is again increased by 4/3, so it is now 16/9 of the initial unit length

Currently, the fractal Brownian motion and fractal Weierstrass-Mandelbrot (W-M) function are used extensively in engineering application because of their simple forms (Majumdar and Tien 1990, Liao and Lei 1999, Jiang *et al.* 2001).

The Weierstrass-Mandelbrot (W-M) function is often applied to study those profiles which appear to have self- affinity and self-similarity. The W-M function can be written as equation (2.1) (Majumdar and Tien 1990)

$$X(t) = G^{(D-1)} \sum_{n=n_1}^{\infty} \frac{\cos 2\pi r^n t}{r^{(2-D)n}} \tag{2.1}$$

Where

D: fractal dimension of the profile

G: scaling constant,

r^n: frequency modes, which correspond to the reciprocal of the wavelength λ

$$r^n = 1/\lambda^n \tag{2.2}$$

n_1: corresponds to the low cut-off frequency of the profile under measurement

$$r^{n1} = 1/L \qquad (L\text{: profile length}) \tag{2.3}$$

r : =1.5 (it is suitable and practicable for general fractal cases, see Majumdar and Tien (1990))

The power spectrum density of the W-M function is very useful for the computation of the parameters D and G, and it can be statistically represented as:

$$S(\omega) = \frac{G^{2(D-1)}}{2\log r} \frac{1}{\omega^{(5-2D)}} \tag{2.4}$$

Equation (2.4) indicates that the W-M function power spectrum density follows the power law, namely the linear relation between log(S) and log (ω) in a double logarithm co-ordination. Since most engineering profiles are fractal, the fractal dimension D and scaling constant G are determined by the power spectrum, and parameters D and G are independent of frequency ω, that means they are scale-independent. This is a typical characteristic of fractal engineering profiles.

When given the measured data of a profile, the power spectrum density analysis can be applied, and then the logarithmic transformation can be made. On the log-log power law plot, the average slope (k) and y-intercept S_y are obtained though linear regression algorithms. The fractal dimension D and scaling constant G are most commonly estimated from equations (2.5) and (2.6):

$$D = \frac{5-k}{2} \tag{2.5}$$

$$G = e^{\frac{S_y + \log(2 \log r)}{2(D-1)}} \tag{2.6}$$

The fractal dimension D reflects the complexity degree of an engineering profile. The procedure of applying the W-M function to analyze the degree of fractal complexity of the microstructure of the component variation and to synthesize the component variations will be presented in Section 2.4.

2.2.2 Wavelet Transform Review

It is well known that Fourier transform is a popular method for signal processing (Paulo *et al.* 2002). A signal can be represented as the sum of a series of sinusoids and cosines by using Fourier transform. Since the sinusoids and cosines that comprise the base of Fourier analysis are non-local functions that have only frequency resolution and no time resolution, the suitable signals for Fourier analysis should be stationary and their statistics do not change with time. If we calculate the frequency composition of non-stationary signal by Fourier theory, the results are the frequency composition averaged over the duration of the signal, which cannot adequately describe the characteristics of the signals in lower frequencies. Although we can use the short-time Fourier transform (STFT) method to deal with non-stationary signals, a high resolution in both time and frequency domain is hardly reached.

Wavelet transform is a fundamentally different approach from Fourier theory (Mallat 1998, Chui 1992). In this novel transformation, a signal is not decomposed into its harmonics, which are global functions that have support on $[-\infty, +\infty]$, but into a series of local basis functions called wavelets, which are of a waveform of effectively limited duration and having an average value of zero. At the finest scale, the wavelets may be very long. By wavelet transform, any particular local features of signals can be detected and identified from the scale and the position of the wavelets. The structure of non-stationary signals can be analyzed with local features represented by a close-packet wavelet of short length.

Given a time varying signal $f(t)$, wavelet transform (WT) consists of computing a coefficient that is the inner product of the signal and a family of wavelets. In the continuous wavelet transform (CWT), the wavelet base is constructed by dilating and translating a single function $\psi(t) \in L^2(R)$, which is named the mother function and has a zero average

$$\int |\psi(t)|^2 \, dt < +\infty \tag{2.7}$$

and

$$\int \psi(t)dt = 0 \tag{2.8}$$

The wavelet base or wavelets can be written as equation (2.9)

$$\psi_{a,b} = \frac{1}{\sqrt{|a|}}\psi\left(\frac{t-b}{a}\right) \qquad a,b \in R, a \neq 0 \tag{2.9}$$

where a and b are the dilation (scale) and translation parameters, respectively. The factor $\frac{1}{\sqrt{|a|}}$ is for energy normalization.

The continuous wavelet transform of function $f(t)$ at scale a and position b is defined as follows:

$$w_f(a,b) = \int f(t)\psi^{*}_{a,b}(t)dt \tag{2.10}$$

where "*" denotes the complex conjugation.

With respect to $w_f(a,b)$, the signal $f(t)$ can be reconstructed by

$$f(t) = \frac{1}{C_\psi}\int_{-\infty}^{+\infty}\int_{0}^{+\infty} w_f(a,b)\frac{1}{\sqrt{|a|}}\psi\left(\frac{t-b}{a}\right)dadb \tag{2.11}$$

where C_ψ is calculated by equation (2.12)

$$C_\psi = \int_0^{\infty}\frac{|\psi(\omega)|^2}{\omega}d\omega < +\infty \tag{2.12}$$

In equation (2.12), $\psi(\omega)$ is the Fourier transform of $\psi(t)$.

Similar to the Fourier transform, $w_f(a,b)$ and $f(t)$ constitute a pair of wavelet transform.

When $a = 2^j$, $b = k2^j, j, k \in$ Z, the wavelets are given by

$$\psi_{j,k} = 2^{-\frac{j}{2}}\psi(2^{-j}t-k) \tag{2.13}$$

The discrete wavelet transform (DWT) is defined as follows:

$$c_{j,k} = \int f(t)\psi_{j,k}(t)dt \tag{2.14}$$

where $c_{j,k}$ is defined as the wavelet coefficient. It may be considered as a time-frequency map of the original signal $f(t)$.

Multi-resolution analysis is used in discrete scaling function:

$$\phi_{j,k} = 2^{-\frac{j}{2}}\phi(2^{-j}t-k) \tag{2.15}$$

where $\phi(t)$ has a relationship with $\psi(t)$ which is described by their Fourier transforms in the equation (2.16)

$$|\phi(\omega)|^2 = \int_{a_0}^{\infty}\frac{1}{a_0}|\psi(a\omega)|^2 da \tag{2.16}$$

where a_0 is a specific scale level (constant).

The equation (2.16) shows that the scaling function $\phi(t)$ is an aggregation of wavelets at the scales larger than a_0.

The scaling functions and the wavelets have the following orthogonal properties (Mallat 1998):

1) The scaling functions are orthonormal to each other at the same scale.

$$\int\phi_{j,n}(t)\cdot\phi_{j,m}(t)dt = \delta(m-n) = \begin{cases} 1, & if \quad m=n \\ 0, & if \quad m\neq n \end{cases} \tag{2.17}$$

2) The scaling functions are orthonormal to the wavelets at the same scale

$$\int\phi_{j,n}(t)\cdot\psi_{j,m}(t)dt = 0 \tag{2.18}$$

3) The wavelets at all scales are orthonormal

$$\int \psi_{j,n}(t) \cdot \psi_{j,m}(t) dt = \delta(m-n) = \begin{cases} 1, & if \quad m=n \\ 0, & if \quad m \neq n \end{cases} \tag{2.19}$$

By using the discrete scaling function $\phi_{j,k}$ (t), the signal $f(t)$ can be decomposed as the following equation

$$d_{j,k} = \int f(t) \phi^*_{j,k}(t) dt \tag{2.20}$$

where $d_{j,k}$ is called the scaling coefficient.

Wavelet coefficients $c_{j,k}$ (j = 1, 2, …, J) and the scaling coefficient $d_{j,k}$ can be further represented as follows

$$c_{j,k} = \sum_n f[n] h_j[n - 2^j k] \tag{2.21}$$

and

$$d_{j,k} = \sum_n f[n] g_j[n - 2^j k] \tag{2.22}$$

where $f[n]$ is the discrete-time signal; $h_j[n - 2^j k]$ are the analysis discrete wavelets, and the discrete equivalents to $2^{-j/2} \psi(2^{-j} t - k)$; $g_j[n - 2^j k]$ are called the scaling sequence (Mallat 1998).

At each resolution $j > 0$, the scaling coefficients and the wavelet coefficients can be written as follows:

$$c_{j+1,k} = \sum_n g[n-2k] d_{j,n} \tag{2.23}$$

$$d_{j+1,k} = \sum_n h[n-2k] d_{j,n} \tag{2.24}$$

The above two equations state that the scaling coefficients on the scale j can be decomposed into the wavelet coefficients and the scaling coefficients on the next higher scale $j+1$. Therefore, the scaling coefficients on the scale j can be also reconstructed by the wavelet coefficients and the scaling coefficients on the scale $j+1$

$$d_{j,k} = \sum_n h[k-2n] d_{j+1,n} + \sum_n g[k-2n] c_{j+1,n} \tag{2.25}$$

The terms g and h in equations (2.23), (2.24) and (2.25) can be considered as high-pass and low- pass filters derived from the analysis of wavelets and the scaling function, respectively.

From equations (2.23), (2.24) and (2.25), it is found that the wavelet decomposition and reconstruction is calculated with discrete convolutions (Mallat 1998, Chui 1992). Figure 2.3 shows the decomposition and reconstruction process of three-level wavelet transform. By applying such wavelet transform, a given signal can be decomposed into components in different levels, and also can be reconstructed by these components. In the multi-resolution analysis, the components synthesized by the scaling coefficients and the wavelet coefficients are called approximations and details, respectively. The frequencies of components in higher levels (i.e., higher scale) are less than those of components in lower levels (i.e., lower scale), but in the same level, the frequency of detail is definitely greater than that of approximation.

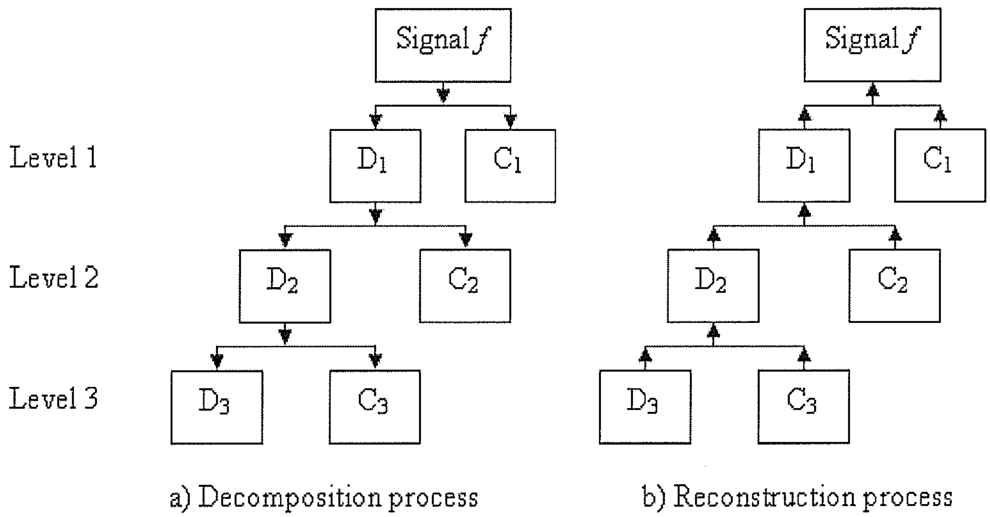


Figure 2.3 Three-level wavelet transform: decomposition and reconstruction process

Among many wavelet families, the Daubechies wavelet base is the most common orthogonal wavelet base and is widely applied in signal processing. In the Section 2.5, the Daubechies wavelets will be applied to analyze the part variations with general multi-scale microstructure.

2.3 Non-rigid Sheet Metal Assembly Modeling

In order to analyze the non-rigid assembly variation in a typical assembly station, it is necessary to model the actual complex assembly process. One of the most widely used approaches to model an assembly process is the mechanistic simulation methodology developed by Liu and Hu (1997b). This methodology is based on the following assumptions on the assembly procedure:

1) All of the process operations occur simultaneously;

2) The component deformation is linear and elastic;

3) The component material is isotropic;

4) Fixtures and tools are rigid;

5) No or negligible thermal deformation occurs during the assembly process; and

6) The stiffness matrix remains constant for deformed component shapes.

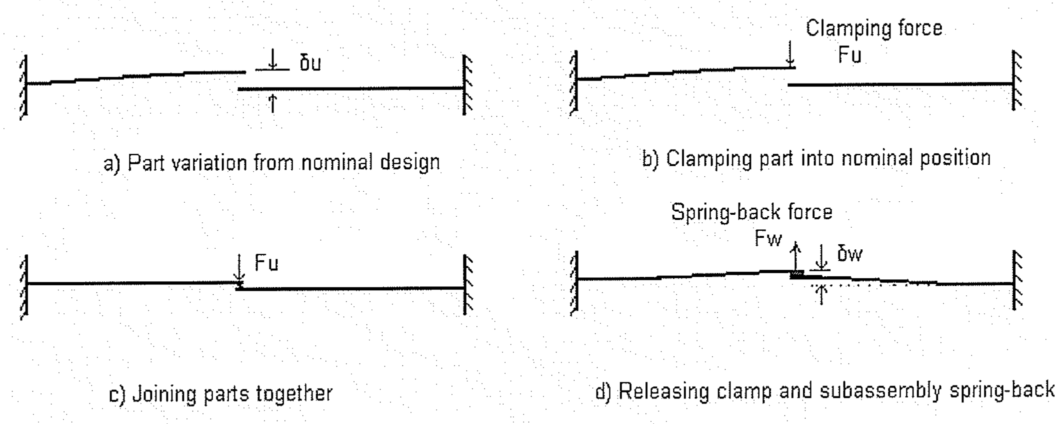
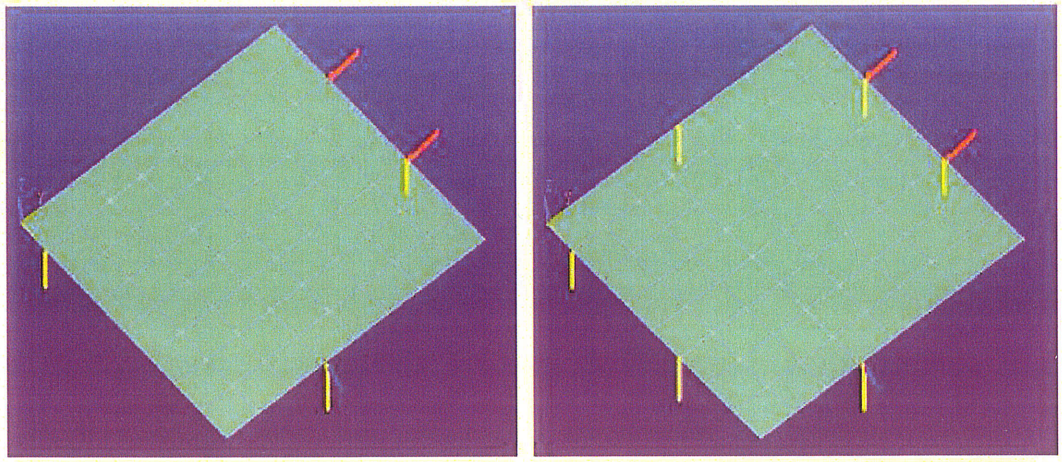


Figure 2.4 The non-rigid assembly process

The assembly processes of components and subassemblies in a typical assembly station can be illustrated by Figure 2.4, and represented as the following steps:

i) Placing components (Figure 2.4a)

Components are loaded and placed on fixtures using a locating scheme (Figure 2.4a). Since the fabrication error of components is a natural phenomenon in component manufacturing, the component variation $\{\delta_u\}$ offset from the design nominal will inevitably cause the initial matching gap. Here, index *u* refers to un-joined components. The N-2-1 (N>3) fixture scheme not 3-2-1 scheme (shown in Figure 2.5) is utilized to assure the dimensional quality because of the assembly deformation (Cai *et al.*1996 b).



a) "3-2-1" fixture scheme　　b) "N-2-1" (N=6) fixture scheme

Figure 2.5 Two types of fixture schemes

ii) Clamping components (Figure 2.4b)

The initial matching gap between components and subassemblies is forced to close by deforming components to the nominal position. Considering the component stiffness matrix $[K_u]$ that could be built through the finite element method, the relationship of the required clamping forces $\{F_u\}$ to the closed gap $\{\delta_u\}$ can be given by equation 2.26

$$\{F_u\} = [K_u]\,\{\delta_u\} \tag{2.26}$$

iii) Joining components (Figure2.4c)

When using a joining method, such as welding, riveting, or gluing, to join two components, deformation occurs at each joint point as the gap between components is closed. The assembly force $\{F_u\}$ is still being applied.

iv) Releasing clamps/fixtures and subassembly spring-back (Figure 2.4d)

After assembling the two components, the clamps/fixtures are removed. The joined components will spring back to release the stored strain energy during the assembly operation. It is reasonable to assume that the spring-back force $\{F_w\}$ is equal to the clamping force $\{F_u\}$. Therefore, applying FEM to get the component and assembly stiffness matrix, the value of spring-back variation $\{\delta_w\}$ can be calculated by removing displacement boundaries both at clamping points and the releasing fixture locations to simulate clamps/fixtures release, as described in the following equations (2.27)~(2.30):

$$\{F_w\} = [K_w]\ \{\delta_w\} \tag{2.27}$$

$$\{F_w\} = \{F_u\} \tag{2.28}$$

$$\{\delta_w\} = [K_w]^{-1}\ [K_u]\ \{\delta_u\} \tag{2.29}$$

$$\{\delta_w\} = \{S_{uw}\}\{\delta_u\} \tag{2.30}$$

where $\{S_{uw}\}$ is the sensitivity matrix. Index *w* represents the assembly variation at the measurement points. $\{S_{uw}\}$ represents the linear mapping relationship between the assembly variation and the component variation.

For a given specific assembly process and station, getting the stiffness matrix $[K_u]$ and $[K_w]$ by using commercial FEM software is the key issue to the assembly variation analysis procedure, because most software provides no direct means for users to access and operate the FEM stiffness matrix. The influence coefficients method, which is developed by Liu and Hu (1997b), could be used to indirectly construct the sensitivity matrix $\{S_{uw}\}$ if the commercial FEM software embeds an application-oriented development language. In fact, this method uses FEM to compute the stiffness matrix $[K_u]$ and $[K_w]$, and obtains the sensitivity matrix $\{S_{uw}\}$ by Eq. $\{S_{uw}\}= [K_w]^{-1}\ [K_u]$.

The procedure to achieve the stiffness matrix of assembly and/or component can be described as follows: a unit force is applied at each source of variation with the same direction of the deviation; FEM is then used to calculate the response at some specific points; after such response computation for all sources of variation, a response matrix can be constructed; the stiffness matrix can be obtained by inverting the response matrix since it is symmetric. Details about this method are in the Liu and Hu 1997b).

2.4 Assembly Variation Analysis Method by Fractals

The dimensional quality of product assembly is one of the most concerned issues in modern product design and manufacturing. Applicable and effective approaches to analyze the detailed variation structure in the tolerance zone and its impact on the product dimensional quality are demanded for high-precision product design. Since the non-rigid assembly is widely used in industry and the current dimensional variation analysis methods are not applicable in this situation, a new method based on the fractal W-M function is firstly developed in this section to deal with fractal part variations and provide an applicable way for the high precision non-rigid sheet metal assembly variation analysis and control.

2.4.1 Component Variation Microstructure Modeling Using W-M function

It is inevitable that any manufactured component has fabrication variations due to uncertainties in manufacturing systems (Majumdar and Tien 1990, Liao and Lei 1999). The maximum and minimum of deviation should be identified under strict measurement and control so that the final product can satisfy the design requirements. Recent studies show that not only the amount of manufacturing variations but also the variation's microstructure influences a component's performance and function (Majumdar and Tien 1990, Jiang *et al.* 2001).

The microstructure of manufacturing variation for non-rigid components is investigated in this chapter by using the fractal W-M function in order to numerically analyze the effect of the variation microstructure on the final assembly dimensional quality.

The microstructure of component variation is very complex. Experiments show that most engineering surfaces / profiles appear to be irregular, and the portion of surfaces / profiles looks similar to the whole as it is amplified (Falconer 1990, Jiang *et al.* 2001). Even on a very small scale, the surfaces / profiles are obviously irregular. Self-affinity and self-similarity are the main characteristics of the topography of most engineering surfaces / profiles. Therefore, we can use such topography characteristics of a component profile to analyze the microstructure of component variation.

The fractal W-M function is widely used in engineering profile analysis since it has a simple mathematical equation and is easily understood. In W-M function, there are two main parameters, i.e. the fractal dimension D and scaling constant G. D reflects the complexity degree of an engineering profile.

The W-M function is utilized in this study to analyze the degree of fractal complexity of the microstructure of the component variation, and to synthesize the component variations. The procedure is illustrated in Figure 2.6. The synthesized component variation has the same fractal characteristics as the original, and statistically reflects the uncertainty in manufacturing system. Since it is represented by the W-M function, the synthesized variation can be easily applied for further analysis of the assembly variation.

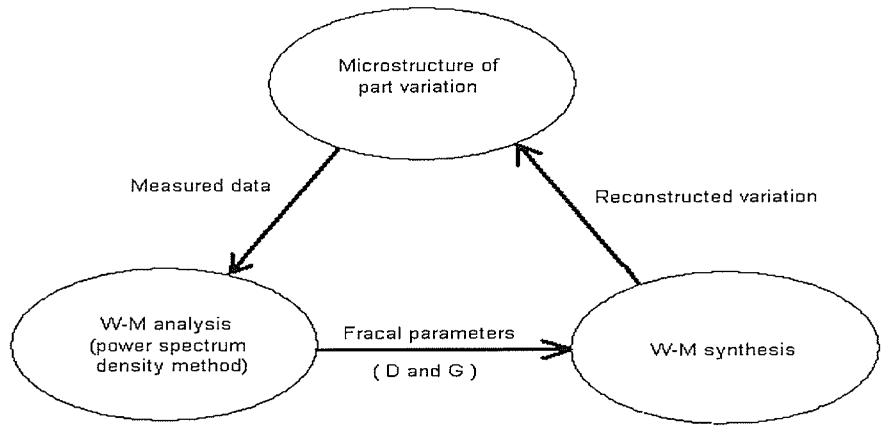


Figure 2.6 Procedure of component variation modeling by W-M function

From the viewpoint of manufacturing, different fractal dimensions D corresponds to different manufacturing conditions. For example, a grinding profile generally has a smaller fractal dimension D than a milling profile (Majumdar and Tien 1990, Liao and Lei 1999, Jiang *et al.* 2001), so in general the quality of a grinding profile is better than that of a milling profile. Therefore, it is possible to make a good manufacturing plan by analyzing the microstructure of component variation.

2.4.2 Assembly Variation Simulation Procedure by Fractals

Based on the four steps of the assembly process of components and subassemblies in a typical assembly station (shown in Figure 2.4) and the method on the component variation modeling by using the W-M function, the assembly variation simulation flowchart is summarized in Figure 2.7.

The entire analysis procedure shown in Figure 2.7 consists mainly of two portions. One is the microstructure modeling of the component variation by using the W-M function;

another is the four-step assembly process simulation based on the finite element analysis method.

In fact, the W-M function statistically represents the component variation, and it can be one of the displacement boundaries in FEM; thus, the deformation due to component variation can be computed through equation (2.30) derived in Section 2.3.

Generally, the FEM model can be created by "map-mesh" with structural elements so that the jointed spots are definitely together. The minimum clamping force is dependent on the material property and dimensions of the components. Since focus is on the microstructure of component variation and its contribution to the final product dimension variation, it is apparent that the more flexible the component material and the smaller the component dimensional size, the more prominent the influence will be. Therefore, it is important to develop high-precision dimensional variation modeling and analysis for non-rigid assemblies with large compliant parts.

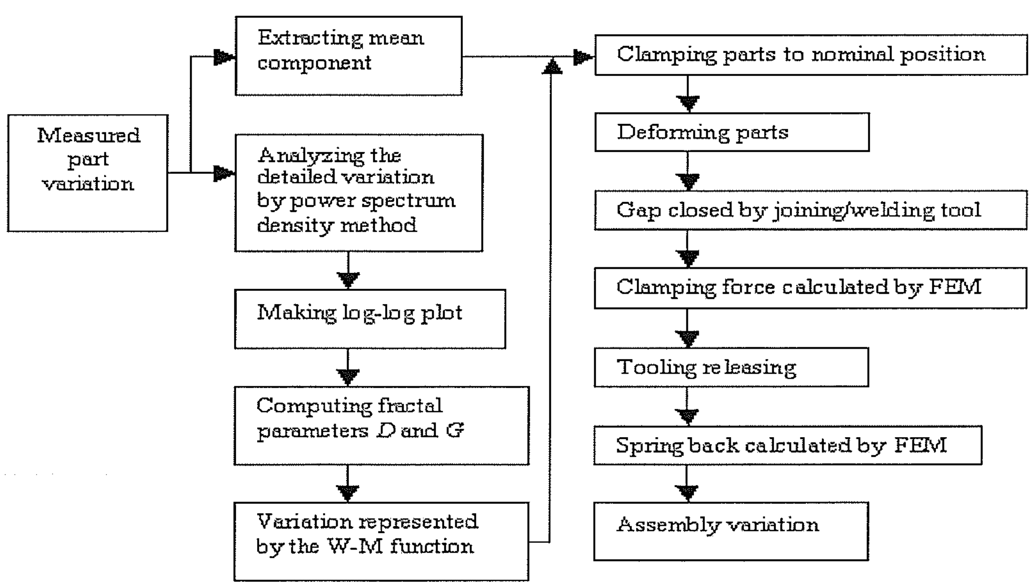


Figure 2.7 Flowchart of the assembly variation simulation procedure

The component joining process is simulated through coupled nodes in the FEM model, while the tool releasing process is simulated by removing the displacement boundaries at the released clamp / fixture points. The whole assembly process is assumed to be non-frictional and linear.

For non-rigid assembly, it is often to determine a set of points on components to be critical points (CPs) that are used to assure the assembly dimensional quality (Hu 2001). The characteristics of the CPs usually significantly affect the target value of the controlled variation, the performance of component function, and customer satisfaction. However, it is difficult to decide on the locations of CPs. The determination of CPs relies on such factors as the component shape, assembly process, component or subassembly performance, and assembly variation requirements.

The proposed assembly variation simulation procedure shown in Figure 2.7 provides a method to analyze the fractal microstructure of the component variation and its influence on the product assembly variation. It can be implemented by using the software ANSYS and Matlab. ANSYS is used to generate the FEM model, compute component deformation and the clamping force, simulate the joining and releasing process, calculate the spring back, and get the assembly variation; while the Matalb can be applied to develop the program for the component variation analysis and synthesis procedures. It is very effective and fast to obtain the fractal microstructure of component variation by using the W-M function.

2.4.3 Case Study: Assembly of Two Flat Sheet Metal Components

An assembly of two identical flat sheet metal components by lap joints is selected as an example to verify the proposed approach. Assuming that these two components are manufactured under identical conditions, their fabrication variations are expected to be identical. The task then is to find the variation at each point in the assembly that corresponds to the microstructure of the component variation.

1) Component geometry and material

The size of the flat sheet metal components used in this case study is 100×100×1mm. Suppose that the component material's Young's modulus $E = 2.62e+4$ N/mm^2 and Poison's ratio $\nu = 0.3$.

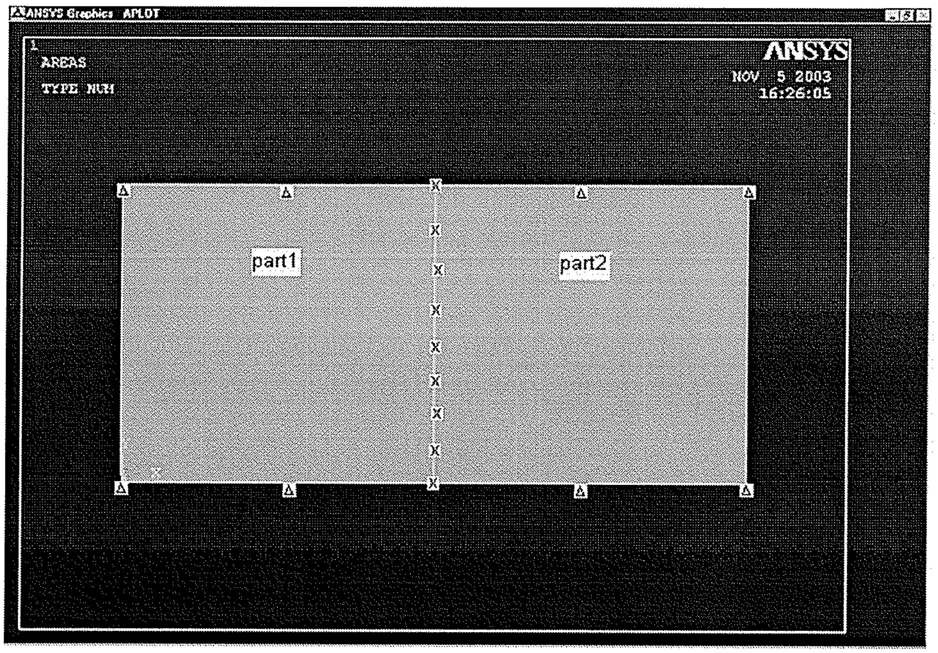


Figure 2.8 Assembly of two flat sheet metal components

2) Fixture and joining scheme

Due to the flexibility of the sheet metal components, the N-2-1 ($N > 3$) style of fixture scheme (Cai *et al.* 1996 b) is adopted to each component in this example (shown in Figure 2.8). The positions of symbol 'Δ' indicate the fixture locations. All pair joint spots, indicated by symbol 'x', are simultaneously assembled together.

3) Component variation modeling

A variation signal from the component profile (shown in Figure 2.9) is sampled by using a Coordinate Measurement Machine (CMM). For the measured data of the component variation, the mean variation is computed first, and then the detailed variation is modeled by using the W-M function. The mean variation is 0.5mm. The log-log power spectrum density of the detailed variation is obtained in Figure 2.10, and the fractal parameters computed from Figure 2.10 are given in Table 2.1. The variation synthesized by using the W-M function is shown in Figure 2.11. The synthesized part variation has the same fractal characteristics as the original CMM measured part variation, and the microstructure of part variation is also further quantitatively represented by the fractal parameters of W-M function. The analysis and synthesis programs are developed using Matlab.

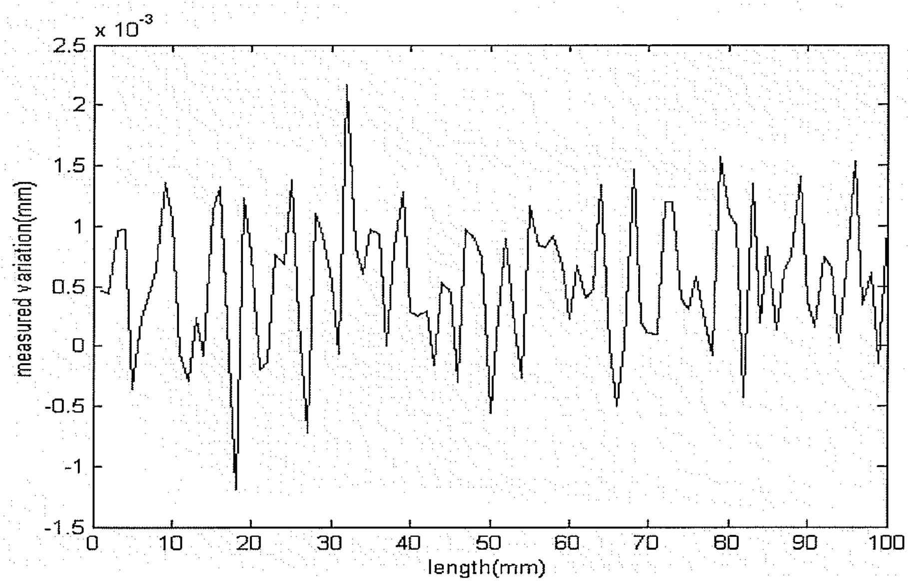


Figure 2.9 The sampled component variation

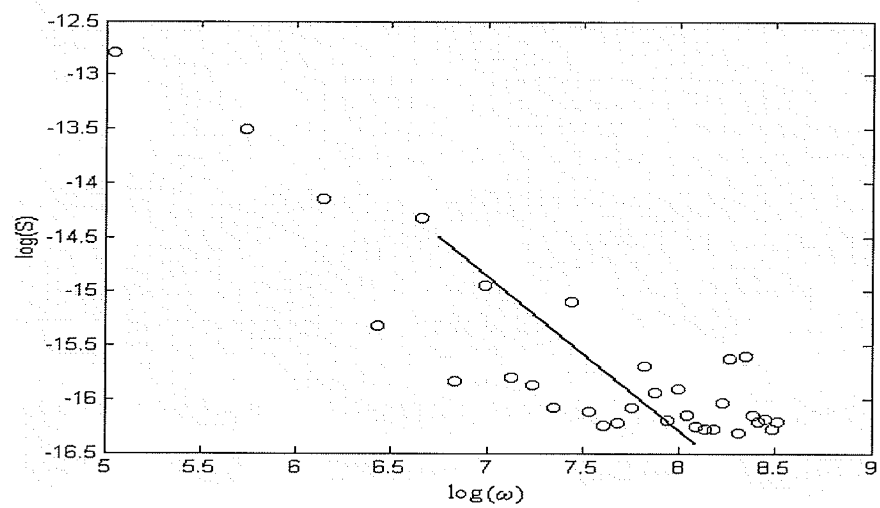


Figure 2.10 The log-log power spectrum density of detailed variation

Table 2.1 Parameters in W-M function

D (fractal dimension)	G (scaling constant)	r (constant)	n_l (the lowest cut-off frequency mode)	L (sample length)
1.55	1.67e-8	1.5	-11.36	100 mm

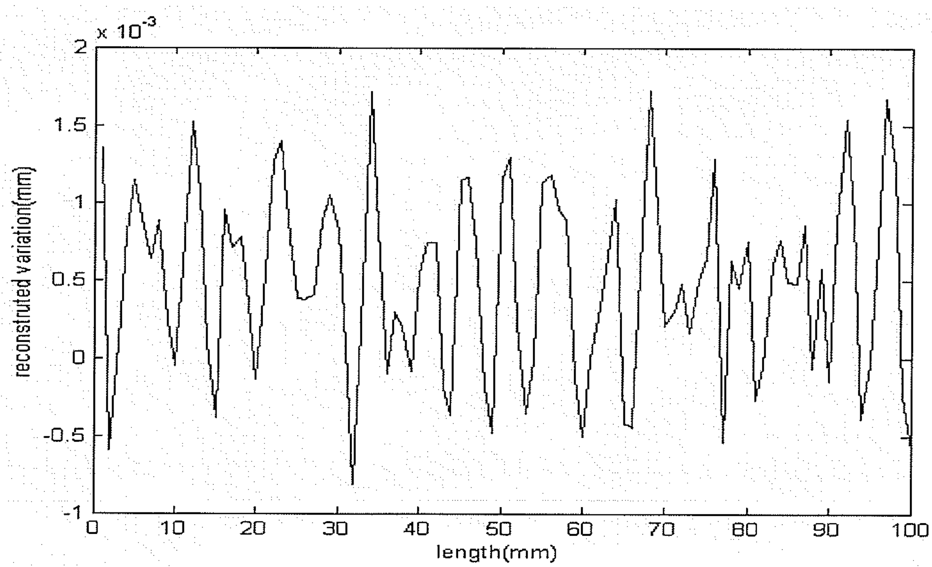


Figure 2.11 The variation reconstructed by W-M function

4) FEA modeling

The FEA model of the assembly of two flat sheets, shown in Figure 2.12, is created in ANSYS by assuming that small elastic deformation does not significantly change the component geometry size. The element type is SHELL63. The number of elements and the number of nodes are 128 and 162, respectively. There are 9 pairs of nodes to be connected together in this model, corresponding to the 'x' symbols in Figure 2.12.

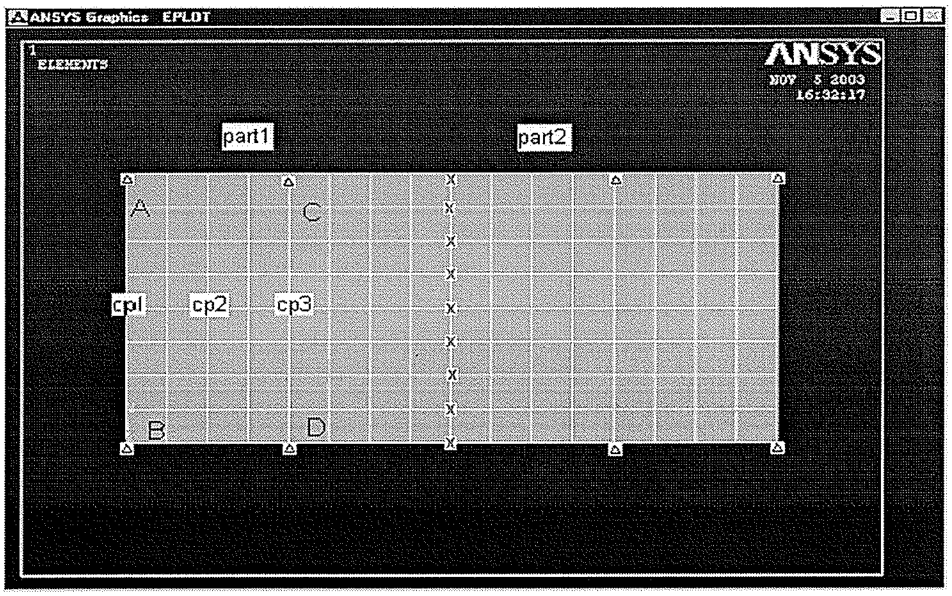


Figure 2.12 The FEA model of two flat sheet metal assemblies

Table 2.2 Tool releasing schemes

	Scheme 1	Scheme 2	Scheme 3
	Releasing all clamps	Releasing clamps + partial fixtures (A, C and D, see Figure 2.12) on part1	Releasing clamps + all fixtures (A, B, C and D, see Figure 2.12) on part1
Assembly variation due to mean component variation	Assembly variation distribution shown in Figure 2.13 a1)	Assembly variation distribution shown in Figure 2.13 a2)	Assembly variation distribution shown in Figure 2.13 a3)
Assembly variation due to detailed component variation	Assembly variation distribution shown in Figure 2.13 b1)	Assembly variation distribution shown in Figure 2.13 b2)	Assembly variation distribution shown in Figure 2.13 b3)

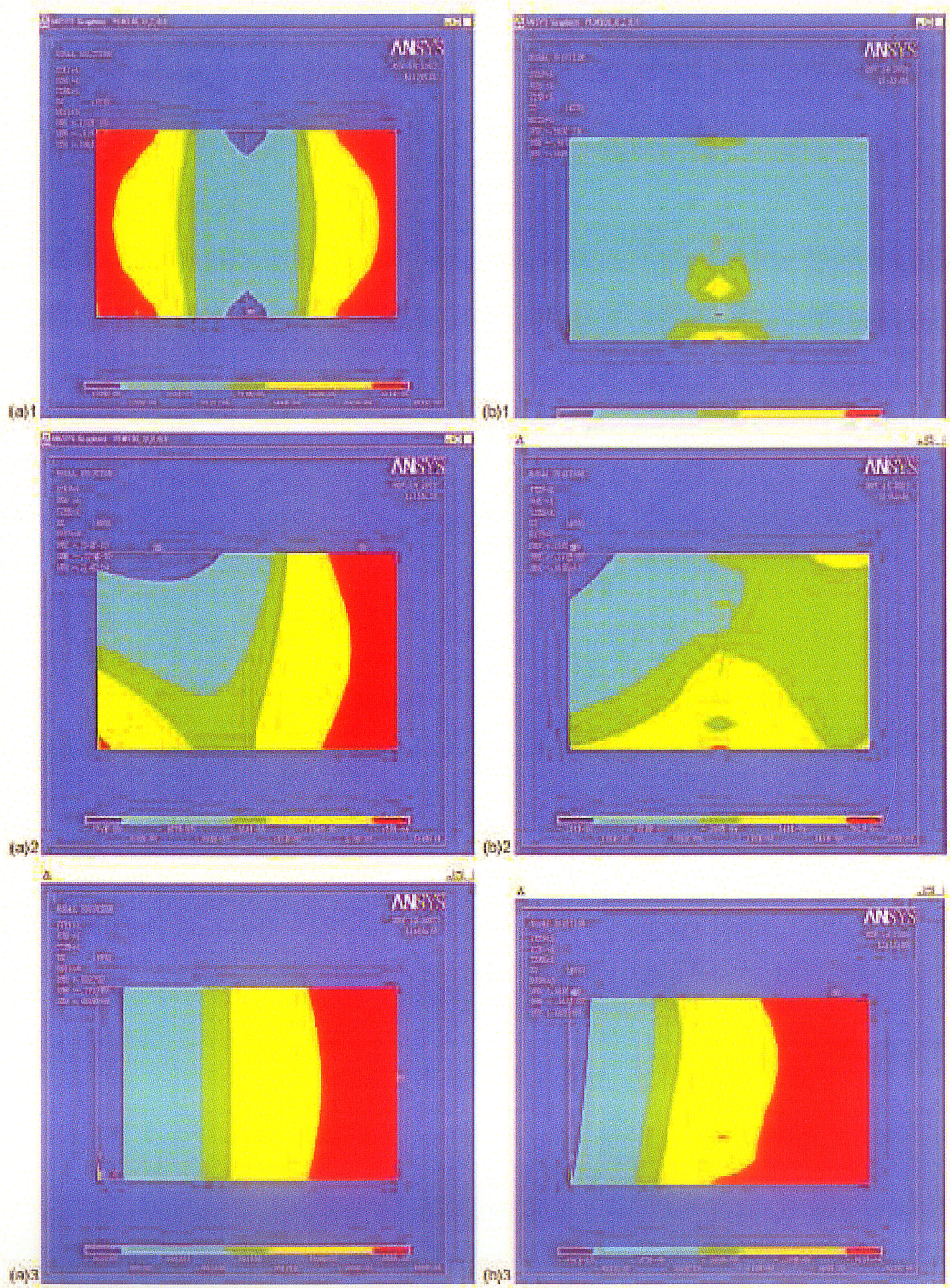
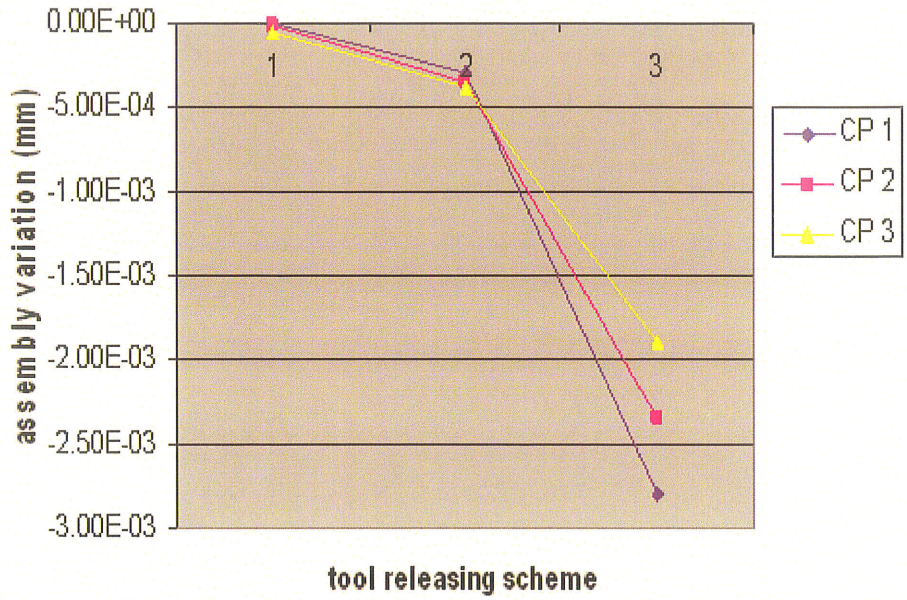
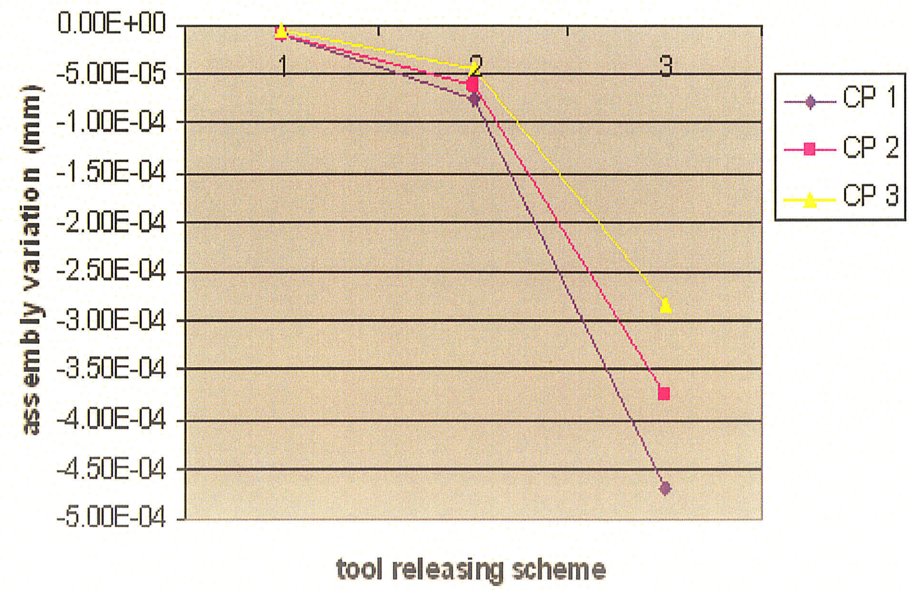


Figure 2.13 Assembly variations corresponding to component variations and tool releasing schemes



(a)



(b)

Figure 2.14 Assembly variation of 3 CPs. (a) Assembly variation due to the mean component variation. (b) Assembly variation due to the detailed component variation

5) Computational results

After the FEM model for simulating the assembly process and the microstructure characteristics of the component variation are obtained, the assembly variation that results from the detailed component variation can be computed by using equation (2.30) derived in Section 2.3. In this example, corresponding to the mean variation and the detailed variation in the component profile, the assembly variation distribution (Figure 2.13) is obtained under three different tool-releasing schemes respectively (see Table 2.2). The computational procedure is coded by APDL (ANSYS Parametric Design Language) in ANSYS.

From Figure 2.13 a1) ~ b3) we can see that the component variation propagation heavily relies on the assembly process. Different tool releasing scheme results in quite different assembly variation distribution. The complete fixture releasing scheme (Scheme 3 in Table 2.2) generates much larger assembly variation than the partially fixture releasing scheme (Scheme 2 in Table 2.2). Therefore, it is necessary to design the assembly process that meets the product dimensional tolerance.

In addition, the assembly variation caused by the detailed component variation is considerable, which is also asymmetrical even if the assembly condition is symmetrical. It is because the microstructure of component variation is complex and asymmetric, demonstrating fractal characteristics.

Some CPs in components are determined to check the influence of component variation on the assembly dimensional quality. In this example, suppose that there are 3 CPs (shown in Figure 2.12). The assembly variations of these 3 CPs under 3 different tool-releasing schemes are extracted from computation results (see Figure 2.13), and are shown in Figure 2.14. It can be seen from Figure 2.14 that both assembly variations caused by the mean and the detailed component variation increase as more fixtures are released. The contribution of the detailed variation microstructure to the final assembly variation is significant for Scheme 3. Thus, the incorporation of the analysis of microstructure of component variation can give a more accurate prediction of the final assembly quality.

2.5 Assembly Variation Analysis Method by Wavelet Transform

The fractal- based method presented in Section 2.4 is applicable and effective to model and analyze the microstructure of part variations with fractal characteristics, but it is not accurate to handle the part variation with general multi-scale microstructures which result from the uncertainties in manufacturing process. Knowing the multi-scale microstructures of part variation can help one to identify the characteristics of each variation source and its contribution to the final assembly variation. In this section, a new method based on wavelet transform is developed to deal with the general part variation and analyze its multi-scale microstructure's impact on the final assembly quality.

2.5.1 Component Variation Microstructure Analysis by Wavelet Transform

Based on the theory of wavelet transform mentioned in Section 2.2.2, a given signal can be analyzed by choosing a suitable wavelet base and the desired decomposition level. In the past decades, many wavelet bases with different characteristics have been developed. The Daubechies wavelet base is the most common orthogonal wavelet base and is widely applied in signal processing (Mallat 1998). Figure 2.15 shows the scaling function and wavelet function of Daubechies of order 2, 6 and 10. The higher order of Daubechies will result in better amplitude transmission.

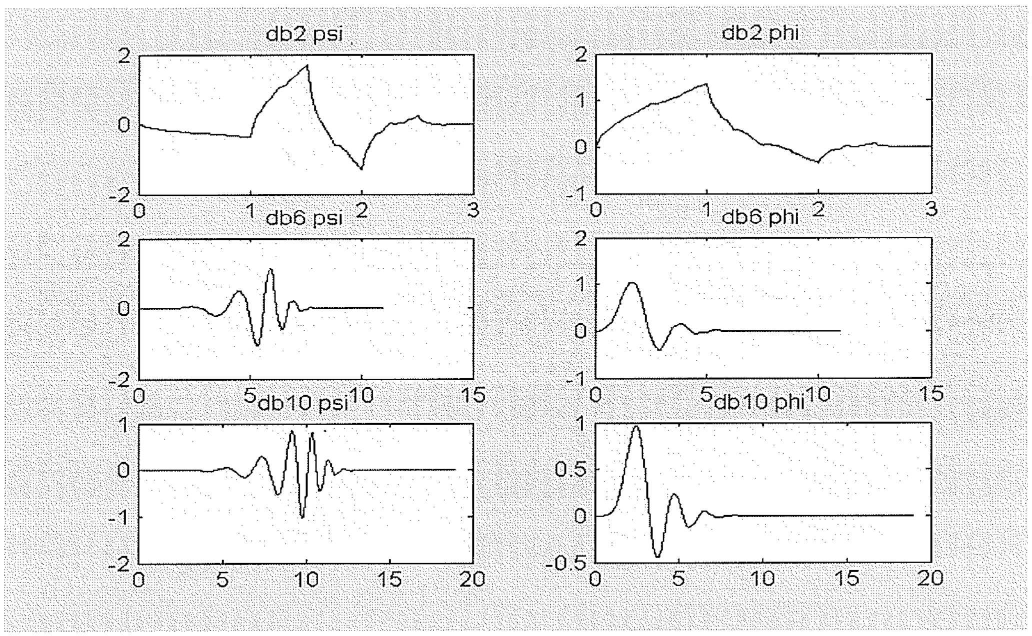


Figure 2.15 The scaling function (left) and wavelet function (right) of db2, db6, and db10

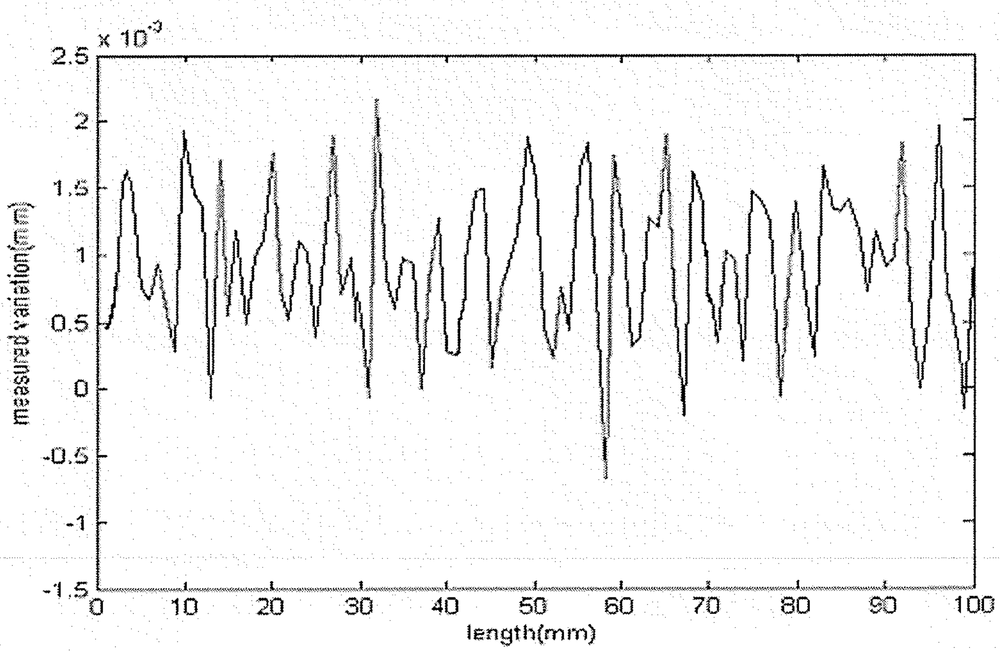


Figure 2.16 The measured part variation (Jiang *et al.* 2001)

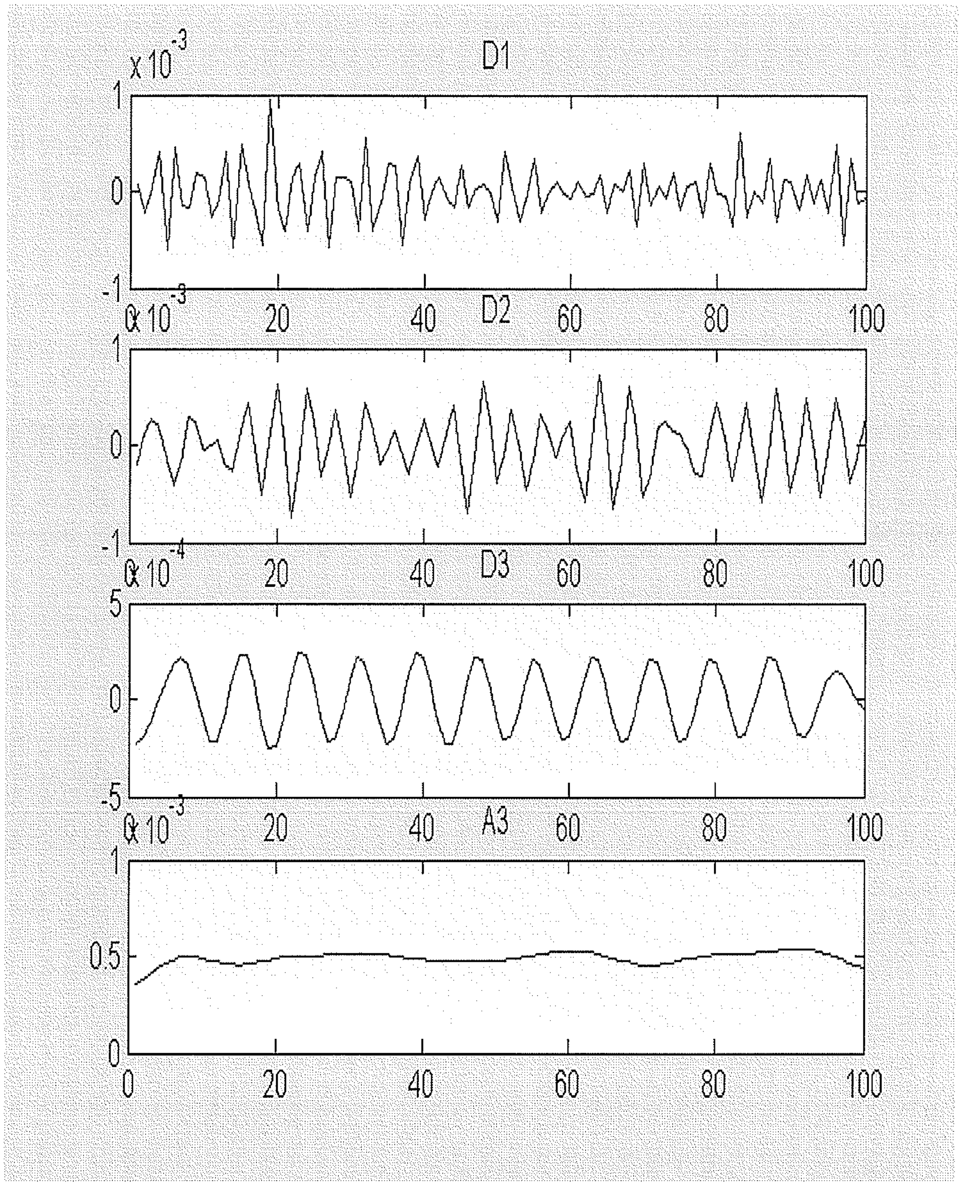


Figure 2.17 The wavelet analysis of the part variation of different components by db10

The profile variation of manufactured parts can be considered as a signal (Jiang *et al.* 2001). This variation signal may be non-stationary due to the uncertainties in manufacturing system. Figure 2.16 shows a measured sample profile variation of a flat sheet metal part from Jiang *et al.* (2001). By applying wavelet function of Daubechies of order 10 (db10), the part variation showed in Figure 2.16 can be decomposed into different components. Figure 2.17 shows its decomposition up to level 3. It represents that 4 different components in part variation are identified, including level 3 approximation (A3), level 3 detail (D3), level 2 detail (D2), and level 1 detail (D1). Choosing the decomposition level depends on the specific problem at hand and the goal you want to reach. Once the different frequency components in part variation are available, their contribution to the final non-rigid assembly variation can be further investigated.

2.5.2 Assembly Variation Simulation Procedure

Based on the four steps of the assembly process of components and subassemblies in a typical assembly station (shown in Figure 2.4) and the method on the component variation analysis by using the wavelet transform, the non-rigid assembly variation simulation flowchart is summarized in Figure 2.18.

The entire analysis procedure shown in Figure 2.18 consists mainly of two portions. One is the component variation analysis by using the wavelet transform; another is the four-step assembly process simulation based on the finite element analysis method.

The proposed assembly variation simulation procedure shown in Figure 2.18 provides a method to analyze the different scale components of part variation in the tolerance zone and their contributions to the final assembly variation. It can be implemented by using the software ANSYS and Matlab. ANSYS is used to generate the FEM model, compute component deformation and the clamping force, simulate the joining and releasing process, and calculate the spring back and the assembly variation. Matlab is applied to develop the program for the component variation analysis.

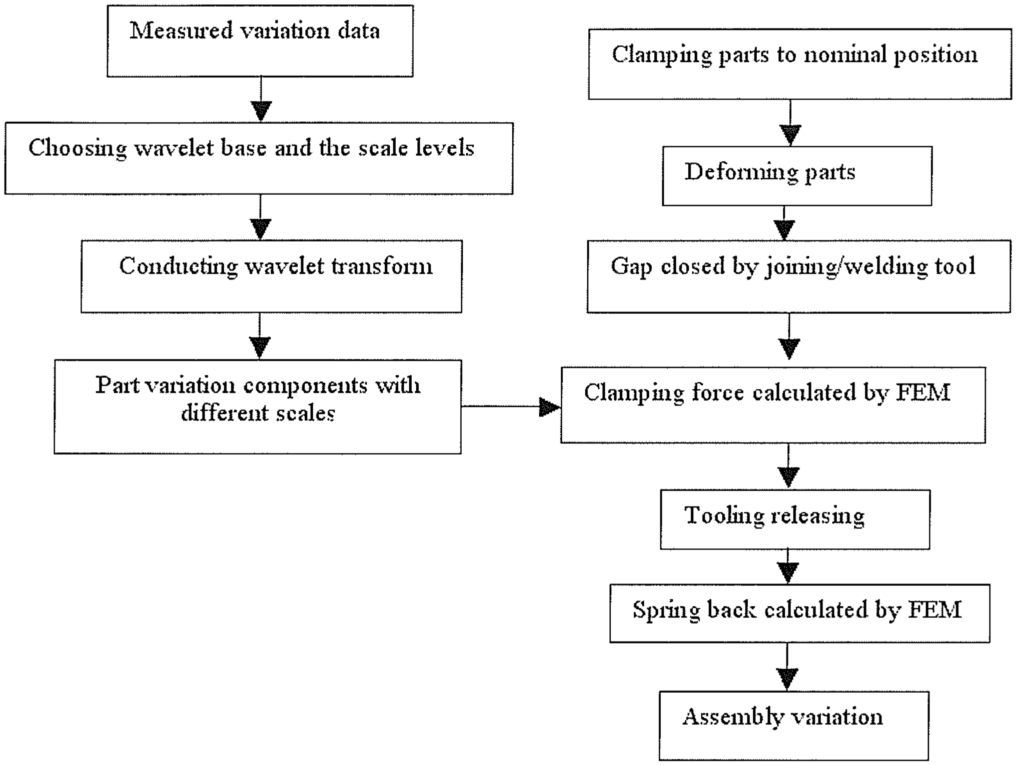


Figure 2.18 Flowchart of the assembly variation simulation procedure

2.5.3 Case Study: Assembly of Two Flat Sheet Metal Components

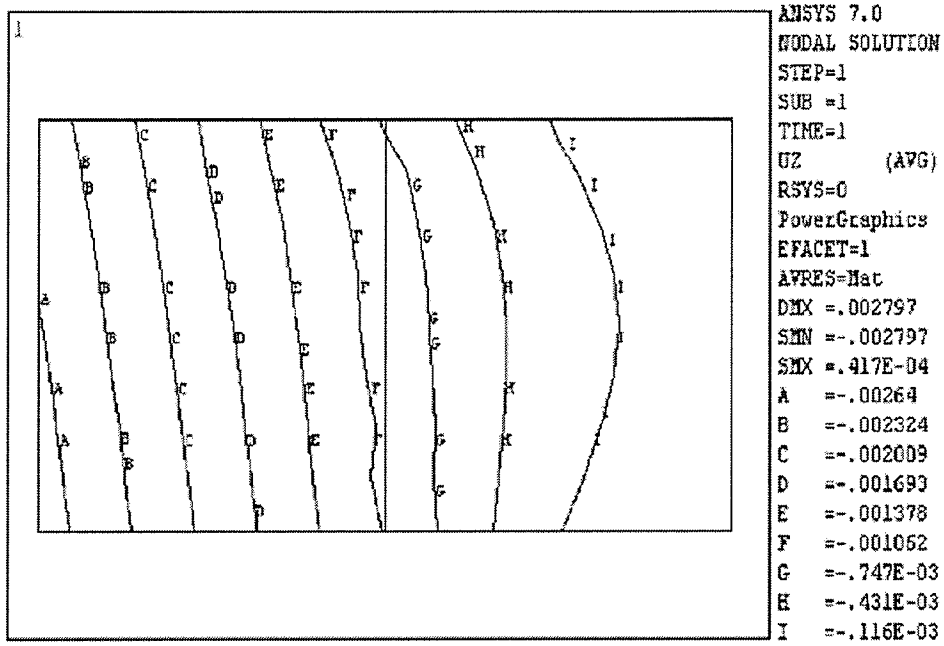
An assembly of two identical flat sheet metal components by lap joints, shown in Figure 2.8, is selected as an example to verify the proposed approach. Its FEA model is shown in Figure 2.12.

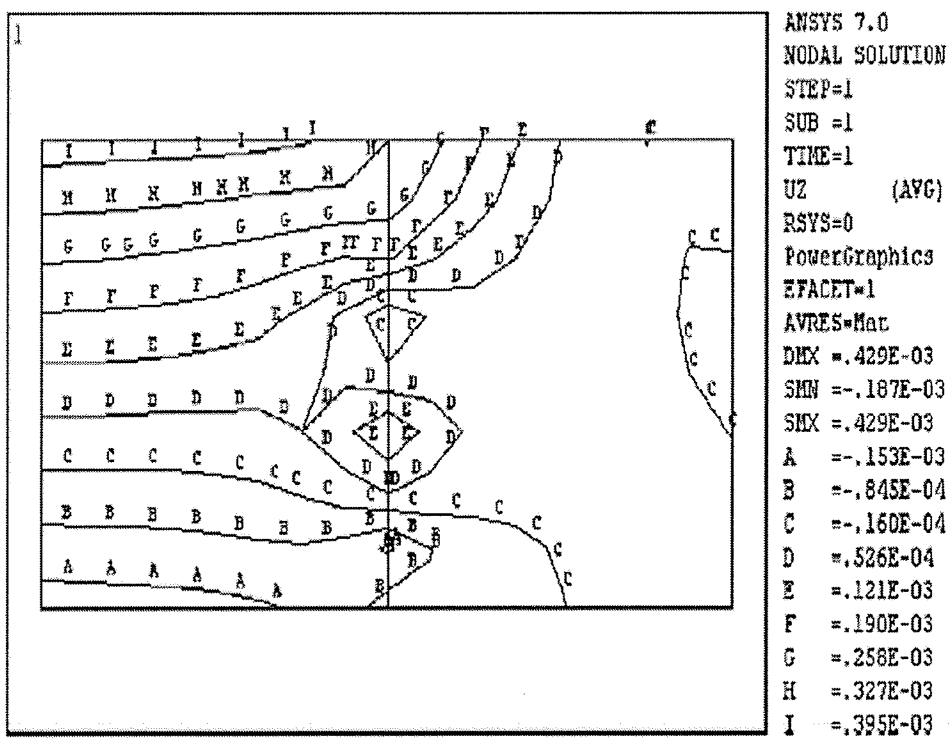
Suppose we have the measured variation signal from the component profile and its decomposition by wavelets db10 (see Figure 2.16 and Figure 2.17). The assembly variation that results from different scale components of part variation can be computed by the procedure shown in Figure 2.18.

In this numerical simulation, corresponding to the 4 different components of part variation, the assembly variation distribution (Figure 2.19) is obtained, respectively, when releasing all fixtures in Part 1. The assembly variations of 3 CPs (shown in Figure 2.12) are also extracted from computation results, and are shown in Figure 2.20. The computational procedure is coded by ANSYS APDL.

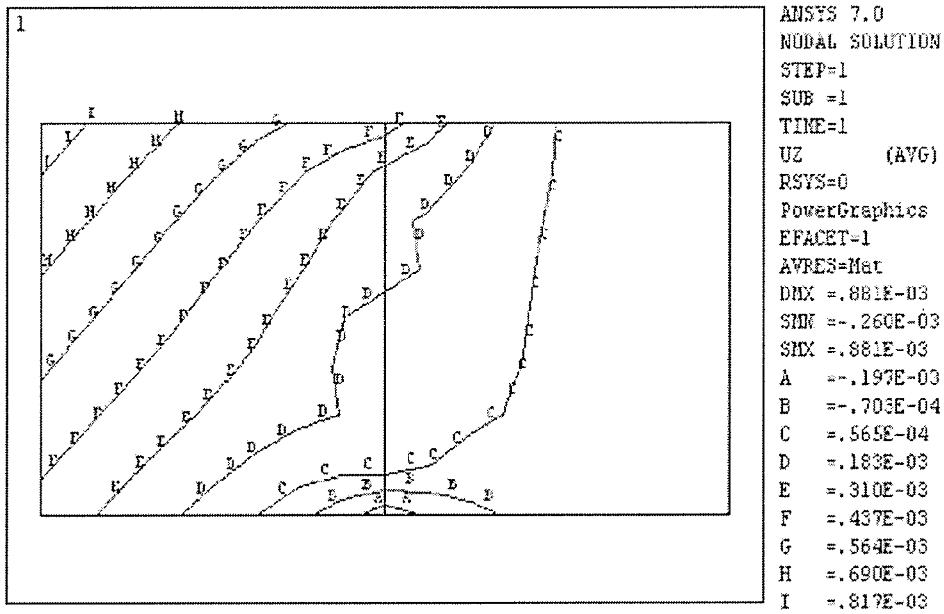
From Figure 2.19 and Figure 2.20 we can see that different scale components of part variation have different impact on the final assembly variation. The main component, i.e. the level 3 approximation (A3) of part variation in this case study, contributes much more than other detailed components (D3, D2, and D1). Moreover, the influence of the detailed components to the final assembly variation can not be ignored. For example, the contribution of D1 to the assembly variation of CP3 is about ¼ of that of A3, see Figure 2.20. Furthermore, it is also revealed in this case study that the detailed component D2 has a higher contribution than D3 and D1.

Since the different components of part variation are resulted from a kind of uncertainties in manufacturing system, the uncertainty that corresponds to D2 can be identified by detecting the signal that has the same frequency characteristics as D2. Therefore, it can enable one to find the uncertainty's cause and take action to control it.

(a)

ANSYS 7.0
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
UZ (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.002797
SMN =-.002797
SMX =.417E-04
A =-.00264
B =-.002324
C =-.002009
D =-.001693
E =-.001378
F =-.001062
G =-.747E-03
H =-.431E-03
I =-.116E-03

(b)

ANSYS 7.0
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
UZ (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.429E-03
SMN =-.187E-03
SMX =.429E-03
A =-.153E-03
B =-.845E-04
C =-.160E-04
D =.526E-04
E =.121E-03
F =.190E-03
G =.258E-03
H =.327E-03
I =.395E-03

(c)



(d)

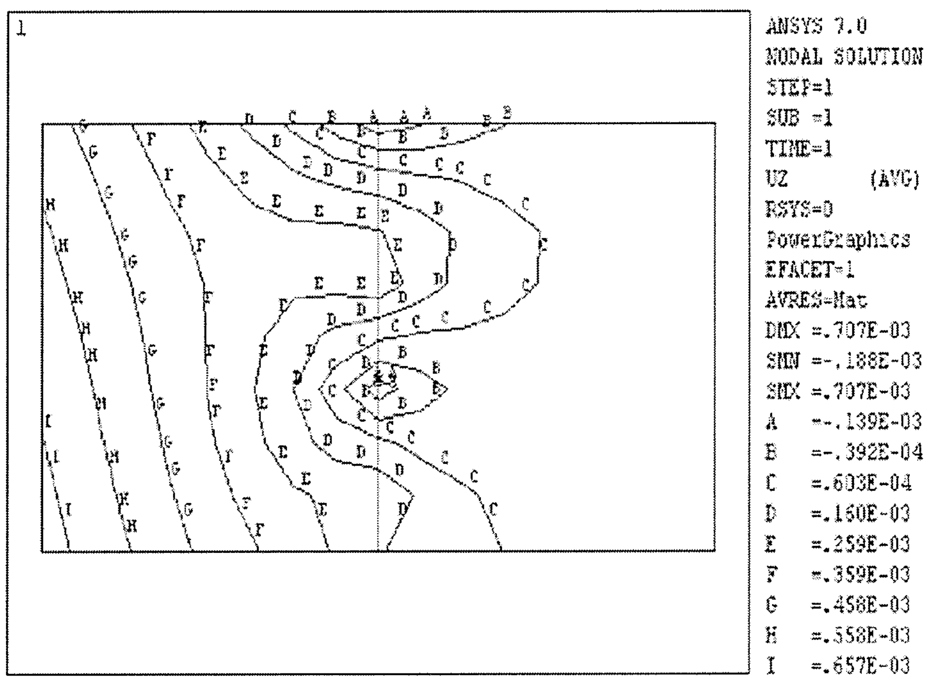


Figure 2.19 Assembly variation distribution. a) assembly variation corresponding to the level 3 approximation (A3) of part variation. b) assembly variation corresponding to the detailed level 3 component (D3) of part variation. c) assembly variation corresponding to the detailed level 2 component (D2) of part variation. d) assembly variation corresponding to the detailed level 1 component (D1) of part variation.)

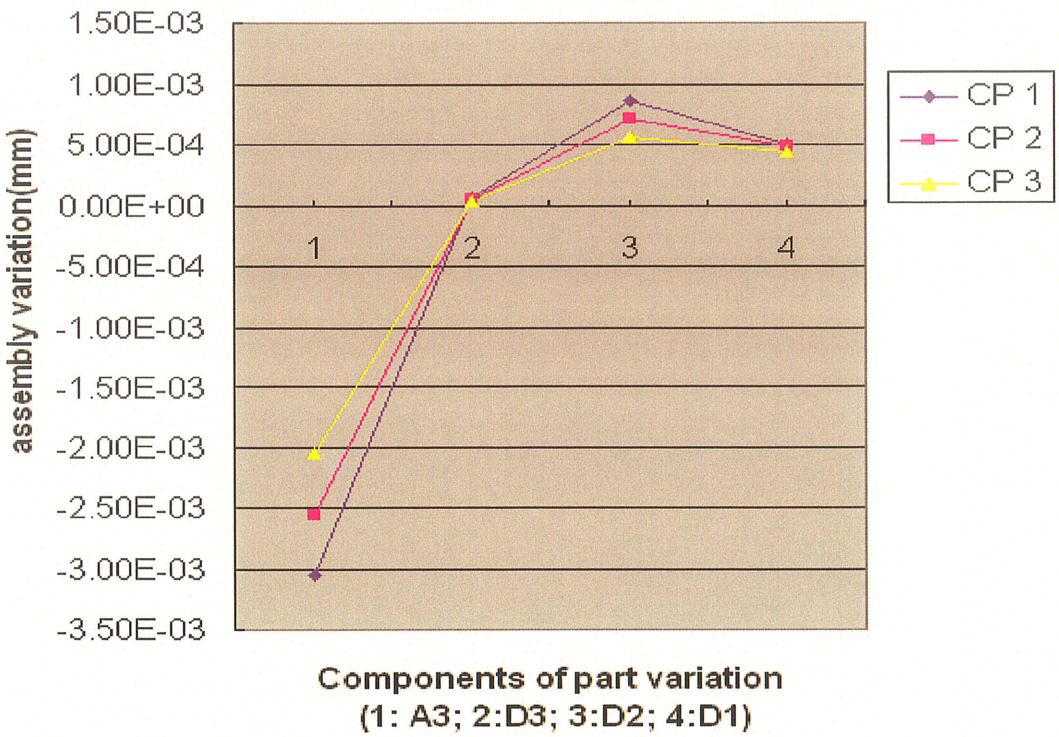


Figure 2.20 Assembly variation of 3CPs

2.6 Summary

Two novel methods for investigating the propagation of the detailed part variation and the influence of the component variation microstructure on the assembly dimensional variation are developed in this chapter, by integrating the finite element method with fractal geometry and wavelet transform, respectively.

Firstly, the fractal function, named Weierstrass-Mandelbrot (W-M) function is used to model the fractal part variation. For general application, wavelet transform is introduced to decompose and synthesis part variations with multi-scale microstructure. Then, the assembly process modeling of sheet metal components and subassemblies in a typical assembly station is described. At last, the assembly variation simulation procedure by fractals and wavelet transform is developed and illustrated by examples.

It is the first time that the impact of the detailed microstructures of part variation on the final non-rigid sheet metal assembly dimensional quality is modeled by fractals and wavelet transform. Insight on the detailed part variation propagation during the assembly process is provided. The approaches developed in this chapter contribute to the researches and engineering applications in high-precision non-rigid sheet metal product design and manufacturing.

Chapter 3

Simultaneous Optimization for Fixture and Joint Positions

3.1 Introduction

In the assembling of non-rigid sheet metal components, fixtures are indispensable to locate and hold a work piece. Fixture design is very important for an assembly process (Hu *et al.* 2003). One of the primary concerns for fixture design is determining the layout of the fixture elements so that the spring-back deformation of assemblies is minimized after releasing some fixtures.

Many researchers have addressed the fixture layout optimization. Rearick *et al.* (1993) proposed an optimization algorithm to obtain the optimal number and location of clamps that minimize the deformation of compliant parts. The N-2-1 fixture principle for the compliant sheet metal assembly was proposed by Cai *et al.* (1996b). In their work, an optimization algorithm to find the optimal location for N fixtures that minimize the work piece deflection under a given force was also presented. The work piece deformation was calculated by using FEA.

A general method to predict the effect of fixture design in compliant assembly was proposed in Dahlstrom and Camelio (2003). It focused on the impact of fixture layout, as well as locators and clamp positions on the dimensional quality of sheet metal assemblies. FEA and design of computer experiments were used to derive the response models. The response models were used to analyze the final assembly sensitivity to fixture, part and tooling variation for different assembly configurations. A genetic algorithm (GA)-based optimization method was studied in Liao (2002) to automatically select the optimal number of locators and clamps as well as their positions for sheet metal assemblies. In addition, Lai *et al.* (2004) presented a method that directly minimized work piece location errors due to its fixture elastic deformation. They developed a variation of genetic algorithm to solve the fixture layout problem.

The joint position in sheet metal assembly also impact on the final assembly variation. Liu and Hu (1997a) performed a study of joint performance in the sheet metal assembly. Since different joint configurations have different performance characteristics, they considered the level of dimensional variation in the assembly as one of the performance criteria. Three kinds of most commonly used joints in sheet metal assembly: lap joints, butt joints, and butt-lap joints were parametrically modeled and evaluated based on the assembly variation levels. Lee and Hahn (1996) conducted a comparison study on the existing joint technology, such as discrete fasteners, metal welds, and adhesive bonds that are commonly used in the design and assembly of transportation systems. Bhalerao *et al.* (2002) also discussed the FEM method and techniques for analyzing the functionality of a variety of joints. Zhang and Taylor (2001) presented the optimization problem of a spot-welded structure, whose optimal position of the spot welds in the structure yielded the maximum stiffness or fatigue life. But they did not address the influence of joint positions on the assembly deformation.

The above methodologies only focused on or separately studied fixture layout or joint configurations optimization. To date, no reports are found on the integrated design and production processes of non-rigid sheet metal assemblies.

The objective of this chapter is to establish the mathematical model of the simultaneous optimization problem of the fixture layout and joint positions based on the non-rigid sheet metal assembly process modeling. The fixture and joint positions are considered as the sources of assembly variation and treated as the design variables in this study since they affect the final assembly dimensional quality. The Mode-pursuing sampling method (MPS), one of the global optimization algorithms, is used to solve the optimization problem. The implementation of this approach by integrating ANSYS and Matlab is discussed and demonstrated through an application example.

3.2 Assembly Variation Analysis Considering Fixture Errors

Following the mechanistic simulation methodology developed by Liu and Hu (1997b), the non-rigid sheet metal assembly process in a typical assembly station can be modeled as a four step procedure (see Figure 2.4), i.e., placing components, clamping components, joining components, and releasing clamps/fixtures.

It is inevitable that the fabrication error $\{\delta_u\}$ of components will cause the matching gap between components and subassemblies after the components are loaded and placed on fixtures using a locating scheme. In the meanwhile, the errors of fixtures $\{\delta_t\}$ that are in the direction of flexible deformation, i.e., the out-of-plane fixture variation would also contribute to the matching gap. This gap shall be forced to close by deforming components to the nominal position.

Suppose that $\{F_u\}$ and $\{F_t\}$ are the assembly forces that need to close the gap induced by the fabrication error $\{\delta_u\}$ of components and the errors of fixtures $\{\delta_t\}$, respectively. The total assembly force $\{F_a\}$ would be written as follows,

$$\{F_a\} = \{F_u\} + \{F_t\} \tag{3.1}$$

where $\{F_u\}$ and $\{F_t\}$ can be computed according to the influence coefficient method which is introduced in details in Section 2.3 (Liu and Hu 1997b).

When using a joining method, such as welding, riveting, or gluing, to join two components, deformation occurs as the gap between components is closed. The total assembly force $\{F_a\}$ is still being applied. It is reasonable to assume that the spring-back force $\{F_w\}$ is equal to the total assembly force $\{F_a\}$ when some fixtures are released. Therefore, the final assembly variation $\{\delta_w\}$ can be calculated by applying the spring-back force $\{F_w\}$ on the assembly structure.

3.3 Mathematical Optimization Modeling for Fixture and Joint Positions

In this study, the simultaneous optimization problem of fixture and joining positions for non-rigid sheet metal assembly can be described as the following: in the presence of part variation and fixture variation, as well as the constrains from assembly process and designed function requirements, find the best locations of fixtures and joining points so that the non-rigid sheet metal assembly can achieve the minimal assembly variation. Therefore, firstly the key to this simultaneous optimization problem is to set up the objective function and corresponding constraints.

3.3.1 Objective Function

The characteristics of the CPs in non-rigid sheet metal assembly usually significantly affect the target value of the controlled variation, performance of component function, and customer satisfaction (Camelio *et al.* 2002 a). The optimization objective in this study is to minimize the variations at these critical points to improve the assembly dimensional quality.

Suppose that there are j fixtures, and k joints in an assembly, the position of fixtures and joints can be expressed as a vector $V = \{V_1, V_2, \ldots, V_j, V_{j+1}, \ldots V_{j+k}\}$, which has $V_i = [V^i_x, V^i_y, V^i_z]$, $i = 1, 2, .., j, j+1, \ldots, j+k$.

According to the general computation formation of finite element analysis

$$\mathrm{K\,U} = \mathrm{F_w} \tag{3.2}$$

Where K is the total stiffness matrix of the sheet metal assembly

U is the vector of total node deformation

$\mathrm{F_w}$ is the vector of spring-back force, which is equal to the $\mathrm{F_a}$ in equation (3.1)

For a given fixture layout and joint positions V, the deformation at each node can be computed by applying the boundary conditions which correspond to both fixture and joint positions.

Assume there are r number of CPs; the deformation of r CPs in an assembly can be extracted as

$$\boldsymbol{U}_\mathrm{i} = [\boldsymbol{U}^\mathrm{i}_\mathrm{x} \quad \boldsymbol{U}^\mathrm{i}_\mathrm{y} \quad \boldsymbol{U}^\mathrm{i}_\mathrm{z}], \qquad i = 1, 2, \ldots, r \tag{3.3}$$

Confining the study only on the out-of-plane deformation (z direction) while without losing its generality, the total absolute values of assembly variation of the r CPs can be obtained as

$$\Theta = \sum_{i=1}^{r} | U_z^i | \tag{3.4}$$

where the $|\cdot|$ gives the absolute value.

From equation (3.2), it is known that the assembly variation is determined by the positions of fixtures and joints. Therefore, equation (3.4) can be rewritten as

$$\Theta = \sum_{i=1}^{r} | U_z^i | = f(V_1, V_2, \ldots, V_{j+k}) \tag{3.5}$$

Equation (3.5) is the objective function for the simultaneous optimization problem of non-rigid assembly fixture and joint positions. The optimal solution can be obtained by minimizing equation (3.5) under certain constraints.

3.3.2 Constraints

In the fixture design process, the positions of fixtures and joints are localized at some specific areas according to the design requirements (Rearick *et al.* 1993, Cai *et al.* 1996b). For example, in Figure 3.1 the locators P_1 and P_2 will be inside a square, and joint S will be on a line segment.

Suppose the positions of j fixtures and k joints will be selected in areas Ω_1 and Ω_2, respectively, we have

$$V_i(x, y, z) \in \Omega_1 \qquad i = 1, 2, \ldots, j \tag{3.6}$$

and

$$V_i(x, y, z) \in \Omega_2 \qquad i = j+1, j+2, \ldots, j+k \tag{3.7}$$

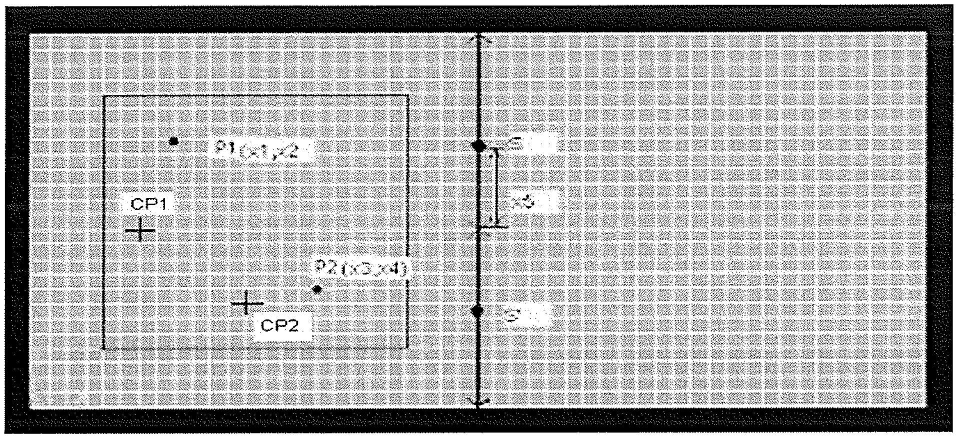


Figure 3.1 Two sheet metal parts assembly

Meanwhile, in consistence with the specifications of product function and assembly technique, any two of fixture/joint positions V_i, V_n should not be very close, and should be kept a distance L_{in}.

$$\left\| V_i - V_n \right\| \geq L_{in} \qquad i,n = 1,2,\ldots,j,j+1,\ldots,j+k \tag{3.8}$$

3.3.3 The Mathematical Formation for Optimization

Therefore, the mathematical formation for simultaneously optimizing the fixture layout and joint position can be summarized as the following

$$\text{Minimize} \qquad \Theta = \sum_{i=1}^{m} | U_z^i | = f(V_1, V_2, \ldots, V_{j+k}) \tag{3.9}$$

$$\text{Subject to:} \quad V_i(x,y,z) \in \Omega_1 \qquad i = 1,2,\ldots,j \tag{3.10}$$

$$V_i(x,y,z) \in \Omega_2 \qquad i = j+1, j+2, \ldots, j+k \tag{3.11}$$

$$\left\| V_i - V_n \right\| \geq L_{in} \qquad i,n = 1,2,\ldots,j,j+1,\ldots,j+k \tag{3.12}$$

From the above mathematical modeling, it is seen that this optimization problem has following specialties:

1) The non-linear objective function is like a "black-box" function and its properties are unknown.

2) The conventional gradient-based method is not suitable for this kind problem since it only gives a local optimum and the gradient calculated from FEA is usually noisy and not reliable (Haftka *et al.* 1998).

3) Application of genetic algorithms (GA) would be too computation intensive since GA needs a large number of function evaluations, and in this case, a FEA is required for each objective function evaluation.

In this chapter, a new effective global optimization algorithm, so-called the mode-pursuing sampling method (MPS) (See Wang *et al.* 2004) is identified and utilized to solve the optimization problem. The MPS algorithm was developed for expensive "black-box" problems and seemed to be suitable for this problem under study. Details of MPS will be elaborated in Section 3.4.

During the optimization process, in order to ensure each fixture and joint position is applied on the finite element node, the multi-point constraint (MPC) method is employed to avoid re-meshing the FEA model (Cai *et al.* 1996 b, Camelio *et al.* 2002 a).

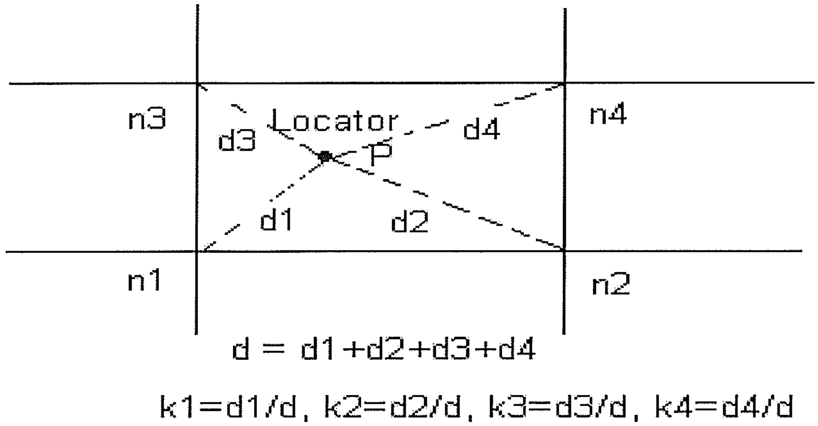


Figure 3.2 Parameters defined for MPC

The basic theory of MPC method is illustrated in Figure 3.2. Suppose one locator P is in a FEA element, which has four nodes n1, n2, n3, and n4. The degree of freedom (DOF) in Z direction for these four nodes is w1, w2, w3, and w4, respectively. Then, the boundary condition applied at locator P can be expressed as a linear function of w1, w2, w3, w4

$$wp = k1*w1+k2*w2+k3*w3+k4*w4 = \text{constant} \tag{3.13}$$

where k1, k2, k3, k4 are coefficients, and k1+k2+k3+k4 = 1. In this study, they are obtained by normalizing the computed distances between locator P and nodes n1, n2, n3, and n4.

3.4 Optimization Algorithms: MPS Method

The Mode-pursuing sampling method (MPS), which was developed by Wang *et al.* (2004), is a general global optimization algorithm on any expensive "black-box" functions.

The MPS is an algorithm based on sampling technology and it searches the design space only with the objective function value and does not need any calculation of gradients. In terms of the total number of expensive function evaluations and the amount of computation, the MPS is proven to be more effective than genetic algorithms when design variables are a few.

Basically, the MPS originates from the random-discretization based sampling method of Fu and Wang (2002), which is a general-purpose algorithm to draw a random sample from any given multivariate probability distribution. To differentiate points evaluated by FEA from points calculated by an approximation model, we refer to the former "expensive points" and the latter "cheap points." Suppose a function $f(x)$ is to be minimized in a compact set $S(f) = [aa, bb]^n$, and $f(x) \geq 0$. The optimization procedure of the MPS method can be described as the following steps:

1) Initialization

Firstly, based on function $f(x)$, m uniformly distributed expensive points $x^{(i)}$, i=1, m are initially generated on $S(f) = [aa, bb]^n$.

2) Construction of probability density function

An approximation function $S_p(x)$ can be obtained based on these m points, such as a linear spline function $S_p(x)$

$$S_p(x) = \sum_i \alpha_i \|x - x^{(i)}\| \tag{3.14}$$

$$\text{Subject to } S_p(x^{(i)}) = f(x^{(i)}),\ i=1, m \tag{3.15}$$

Then a nonnegative function $g(x)$ can be constructed on $S(f) = [aa, bb]^n$ by defining

$$g(x) = C_0 - S_p(x) \geq 0 \tag{3.16}$$

where C_0 is a constant.

3) Sampling points by Fu and Wang (2002)'s method

By applying the sampling algorithm of Fu and Wang, another m random sample points $Y^{(i)}$, i=1, m are drawn from S(f) = [aa, bb]^n according to $g(x)$. These sample points tend to locate around the current maximum of g (x), i.e., the minimum of $S_p(x)$. Then these m points are evaluated by FEA and thus become expensive points.

4) Evaluation and stopping search

Combine the new m points $Y^{(i)}$ (i =1, m) with the old points $x^{(i)}$ (i =1, m) together: X = [X Y], and repeat Steps 2)-3) until a certain stopping criterion is met.

The above MPS optimization algorithm is proved to be very effective and applicable in global optimum through testing with well-known benchmark problems (Wang *et al.* 2004, Shan and Wang 2005). In this study, the MPS will be employed to simultaneously optimize the fixture layout and joint positions for non-rigid sheet metal assemblies.

Based on the mathematical optimization model and the MPS algorithm discussed above, the overall simultaneous optimization for the fixture and joint positions of non-rigid sheet metal assemblies is implemented by integrating the finite element analysis software ANSYS into the Matlab environment. The workflow diagram is show in Figure 3.3.

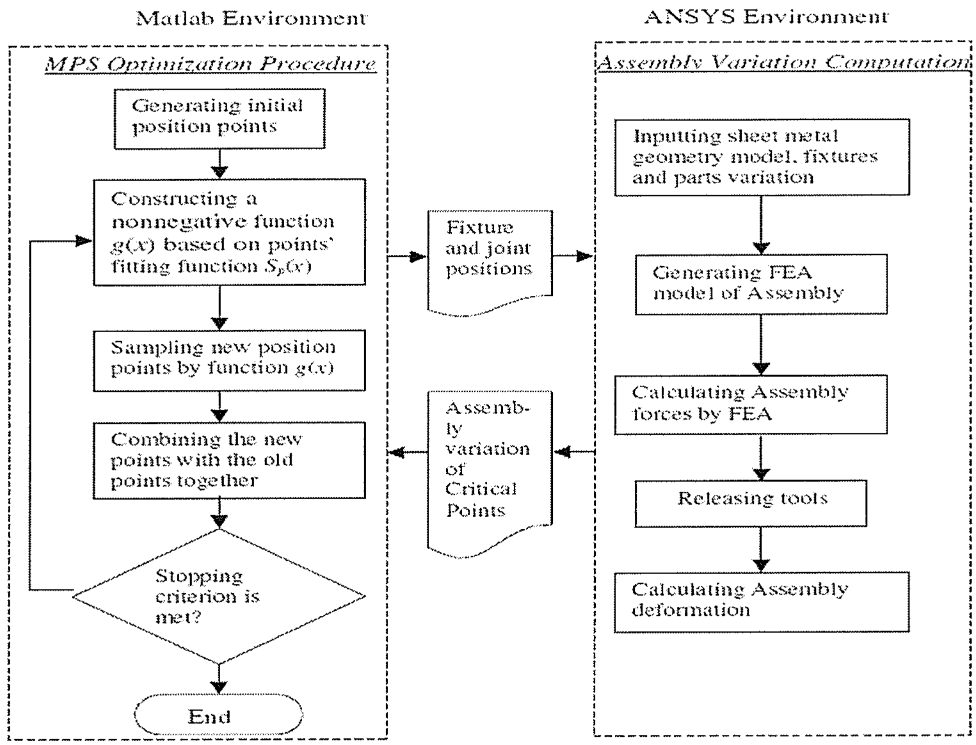


Figure 3.3 The workflow of optimization by integrating Matlab and ANSYS

The basic computation procedure of the sheet metal assembly variation is constructed as a batch file by using ANSYS, while the mainstream of MPS optimization algorithm is coded by applying Matlab. Because the basic FEA model for the assembly variation computation is parametric, the Matlab based MPS optimizer is able to update the basic FEA model by changing its boundary conditions according to the given positions of fixtures and joints until the optimum is obtained.

The proposed optimization flowchart shown in Figure 3.3 provides a seamless process to globally search the optimal positions of fixtures and joints for non-rigid sheet metal assemblies so that the assembly variations at critical points are minimal. The next section will show an example to which the proposed method is applied.

3.5 Application Example

An assembly of two identical flat sheet metal components by lap joints shown in Figure 3.1 is employed to illustrate the proposed method. Assuming that these two components are manufactured under the same conditions, their fabrication variations are expected to be the same. The size of each flat sheet metal parts is 100×100×1mm, with Young's modulus E = 2.62e+4 N/mm^2, and Poison's ratio ν = 0.3. The finite element computation model of the assembly is created in ANSYS. The element type is SHELL63. The number of elements and the number of nodes are 1250 and 1352, respectively.

The fixture scheme N-2-1 (N > 3) is applied and thus the assembly is over constrained. Two locators at P1(x1, x2) and P2(x3, x4) that are assumed having fixture errors, as well as one joint S(x5) (as well as its symmetrical point S' with respect to the part's centre line) are needed to be optimized so that the assembly variation is satisfactory. It is assumed that, according to the assembly requirements, locators P1 and P2 should be chosen in a rectangle area, and joints S and S' should be on a line segment. Locator P1 should not be too close to locator P2, and joint S also should be in a distance from other joints. After assembling, locating fixtures P1 and P2 are released.

The initial conditions applied are: the fixture variation at locators P1 and P2 is 1mm; part variation at joint points that are indicated by "**x**" in Figure 3.1 is 1mm. So the multi-point constraint (MPC) is applied respectively on P1 and P2 to avoid re-meshing the FEA model as the following is specified.

$$k1*w1+k2*w2+k3*w3+k4*w4 = 1 \text{ mm} \qquad (3.17)$$

The assembly variations at critical points CP1 and CP2 shown in Figure 3.1, i.e., the absolute values of U^1_z and U^2_z are determined by positions of P1 (x1, x2), P2 (x3, x4) and S (x5). U^1_z and U^2_z are extracted to form the optimization objective value, and the design variables are x1, x2, x3, x4, and x5, which are gathered into a vector X = [x1, x2, x3, x4, x5].

Suppose that we set up a constraint on locator P1 and P2: $\|P1\text{-}P2\| \geq 10$ mm. The search range is x1, x2, x3, x4 $\in$ [20, 80] and x5 $\in$ [10, 40]. Therefore, the mathematical optimization model for this specific example can be written as the follows

$$\text{Minimize} \quad \Theta(X) = |U_z^1(X)| + |U_z^2(X)| \tag{3.18}$$

$$\text{Subject to} \quad (x1\text{-}x3)^2 + (x2\text{-}x4)^2 \geq 100 \tag{3.19}$$

$$20 \leq x1, x2, x3, x4 \leq 80 \tag{3.20}$$

$$10 \leq x5 \leq 40 \tag{3.21}$$

By applying the proposed algorithm that integrates the mode-pursuing sampling method (MPS) and the FEM-based assembly simulation approach, the optimal fixture and joint positions are obtained as follows

$$P1 = (66.44, 26.38), P2 = (63.63, 52.24), S = 16.0 \tag{3.22}$$

The minimal objective function value is

$$\Theta_{min} = 0.148 \text{ mm} \tag{3.23}$$

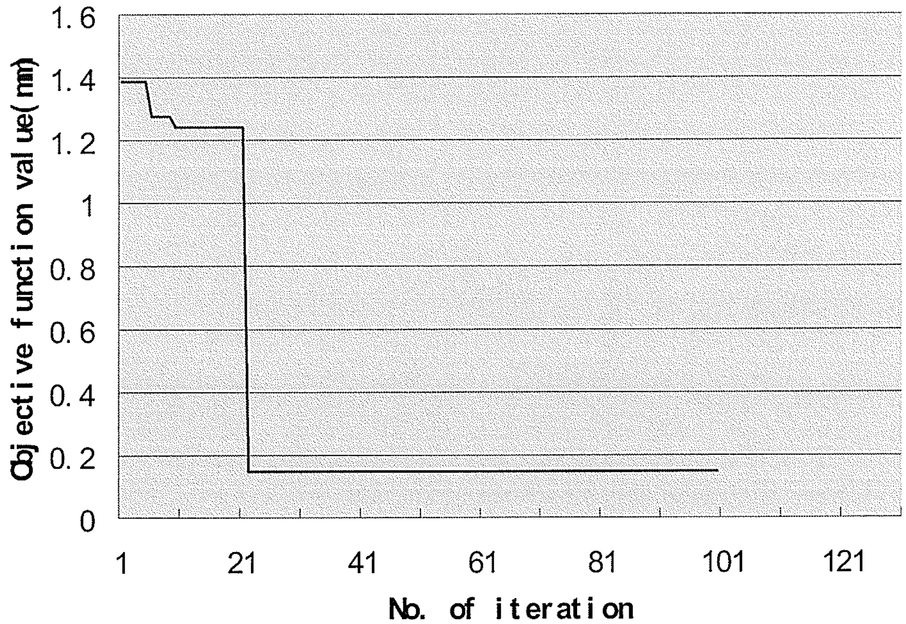


Figure 3.4 The iteration and convergence process of MPS

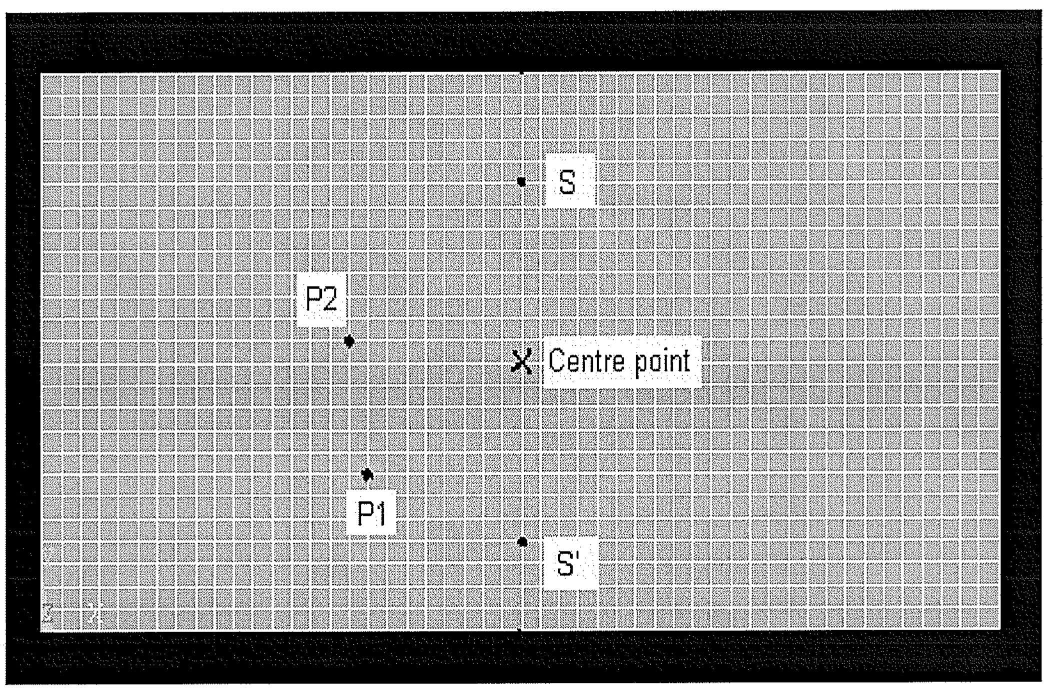


Figure 3.5 The optimal positions for fixtures P1, P2 and joints S, S'

The convergence process is shown in Figure 3.4. It took only 22 iterations and 100 function evaluations (the times of finite element analysis) for MPS algorithm to obtain the optimal results. The optimal positions for fixture P1, P2 and joint S as well as its symmetrical S' are shown in Figure 3.5, and the assembly variation distribution under such optimal fixture and joint positions is shown in Figure 3.6.

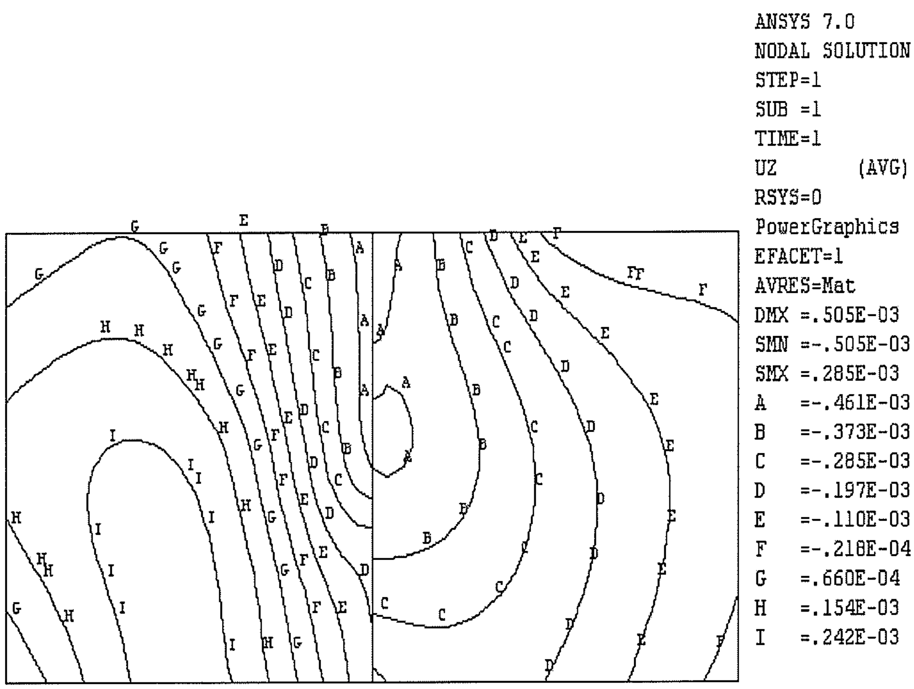


Figure 3.6 The assembly variation distribution under optimal fixture and joint positions

3.6 Summary

In this chapter, the mathematical model of the simultaneous optimization problem of the fixture layout and joint positions based on the non-rigid sheet metal assembly process modeling was developed.

Unlike the most current researches only focusing on fixture layout optimization, this chapter takes the fixture and joint positions into account as the sources of assembly variation and as the design variables, since they affect the final assembly dimensional quality, thus the factors from the design process (joint configuration) and the manufacturing process (fixture layout) are combined together into one mathematical model. The Mode-pursuing sampling method (MPS) is modified and applied to solve this optimization problem. The application example demonstrates that the proposed approach is applicable and effective.

This work contributes to the study of the integrated sheet metal design and production. It can be extended to a multi-objective optimization (MOO) problem which includes structure durability, manufacturing cost, and so on.

Chapter 4

Non-linear Sheet Metal Assembly Variation Analysis by Contact Modeling

4.1 Introduction

A typical sheet metal assembly process starts with loading parts on a fixture, followed by clamping parts in the fixture, jointing them together, and finally releasing the fixtures and clamps, shown in Figure 2.4 (Liu and Hu 1997 b, Mattikalli *et al.* 2002).

It is known that the variation between parts and fixtures can cause gap or interference in the joining area. Assembly tools, such as welding guns and/or clamps, force the two mating surfaces together at the joining area. Non-rigid parts tend to deform during these operations, leading to changes in contact conditions; whereas surfaces that stay in contact may move apart producing gaps (Mattikalli *et al.* 2000, Lian *et al.* 2002).

Furthermore, depending on the joining method, complex multi-physical phenomena may occur in the contact zones and/or joint zones, including a material plastic deformation, thermo-structure interaction, thermo-electrical-structure interaction, linear or non-linear friction application, and so on. These non-linear characteristics make it difficult to perform simulation and dimensional variation analysis for the non-rigid sheet metal assembly.

Generally, nonlinear structural behavior arises from a number of causes, which can be grouped into these principal categories, changing status (e.g. contact), geometric nonlinearities and material nonlinearities. When a structure experiences large deformation, its changing geometric configuration can cause the structure to respond nonlinearly. Geometric nonlinearity is characterized by "large" displacements and/or rotations. Nonlinear stress-strain relationships are a common cause of nonlinear structural behavior.

Many factors can influence a material's stress-strain properties, including load history (as in elastoplastic response), environmental conditions (such as temperature), and the amount of time that a load is applied (as in creep response). Situations in which contact occurs are common to many different nonlinear applications, such as material processing, products assembly process and so on. Contact forms a distinctive and important subset to the category of changing-status nonlinearities.

To date, most current dimension variation methods for non-rigid sheet metal assembly are based on linear elastic mechanics and the contact phenomenon is ignored. There are only few reports on the contact behavior in sheet metal assemblies. For instance, Mattikalli *et al.* (2000) described an approach that involved a model of contact between compliant bodies based on variational inequalities to model the mechanics of assembly. By solving a quadratic programming (QP) problem, the contact situation is resolved and the mechanics of parts during assembly is obtained. But the assembly variation issue was not addressed in the study. Lian *et al.* (2002) studied the effect of elastic contact on variation transformation by a simple beam structure assembly. Dahlstrom *et al.* (2002) indicted that the contact between curved flanges would affect the quality of sheet metal assembly, but they did not further study this issue. Recently, Dalstrom and Lindkvist (2004) studied the contact modeling in the method of influence coefficient (MIC) for variation simulation of sheet metal assemblies. They developed a contact algorithm and combined with the MIC method to perform variation analysis. However, this method needs an extra complex algorithm to conduct contact detection during the analysis process and is difficult to apply in the industrial product design process.

In brief, existing studies of the contact problem of the sheet metal assembly are fairly limited. The contact modeling method of non-rigid sheet metal assembly towards dimensional variation analysis is still under development. Areas that need further investigation include, for instances, establishing the contact model between the assembly surfaces, developing systematic and generally applicable analysis method and software tools for assembly dimensional variations, and developing standard testing methods for model verification and validation.

The objective of this chapter is to investigate the contact problem related to the non-rigid sheet metal assembly variation analysis by applying numerical contact FEA modeling validated by physical experiments. A non-linear dimension variation analysis method is developed by establishing the elastic contact model between the assembly surfaces. The analysis method is implemented by applying ANSYS APDL. Due to the complexity of the sheet metal assembly process, this research focuses on the elastic contact between the assembly surfaces. In order to make comparison, an example of two sheet metal parts assembly is used for the assembly dimensional variation analysis with and without contact modeling, respectively. The physical tests are also performed to validate the proposed approach.

4. 2 General Description of Elastic Contact Problem

Consider a three dimensional contact problem (Hills 1992, Mijar and Arora 2000) with friction between two deformable bodies *Q1* (target) and *Q2* (contactor), shown in Figure 4.1. In the elastic bodies *Q1* and *Q2*, the boundary *Ld* and *Ls* are applied displacements and forces/moments, respectively. Candidate contact surfaces of the target and contactor are denoted by *Lc(1)* and *Lc(2)*, respectively. Define a common contact surface *Lc*, located between *Lc(1)* and *Lc(2)*, and an orthonormal local reference *(t1,t2,n)* on each modes, where *(t1,t2)* represents the plane tangent to the surface and *n* is the outward normal to the surface.

Suppose that the displacement vector and contact force vectors in the orthonormal local reference are $u_c^{(i)} = (u_{t1}^{(i)}, u_{t2}^{(i)}, u_n^{(i)})$ (i=1,2) and $p_c = (p_{t1}, p_{t2}, p_n)$, respectively. Here p_n denotes the normal contact force, and the contact friction force p_t is decomposed into components p_{t1} and p_{t2}.

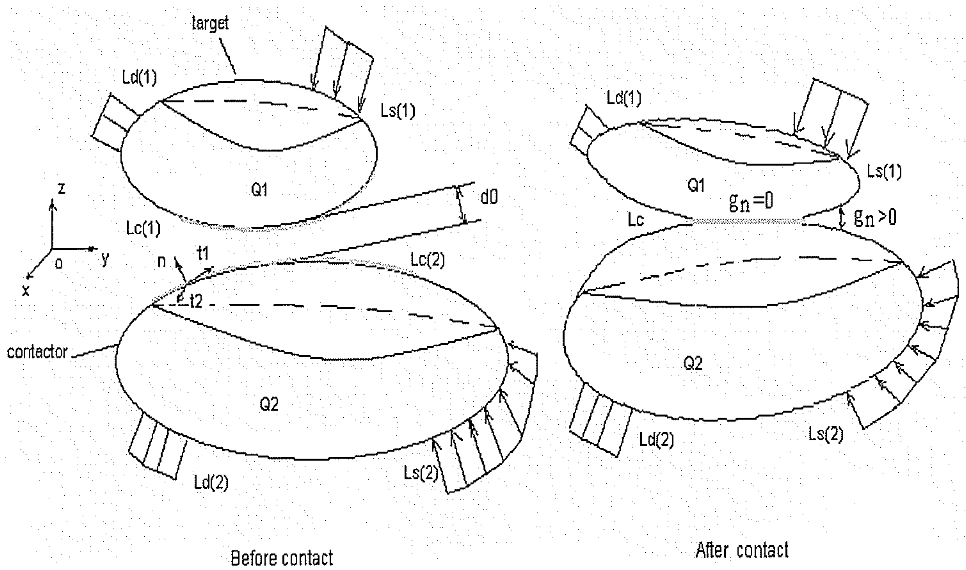


Figure 4.1 The elastic contact problem

To void penetration of the bodies into each other, the normal contact distance $g_n := u_n^{(1)} - u_n^{(2)} - d_0$ (where d_0 is the initial gap), on the contact boundary *Lc*, has to be greater than or equal to zero, i.e. $g_n \geq 0$ (shown in Figure 4.1).

Contact between two bodies Q_1 and Q_2 shown in the Figure 4.1 is now locally characterized by a unilateral contact condition, a compression condition and a complementary condition as follows:

Unilateral contact condition: $g_n \geq 0$ (4.1)

Compression condition: $p_n \leq 0$ (4.2)

Complementary condition: $p_n \cdot g_n = 0$ (4.3)

Since the components are either in a contacting situation or a separate condition. The case $g_n = 0$ and $p_n < 0$ characterises the contacting situation, and the case $g_n > 0$ and $p_n = 0$ corresponds to the separating situation. The unilateral contact condition requires the contact and target not penetrating each other. The compression condition shows that the contractor and target cannot pull each other. Finally, the complementary condition indicates that contactor is either separating from or contacting the target.

For the tangential contact on the boundary *Lc*, according the Coulomb's classical friction law which has been used widely in engineering application, two bodies in steady contact either stick to each other or they slip on each other, depending on the following conditions:

$$|p_t| < \mu\, |p_n| \quad \text{(stick condition)} \tag{4.4}$$

$$|p_t| = \mu\, |p_n| \quad \text{(slip condition)} \tag{4.5}$$

where μ is the coefficient of friction, and $|\cdot|$ gives the absolute value.

For the contact bodies shown in Figure 4.1, under the assumption of small displacement, besides the contact condition above, the classical boundary value problem (BVP) for this frictional contact system should include the following basic equations (Hills 1992, Mijar and Arora 2000).

1) Equilibrium equations

$$\sigma_{ij,j} + b_i = 0 \tag{4.6}$$

2) Strain-displacement relations

$$\varepsilon_{ij} = (u_{i,j} + u_{j,i}) / 2 \tag{4.7}$$

3) Constitutive equations

$$\sigma_{ij} = D_{ijkl}\, \varepsilon_{kl} \tag{4.8}$$

4) On boundary L_d

$$u_i = \underline{u}_i \tag{4.9}$$

5) On boundary L_s

$$\sigma_{ij} N_j = T_i \tag{4.10}$$

where i, j, k, l =1, 2, 3, which represents the three spatial coordinate directions, respectively; σ_{ij} is the stress tensor; ε_{ij} is the strain tensor; D_{ijkl} is the elastic moduli tensor; b_i is the body force vector; u_i is the displacement vector; N_j is the unit vector on boundary L_s; $\underline{u}_i$ is the given displacement on the boundary L_d; and T_i is the given pressure on boundary L_s;

By applying the virtual work theory, the variational equality formulation for the above contact BVP can be written as below:

$$G(u, \delta u) - \int_{Lc} p_c \bullet \delta u ds = 0 \tag{4.11}$$

where the function G is the overall internal energy as caused by the contact, defined as

$$G(u, \delta u) = \int_{Q} \sigma_{ij} \bullet \delta \varepsilon_{ij} dQ - \int_{Q} b \bullet \delta u dQ - \int_{Ls} T \bullet \delta u ds \tag{4.12}$$

Due to the fact that the contact zone and the magnitude of the contact forces are unknown priori to the analysis, and large changes in the contact area are possible including relative sliding with the Coulomb friction or possible separation after contact, it is thus generally difficult to solve an elastic friction contact problem.

Several numerical solution methods have been proposed to solve the variational equation (i.e. equation (4.11)) of the elastic contact problem (Mijar and Arora 2000), including penalty method, augmented Lagrangian method, Lagrange multiplier method and augmented Lagrangian multiplier method. These methods, incorporated to general FEA technology, are applied to solve the contact problem that involves complex geometry shapes. Their characteristics are described as follows.

In the penalty method, the accuracy of the solution depends on the choice of the penalty parameter. Too small a penalty parameter may cause unacceptable error in the solution. Also, the penalty method suffers from ill conditioning as the penalty parameter becomes large.

The augmented Lagrangian method is an iterative series of penalty methods. The contact tractions (pressure and frictional stresses) are augmented during equilibrium iterations so that the final penetration is smaller than the allowable tolerance. Compared to the penalty method, the augmented Lagrangian method usually leads to better conditioning and is less sensitive to the magnitude of the contact stiffness. The Lagrange multiplier method introduces new unknowns for each constraint. Therefore, it always increases the dimension of the system equations to be solved. For large-scale problems where the contact surface consists of a large number of nodes, the number of unknowns introduced by the Lagrange multiplier method is also large. This increases the CPU time to solve the problem.

For the augmented Lagrangian multiplier method, both penalty parameters and Lagrangian multipliers are applied, and penetration is admissible but controlled by allowable tolerance.

General-purpose FEA tools like ANSYS, ABAQUS, ADINA and I-DEAS have implemented frictional contact algorithms by employing incremental/iterative procedures (e.g. Newton-Raphson method) base on variational equality formation (i.e. equation (4.11)). The nonlinear analysis process using the Newton-Raphson method is classified into the following two levels of operations.

1) Load is applied in increments to account for the contact and friction nonlinearity. That is, several substeps or time steps are required to define.

2) At each substep, a number of equilibrium iterations are performed to obtain a converged solution.

The Newton-Raphson equations at the i-th iteration within the time step n are given as

$$K_n^i \Delta u^i = (F^{\alpha})_n - (F^{\beta})_n^i \tag{4.13}$$

$$u^{i+1} = u^i + \Delta u^i \tag{4.14}$$

where K_n^i is the stiffness matrix at iteration i within time step n, $(F^{\alpha})_n$ is the applied force vector at time step n, $(F^{\beta})_n^i$ is the restoring force vector at iteration i within time step n, and Δu^i is an increment for the displacement u^i at the i-th iteration.

At iteration i within time step n, according to the theory of the finite element analysis method (Rao 1999), the stiffness matrix and the restoring force vector in equations (4.13) are assembled by using the structural finite elements and the contact elements as well. The Newton-Raphson iteration within time step n stops until the residual vector $R = (F^{\alpha})_n - (F^{\beta})_n$ is close to zero.

Currently, ANSYS supports node-to-node contact, node-to-surface contact and surface-to-surface contact. In the contact solving process by ANSYS, the Gauss Integration Points (GIP) or the FEM nodes can be used to check the contact condition, shown in Figure 4.2 and Figure 4.3, respectively. The GIP is applied in the present study since it generally provides more accurate results than the nodal detection scheme (especially for the surface-to-surface contact model), and the nodal detection scheme requires the smoothing of the contact surface or the target surface, which is quite time consuming.

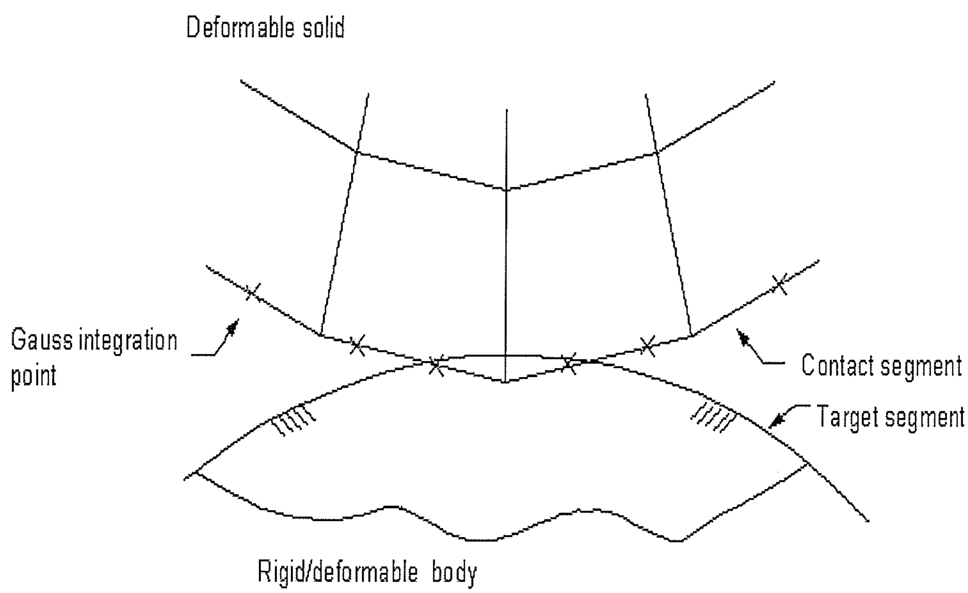


Figure 4.2 Contact detection located at Gauss integration point (GIP)

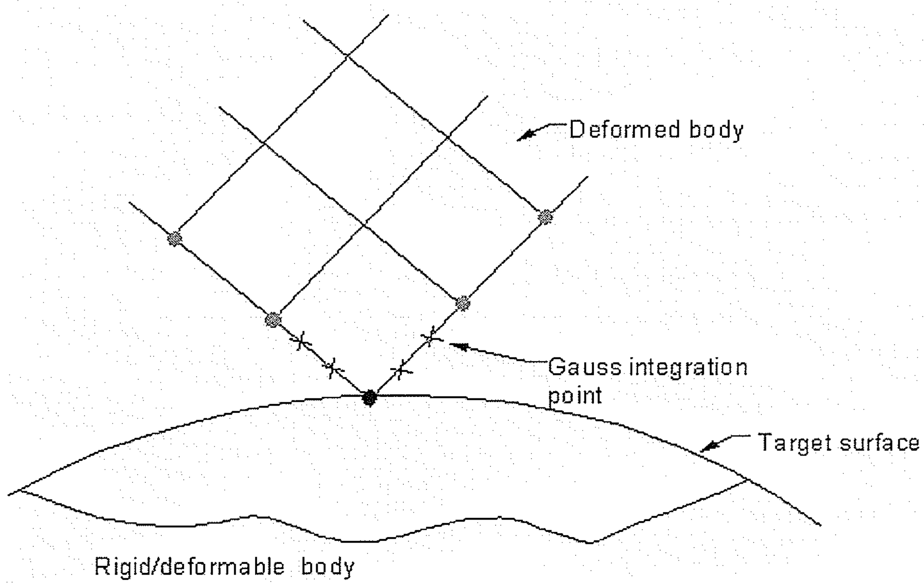


Figure 4.3 Contact detection point located at nodal point

4.3 Non-linear Assembly Variation Analysis Method by Contact Modeling

It is well known that there are many contact pairs during the assembly process, such as the contact between specimen surface patches, the contact between specimens and fixtures, and the contact between the specimens and joining tools (like welding guns). These contact pairs form contact chains that propagate, accumulate, and stack up the dimensional variations. For non-rigid sheet metal assembly, assembly deformation makes it more complex to model dimensional variation propagation due to the fact that the part variations, tool variations, and contact deformation are coupled with each other.

In this chapter, the assembly surfaces are supposed to be smooth, and the friction contact between the surface patches is not considered. With the extension to the assembly process modeling for two sheet metal parts (see Section 2.3), a natural method for analyzing non-linear assembly variation by contact modeling is proposed, with the workflow chart shown in Figure 4.4.

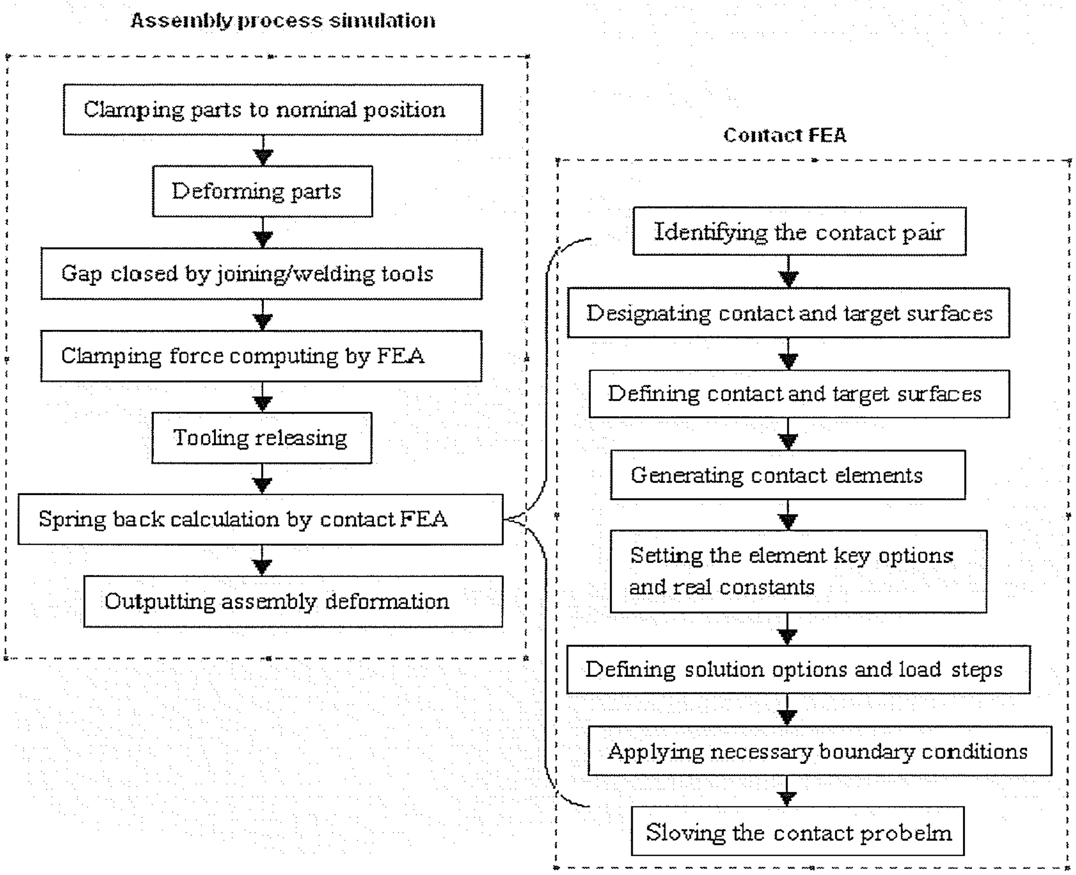


Figure 4.4 The workflow for non-linear assembly dimensional variation analysis by contact modeling

Components are loaded and placed on work-holding fixtures following the N-2-1 (N>3) locating scheme.

Supposing that the gap $\{\delta_u\}$ between two parts due to part variations is needed to close, and the clamping forces $\{F_u\}$, which is equal to$[K_u]$ $\{\delta_u\}$, can be calculated by FEA ($[K_u]$ is the part stiffness matrix).

After joining the parts and releasing the tools, the parts will generate elastic spring back contact deformation. Assuming the contact force $\{F_w\}$ is equal to the clamping force $\{F_u\}$ but with the opposite direction, i.e., $\{F_w\} = - \{F_u\}$, the assembly deformation can be computed by applying contact models between the assembly surfaces under the force $\{F_w\}$.

The entire analysis procedure shown in Figure 4.4 is implemented by using ANSYS APDL code in the ANSYS environment. The component joining process is simulated through coupled nodes in the FEM model, while the tool releasing process is simulated by removing the displacement boundaries at the released clamp / fixture points.

The procedure to conduct contact FEA analysis in ANSYS is described by the following four steps.

The first step for creating contact model is to identify where contact might occur. For non-rigid sheet metal assembly, the joint areas must be contact surfaces. However, it is necessary to check if other areas are supposed to contact during the assembly process.

Secondly, the contact and target surfaces are defined, and the contact elements for each contact pairs are generated.

Thirdly, constants are set up to control the behavior of contact elements. These constants include several element key options, such as the contact detection scheme, time step scale, and the parameters of the contact algorithms, and so on.

Lastly, the contact algorithms are selected, and the contact stiffness for each contact pair is determined prior to running the contact model.

In general, it is difficult to “guess” a good stiffness value for contact elements. To arrive at a good stiffness value, an iterative process is required and a "trial run" is first conducted to estimate the two main control factors, the stiffness-scaling factor, FKN, and the allowable maximum penetration factor, FTOLN.

FKN determines the "step-size" for updating the contact stiffness automatically during the FEA solution process; it thus affects the efficiency of the solution process and the final convergence. The range of this factor FKN is usually from 0.1 to 1.0. FTOLN specifies the tolerance level of penetration. If FTOLN is too small, it is hard for the FEA process to converge, i.e., equation (4.11) is not satisfied, because of the presence of penetration. On the other hand, if FTLON is too large, the result will show significant penetration and affect the accuracy of the solution.

The "trial-run" process is as follows. Firstly, start with a small value of FKN, for instance, FKN = 0.1. Secondly, run the analysis by a fraction of the final load until it is just enough to get the contact fully established. Lastly, check the penetration level and the number of equilibrium iterations used in each sub-step. If the global convergence is difficult to reach, gradually increase the value of FKN and FTOLN. If the penetration level becomes acceptable, further increase of FKN may decrease the convergence speed. After the values of FKN or FTOLN are determined, the full analysis is proceeded until reaching the global convergence.

4.4 Validation of the Proposed Approach: Simulation and Physical Experiments

4.4.1 A Simulation Example

An assembly of two identical flat sheet metal components by lap joints shown in Figure 4.5 is employed to illustrate the proposed method.

The surface A2 of one sheet metal part Q1 will tend to contact with the surface A4 of another sheet metal parts Q2. These two components have the same size, 212.85 $\times$166.37$\times$1.27mm, and the same Young's modules 2.06e+5 N/mm^2, and Poison's ratio 0.3.

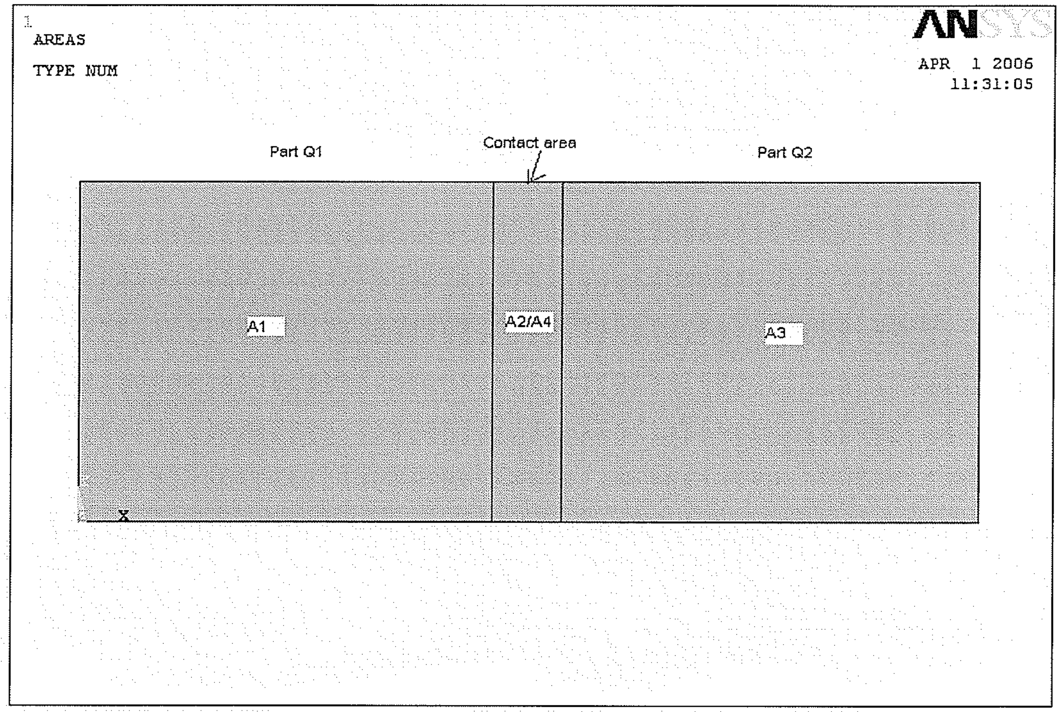


Figure 4.5 An assembly of two identical flat sheet metal parts

The fixture scheme N-2-1 (N > 3) is applied, shown in Figure 4.6. The positions of symbol '●' indicate the fixture locations. In part Q1, the fixtures F11 and F12 constraint the movement in the X, Y and Z directions, while fixtures F13 and F14 only constraint the movement in the Z directions (out-of-plane). In part Q2, the fixtures F21 and F22 constraint the movement in the X, Y and Z directions, while fixtures F23 and F24 only constraint the movement in the Z directions. All pair joint spots as indicated by '▲' are simultaneously assembled together. There are five critical points (CPs), p1, p2, p3, p4 and p5 (shown in Figure 4.6), that are used to check the assembly dimensional quality.

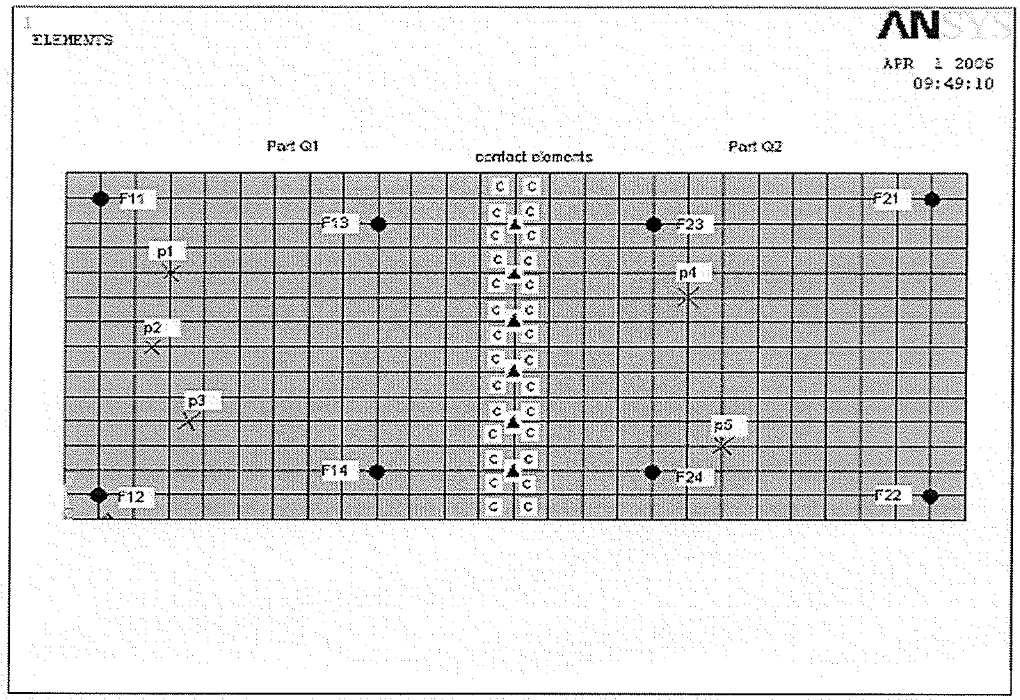


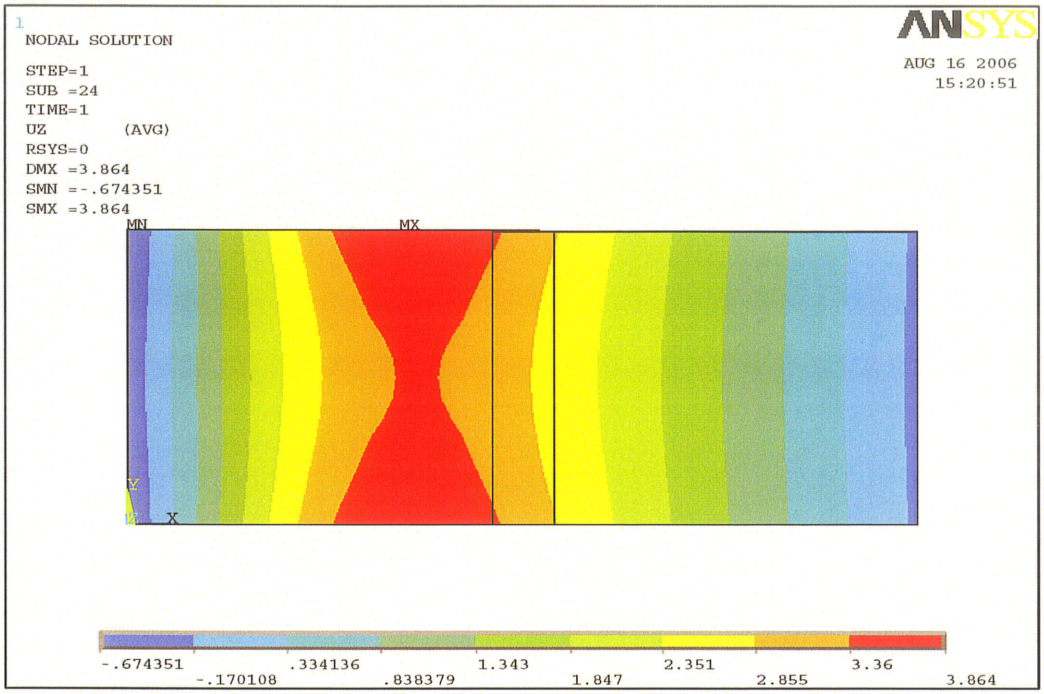
Figure 4.6 The finite element computation model of two sheet metal parts assembly

The finite element computation model of the assembly of two flat sheets, shown in Figure 4.6, is created in ANSYS by assuming that the small elastic deformation does not significantly change the component geometry size. The contact model is created between surface A2 and surface A4 (see Figure 4.5), and is marked by symbol '**C**' in Figure 4.6. The shell element type is SHELL63, the contact element type is CONTA174 and the target element type is TARGE170. There are 6 pairs of nodes to be connected together in this model, corresponding to the '▲' symbols in Figure 4.6.

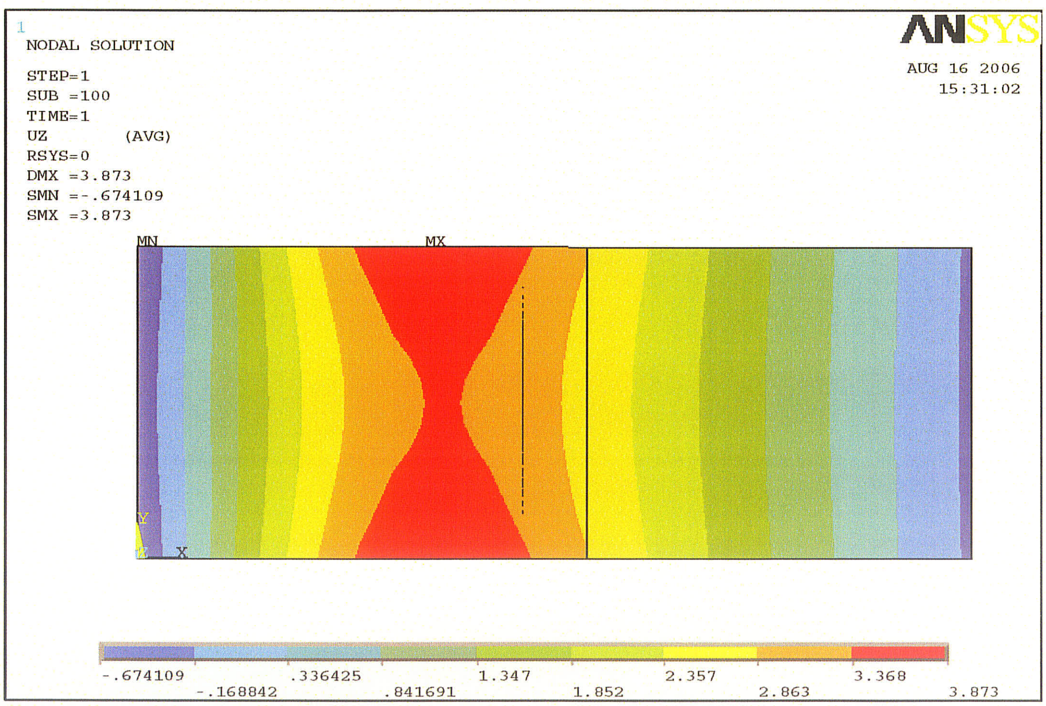
Suppose that the variation at the joint points in part Q1 is 2.4mm, but there are no variations in the joint points in part Q2.

The non-linear assembly dimensional variations can be computed in ANSYS APDL language by using an integrated procedure between sheet metal assemblies modeling and the contact FEA (see Figure 4.4). When releasing the fixtures F13 and F14 in part Q1 and F23 and F24 in part Q2, the assembly dimensional variations distribution is obtained, as shown in Figure 4.7 a). The assembly dimensional variation that ignoring the contact between the assembly contact surfaces is also computed (Figure 4.7 b). Detailed dimensional variation distributions in the assembly contact surface area obtained from contact modeling and non-contact modeling are shown in Figure 4.8 a) and Figure 4.8 b), respectively. The assembly variations in five CPs (shown in Figure 4.6) are extracted from the computation results from contact modeling and non-contact modeling, respectively, is summarized in Table 4.1.

Comparing the computing results of two sheet metal parts assembly dimensional variation obtained by contact modeling and non-contact modeling, there is a difference between the contact modeling results and non-contact modeling results. It can be seen from Table 4.1 that the assembly dimensional variations at these five CPs by contact modeling are greater than by non-contact modeling. The reason can be found by checking the assembly contact surface status in details. From the Figure 4.8 a) and the Figure 4.8 b), we can see that there is penetration in the assembly contact surface if we do not create the contact model. In this situation, the assembly force can not be transferred very well through the contact surfaces, resulting in poor calculation accuracy of the assembly dimensional variation. Therefore, it is necessary to consider the contact modeling in the analysis model when the assembly dimensional variation analysis with high prediction precision is required. The proposed simulation procedure (as shown in the Figure 4.4) provides an applicable way to meet such requirements.

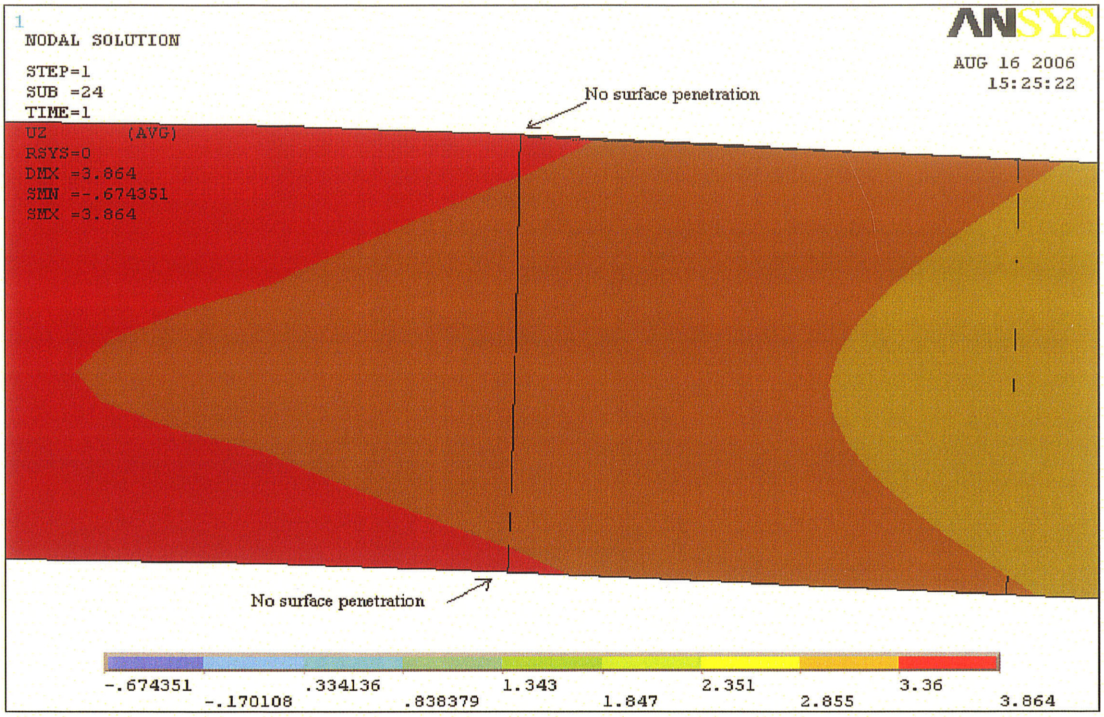


a)

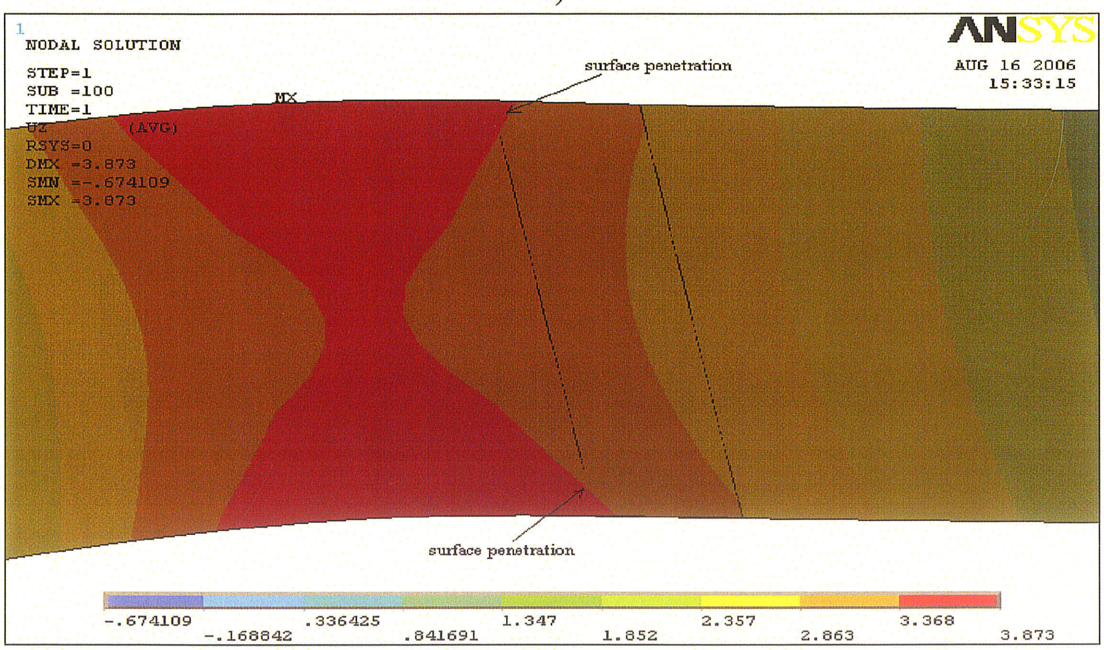


b)

Figure 4.7 The assembly dimensional variation distribution: a) results by contact modeling; b) results by non-contact modeling



a)



b)

Figure 4.8 Detailed dimensional variation distributions in the assembly surfaces: a) results by contact modeling, no penetration between surface A2 and surface A4; b) results by non-contact modeling, penetration happened between surface A2 and surface A4

Table 4.1 The assembly variations in five CPs by different modeling methods (Unit: mm)

	P1	P2	P3	P4	P5
Results by contact modeling	1.26987	0.97115	1.54927	1.75245	1.52017
Results by non-contact modeling	1.26834	0.96841	1.54833	1.74441	1.51181

4.4.2 Physical Experiments and Discussion

In order to validate the proposed approach for non-linear assembly dimensional variation of sheet metal assemblies, physical experiments corresponding to the simulation example that is explained in the Section 4.4.1 are set up.

Two stainless steel plates with a size of 212.85 ×166.37×1.27mm are made. Six holes in each plate are drilled respectively. One end of one of the specimens is bent to generate the required original part variation so that the variations in the joint points (i.e. the centres of the six holes) are 2.4mm.

The assembly station with fixtures (shown in Figure 4.9) is also created and equipped with the Checkmaker Coordinate Measuring Machine (CMM) (Model 216-142 DCC) (shown in Figure 4.10), which is used to measure the assembly variations. The Checkmaker CMM (Model 216-142 DCC) is a probe-contacting type of CMM. Its resolution is 0.000020" (0.5μm), manual repeatability is 0.00016" (4μm), repeatability is 0.00012" (3μm), and linear accuracy is 0.00018" + 0.000006" per inch. The accuracy of CMM machine is sufficient to meet the requirements of the physical tests.

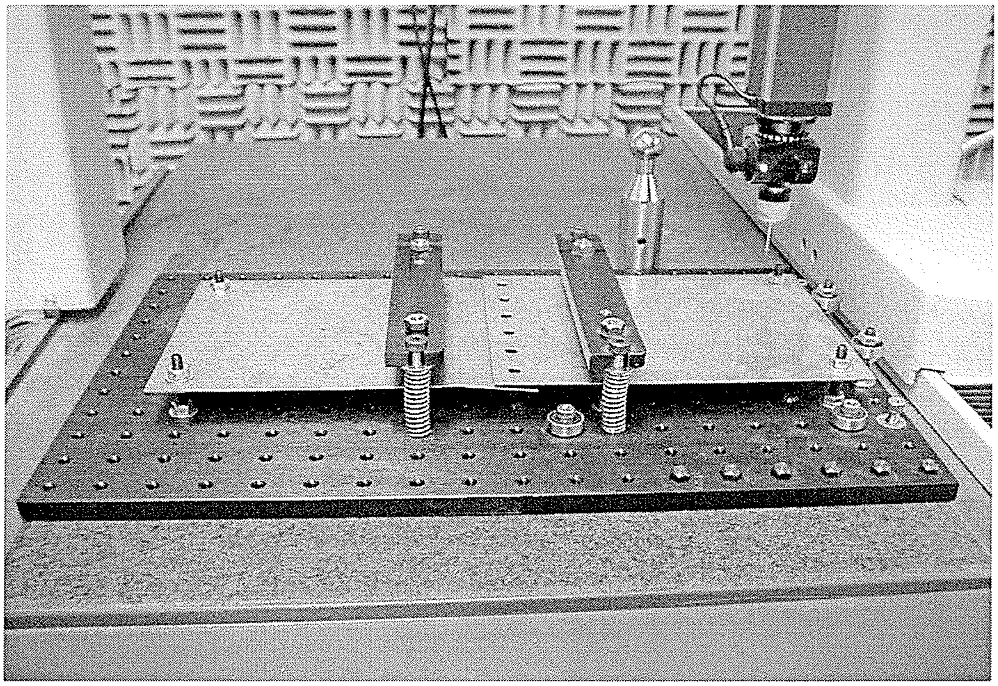


Figure 4.9 The assembly station

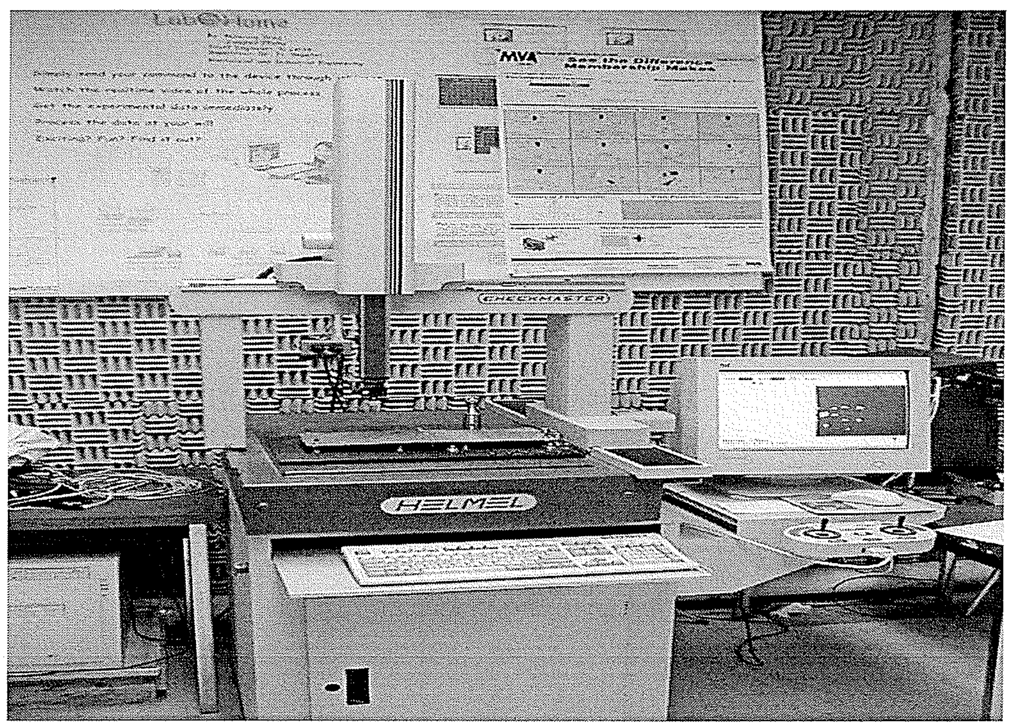


Figure 4.10 The Checkmaker Coordinate Measuring Machine (CMM)
(Model 216-142 DCC)

The procedure of the physical experiment is described as follows.

Firstly, the corresponding positions in these two sheet metal specimens were identified and marked according to the coordinates of the five CPs in the simulation example (Figure 4.6). Those two specimens were placed on the assembly station and fixed by the designed fixtures (shown in Figure 4.9).

Secondly, the CMM machine was used to measure the flatness of the reference plane in the specimens. The height of the fixtures was adjusted until the specimens were in the same height levels (shown in Figure 4.10). After that, the sheet metal parts were bolted together and the middle fixtures were released (Figure 4.11).

Lastly, the assembly variations of the five CPs in the assembly structure were obtained with the CMM machine (Figure 4.12). The average assembly variations at the five CPs with five measurements each are obtained, and listed in the Table 4.2.

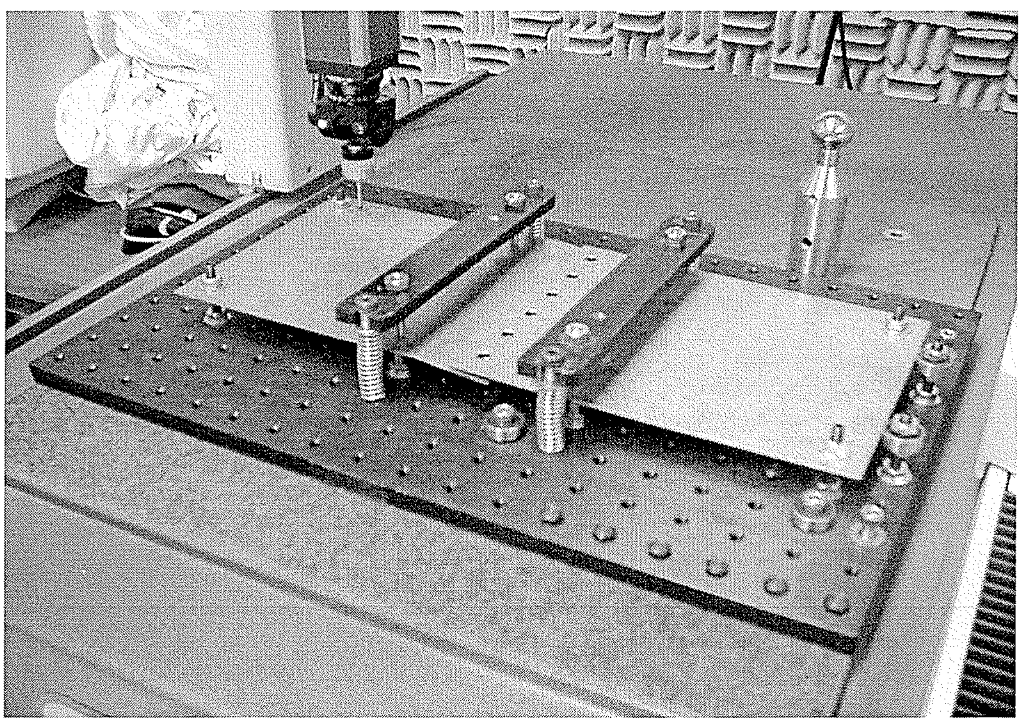


Figure 4.11 Measuring the reference plane in parts to adjust the heights of fixtures

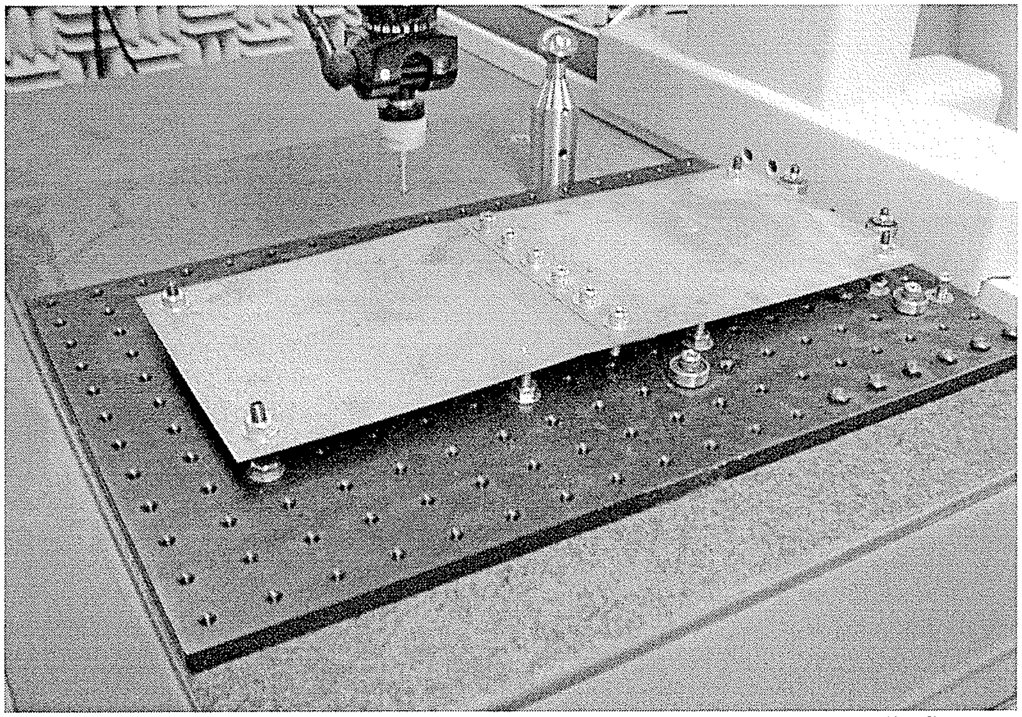


Figure 4.12 Assemble the sheet metal parts together and release the middle fixtures

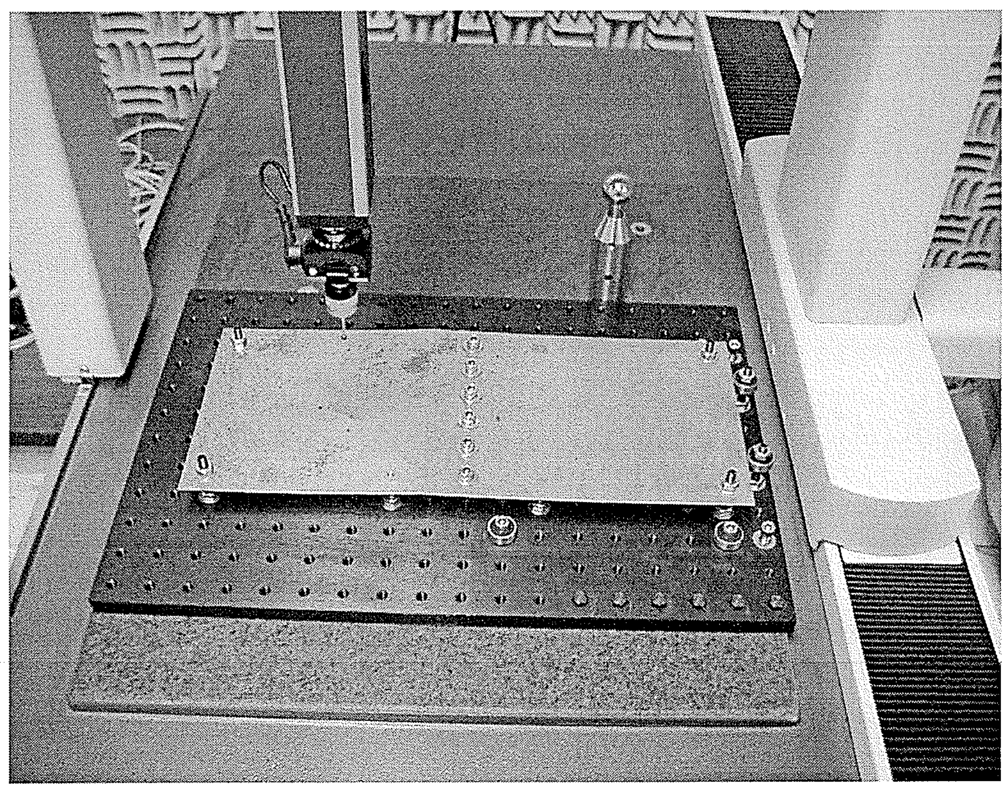


Figure 4.13 Measuring the assembly variation after releasing the fixtures

Table 4.2 Relative errors of the simulation results to the physical test results (Unit: mm)

Critical points	The measured variations (I)	Results by contact modeling (II)	Relative errors of II to I (%)	Results by non-contact modeling (III)	Relative errors of III to I (%)
P1	1.35864	1.26987	-6.53374	1.26834	-6.64635
P2	1.01371	0.97115	-4.19844	0.96841	-4.46873
P3	1.53771	1.54927	0.751767	1.54833	0.690637
P4	1.60122	1.75245	9.444673	1.74441	8.942556
P5	1.56184	1.52017	-2.66801	1.51181	-3.20327
Average relative errors			**-3.20375**		**-4.68517**

The relative errors of the simulation results by contact model and non-contact model with respect to the physical test results are further calculated respectively, and listed in Table 4.2. It can be seen that the simulation results agree well with those from the physical test. Results in Table 4.2 also show that the simulation results by contact modeling are closer to the physical test results (with an error of 3.20%) than those by non-contact modeling (with an error of 4.68%). This difference suggests that the proposed non-linear assembly dimensional variation analysis approach by contact modeling is more accurate than non-contact modeling since it simulates the real physical contact behaviour of the sheet metal assemblies.

4.5 Summary

The elastic contact phenomenon in the sheet metal assembly process that affects the assembly dimensional quality is extensively studied in this chapter. A non-linear assembly dimensional variation analysis method is proposed by establishing the elastic contact model between the assembly surfaces. The simulation is implemented by applying the ANSYS APDL programme. The assembly dimensional variation analysis with and without contact modeling is applied to a case study of an assembly of two sheet metal parts. The corresponding physical experiments are also carried out. The test results agree very well with the simulation results, proving that the proposed approach by non-linear contact modeling is applicable and effective as well as with high precision for sheet metal assembly variation analysis. Although the non-contact model works in many situations, the contact problem should be involved in the assembly dimensional variation analysis modeling when a high precision assembly is required.

The proposed method and analysis tools are applicable in engineering practice. Moreover, this work not only gives us a deeper understanding about the non-linear characteristics of sheet metal assembly variation, but also contributes to the research of the non-linear product dimensional variation analysis and control.

Chapter 5

Conclusions

5.1 Contributions of this Thesis

Dimensional variation analysis and process design for non-rigid sheet metal assemblies has been a challenging problem and attracted much attention over the past years. Understanding the coupled propagation mechanism of dimensional variations during the assembly process and establishing the analysis methods are very important in non-rigid sheet metal product design and manufacturing. This thesis presents a number of novel, systematical, and generally applicable methods for analyzing and optimizing the non-rigid sheet metal assembly variations. From the work in this thesis, contributions have been made in following areas.

1) Fractal geometry is applied to model the variation of surface microstructure of the assembly components when the part variations appear fractal characteristics. The influence of the variation of surface microstructure of the assembly components on the final assembly variation is studied by applying the finite element method (FEM). It is found that different tool releasing schemes produce quite different assembly variation distributions. With more fixtures released, the contribution of the variation of component surface microstructure to the final assembly variation becomes more significant. Moreover, the final assembly variation could be asymmetrical even under a fairly symmetric assembly condition when the variation of surface microstructure of assembly components is taken into consideration. The assembly variation caused from the variation of surface microstructure of assembly components should not be neglected in an assembly process

plan for high precision assemblies with very compliant components.

2) A new methodology based on wavelet transform is developed to analyze the contribution of variation components with different scales to the final dimensional variation for non-rigid sheet metal assemblies. The wavelet transform is used to identify different scale components of part variation in the tolerance zone, while the finite element method (FEM) is utilized to calculate the deformation of non-rigid assemblies that corresponds to these different scale components. The integrated procedure of wavelet transform and FEM for non-rigid assembly variation analysis is set up and implemented by using ANSYS and Matlab. Basically, this methodology is more advantageous than the approach based on the fractal geometry in that it can deal with all kinds of non-stationary part variations, not only limited to the fractal variation. Since it is inevitable that the uncertainties in manufacturing environment result in different scale structures of the part variation, the proposed methodology provides an interesting opportunity to identify the components of large variation, to avoid such variations in the manufacturing process, and to design a good process plan. The work on the wavelet-based method and the fractal-based method contributes significantly to the research and application of the detailed part variation modeling in controlling the final assembly quality.

3) A simultaneous optimization method for fixture layout and joint configuration is developed since not only the fixture layout but also the joint configurations have impact on the non-rigid sheet metal assembly quality. It is the first time that the fixture layout and joint configuration are included in the optimization model and optimized simultaneously for non-rigid assemblies. The global optimal solution is obtained by employing a new global search procedure, the mode-pursuing sampling method (MPS), which could

significantly reduce the amount of computation while obtaining a global optimum. ANSYS and Matlab are integrated to implement the proposed FEM-based non-rigid sheet metal assembly modeling and optimization algorithms. The simulation tests on an assembly with two identical flat sheet metal components by lap joints demonstrate that the proposed method is effective and reliable. This work provides the strategies and tools for non-rigid sheet metal dimensional variation modeling and optimization, and contributes to the integration research on the sheet metal product design (joints configuration) and manufacturing (fixture layout).

4) The elastic contact phenomenon in the sheet metal assembly process that affects the assembly dimensional quality is studied. A non-linear assembly dimensional variation analysis method is proposed by establishing the elastic contact model between the assembly surfaces. The simulation is implemented by applying the ANSYS APDL programme. The assembly dimensional variation analysis with and without contact modeling is applied to an assembly with two non-rigid sheet metal parts. Simulation results suggest that the contact problems should be considered in the assembly dimensional variation analysis modeling, otherwise the assembly contact surfaces in the FEA based analysis model will penetrate each other and cannot well transfer the assembly force. The corresponding physical experiments are also carried out. The test results agree very well with the simulation results, proving that the proposed approach is applicable and effective for non-rigid sheet metal assembly variation analysis. The presented work provides important insight on the non-linear propagation of the part variation through assembly contact surfaces. It also contributes directly to the non-linear dimensional variation analysis and control for the non-rigid sheet metal assemblies in that the contact

modeling considers the fact that it is the contact surface that transfers the assembly forces.

Overall, the developed methods on assembly variation analysis and fixture/joint position optimization for non-rigid sheet metal assemblies by employing fractal geometry, wavelet transform, contact modeling, and global optimization algorithms have provided a deeper understanding of the coupling influence of component flexibility, detailed part variation, and assembly tool variations on the final assembly geometry quality, and the non-linear behavior of assembly variation propagation in assembly process. The research has basically enriched the study of integrated design and manufacture of non-rigid sheet metal assemblies, and it can benefit both the academic research and industrial applications.

5.2 Future Work

The approaches and tools presented in this thesis are believed to be able to be further extended. In particular, the fractal and/or wavelet transform based modeling method can be applied to the optimization problem of fixture layout that needs to consider the microstructure of part variations; the assembly contact surface modeling and the microstructure of part variations modeling may also be included in one non-linear assembly dimensional variation analysis model. Furthermore, applying these analysis methods to the fixture diagnosis (Camelio and Hu 2004) is also needed for further study.

In addition, the simultaneous optimization problem of the fixture layout and joint configuration based on the non-rigid sheet metal assembly process modeling can be extended to a multi-objective optimization (MOO) problem which includes structure durability, manufacturing cost, and so on. The optimization algorithm for this MOO problem is another interesting research topic.

Meanwhile, the non-linear assembly dimensional variation analysis method by elastic contact mechanics can be further investigated by considering more complex physical phenomena in the assembly contact surface during assembly process, e.g., the thermal-elastic-plastic interaction.

References

Adams, V., "Building better products with finite element analysis", 1st ed. *Santa Fe, NM: OnWord Press* (1999)

ANSYS, Inc., "APDL programmer's guide, ANSYS release 6.1" (2002)

Bhalerao, R., Heers, B., Bohm, M., and Shrank, M., "Finite element simulations of joints used in the automotive industry", *2002 ASME International Mechanical Engineering Congress and Exposition*, Nov. 17-22, New Orleans, Louisiana, Paper Number: IMECE2002-32345 (2002)

Bihlmaier, B. F., "Tolerance Analysis of Flexible Assemblies Using Finite Element and Spectral Analysis", *M.S. Thesis, Mechanical Engineering Department, Brigham Young University* (1999)

Cai , W. J., and Hu , S. J., , "Optimal Fixture Configuration Design for Sheet Metal Assembly with Springback", *Transactions of NAMRI/SME*. pp. 229-234, May (1996a)

Cai, W., Hu, S.J., and Yuan, J.X., "Deformable sheet metal fixturing: principles, algorithms, and simulations", *ASME Journal of Manufacturing Science and Engineering*, Vol. 118, pp. 318-324 (1996b)

Camelio, J.A, Hu, S. J., "Multiple fault diagnosis for sheet metal fixtures using designated component analysis", *ASME Journal of manufacturing Science and Engineering*, Vol. 126, pp. 91-97 (2004)

Camelio, J.A., Hu, S.J., and Ceglarek, D.J, "Modeling variation propagation of multi-station assembly systems with compliant parts", *Proceedings of DETC'01, ASME 2001 Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, September 9-12, Pittsburgh, Pennsylvania, Paper Number: DETC2001/DEM-21190 (2001)

Camelio, J.A., Hu, S.J., and Ceglarek, D.J, "Impact of fixture design on sheet metal assembly variation", *Proceedings of DETC'02, ASME 2002 Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Sept. 29-Oct.2, Montreal, Canada, Paper Number: DETC2002/DFM-34167 (2002a)

Camelio, J.A., Hu, S.J, and Ceglarek, D.J, "Compliant assembly variation analysis using component geometric covariance", *Proceedings of IMECE2002, ASME international Mechanical Engineering Congress & Exposition*, Nov. 17-22, New Orleans, Louisiana, Paper Number: DETC2001/DEM-21190 (2002b)

Ceglarek, D., and Shi, J., "Dimensional variation reduction for Automotive body Assembly", *Manufacturing Review*, Vol. 8, No. 2, pp. 139-154 (1995)

Ceglarek, D., and Shi, J., "Fixture failure diagnosis for autobody assembly using pattern recognition", *ASME journal of Engineering for Industry*, Vol.118, pp. 55-66 (1996)

Ceglarek, D., and Shi, J., "Tolerance analysis for sheet metal assembly using a beam-based model", *1997 ASME International Mechanical Engineering Congress and Exposition*, Nov.16-21, Dallas, Texas, DE-Vol. 94, pp. 153-159 (1997)

Ceglarek, D., and Shi, J., "Design evaluation of sheet metal joints for dimensional integrity", *ASME Journal of Manufacturing Science and Engineering,* Vol. 120, No. 2, May, pp. 452-460 (1998a)

Ceglarek, D., "Multivariate analysis and evaluation of adaptive sheet metal assembly systems", *J. CIRP Annals - Manufacturing Technology*, Vol. 47, No. 1, pp. 17-22 (1998b)

Ceglarek, D., Huang, W., Zhou, S., Ding, Y, Kumar, R., Zhou Y., "Time –based competition in manufacturing: stream-of-variation analysis (SOVA) methodology review", *International Journal of Flexible Manufacturing Systems*, Vol. 16, No.1, pp.11-44 (2004)

Chang, M., and Gossard, D.C., "Modeling the assembly of compliant, non-ideal parts", *Computer Aided Design*, Vol. 29, No.10, pp. 701-708 (1997)

Chase, K.W., and Parkinson, A.R., "A survey of research in the application of tolerance analysis to the design of mechanical assemblies", *Research Engineering Design*, Vol. 3, No.1, pp.23-37 (1991)

Chui, C.K., "An introduction to wavelets", *Boston: Academic Press* (1992)

Dalstrom, S., and Soderberg, R., "Towards a method for early evaluations of sheet metal assemblies", *7th CIRP International seminar on Computer Aided Tolerancing*, April 24-15, ENS de Cachan, France (2001)

Dalstrom, S., Hu, J.S, and Soderberg,R., "Identifying variable effects on the dimensional quality of compliant assembly, using computer experiments", *Proceedings of DETC'02, ASME 2002 Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Sept. 29-Oct.2, Montreal, Canada, Paper Number: DETC2002/DAC-34035 (2002)

Dahlstrom, S., and Camelio, J.A., "Fixture design methodology for sheet metal assembly using computer simulations", *2003 ASME International Mechanical Engineering Congress and Exposition*, Nov.15-21, Washington, D.C., Paper Number: IMECE 2003-41370 (2003)

Dalstrom, S., and Lindkvist L., "Contact modeling in method of Influence coefficient for variation simulation of sheet metal assemblies", *Proceedings of IMECE04, 2004 ASME International Mechanical Engineering Congress and Exposition*, Nov.13-20, Anaheim, California, USA, Paper Number: IMECE2004-61550 (2004)

Ding, Y., Ceglarek, D.; Shi, J., "Modeling and diagnosis of multistage manufacturing process: Part II-faults diagnostics". *Japan-USA Symposium of Flexible Automation*, July 23-26, Ann Arbor, MI (2000)

Entwistle, K.M., "Basic principles of the finite element method". *London: IOM Communications* (1999)

Falconer, K.J., "Fractal geometry: mathematical foundations and applications", *New York: J. Wiley and Sons* (1990)

Fu, J.C., and Wang, L., "A random-discretization based Monte Carlo sampling method and its applications", *Methodology and Computing in Applied Probability*, Vol.4, pp. 5-25 (2002)

Gladwell, G. M. L. "Contact problems in the classical theory of elasticity", *Alphen aan den Rijn : Sijthoff & Noordhoff* (1980)

Greenwood, W. H., and Chase, K. W., "Design issues in mechanical tolerance analysis", *ASME Manufacturing review*, Vol.1, pp.50-59 (1988)

Haftka, R., Scott, E. P. and Cruz, J. R., "Optimization and experiments: a survey", *Applied Mechanics Review,* Vol. 51, No. 7, pp. 435-448 (1998)

Helmel Engineering Products, Inc., "Handbook of the Checkmaker CMM (Model 216-142 DCC)"

Hills, D.A., "Mechanics of elastic contact", *Boston: Butterworth-Heinemann* (1992)

Hoffman, K., and Santosa, F., "A simple model of sheet metal assembly", *SIAM Review*, Vol 45, No.3, September, pp. 558-573 (2003)

Hsieh, C.C. and Oh, K.P., "A framework for modeling variation in vehicle assembly processes", *Internal Journal of Vehicle Design*, Vol. 18, No.5, pp. 466-473, (1997)

Hsieh, C.C., and Liang, F., "Methods for flexible part clamping simulation and optimization", *American Society of Mechanical Engineers, Manufacturing Engineering Division, MED*, Vol. 13, *Proceedings of the ASME Manufacturing Engineering Division - 2002*, pp. 447-451 (2002)

Hu, M., Lin, Z.Q., Lai, X.M., and Ni, J., "Simulation and analysis of assembly process considering compliant, non-ideal parts and tooling variations", *International Journal of machine tools & manufacture*, Vol. 41, pp. 2233-2243 (2001)

Hu, S.J., "Stream-of-variation theory for automotive body assembly", *The Annals of CIRP*, Vol. 46, No.1, pp. 1-6 (1997)

Hu, S.J., Webbink, R., Lee J., and Long Y., "Robustness evaluation for compliant assembly systems", *ASME Journal of Manufacturing Science and Engineering*, Vol. 125, June, pp. 262-267 (2003)

Hu, S.J., and Wu, S.M., "Identifying sources of variation in automotive body assembly using principal component analysis", *Transaction of NAMRI/SME*, Vol. 20, pp. 311-316 (1992)

Huang, W., and Ceglarek, D., "Mode-based decomposition of part form error by discrete-cosine-transform with implementation to assembly and stamping system with compliant parts", *Annals of CIRP*, Vol. 51, No. 1, pp.21-26 (2002)

Jiang, Z., Wang, H., and Fei, B., "Research into the application of fractal geometry in characterising machined surfaces", *International Journal of Machine Tools & Manufacture*, Vol. 41, pp. 2179-2185 (2001)

Kashyap, S. and DeVries, W., "Finite element analysis and optimization in fixture design", *Structure Optimization*, Vol. 18, pp. 193-201 (1999)

Lai, X., Luo, L. and Lin, Zh., "Flexible assembly fixturing layout modeling and optimization based on genetic algorithm", *Chinese Journal of Mechanical Engineering*, Vol. 17, No. 1, pp. 89-92 (2004)

Lee, D.E., and Hahn, H.T., "Assembly modeling and analysis of integral fit joints for composite transportation structures", *Proceedings of DETC'96, ASME 1996 Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Irvine, California, August 18-22 (1996)

Lee, J., and Haynes, L., "Finite element analysis of flexible fixturing system", *ASME Journal of Engineering for Industry*, Vol. 109, pp. 579-584 (1987)

Lee, W. J., and Woo, T. C, "Tolerances: their analysis and synthesis", *ASME Journal Engineering for Industry*, Vol. 112, May, pp. 113-121 (1990)

Li, B., Shiu, B.W., and Lau, K.J., "Principle and simulation of fixture configuration design for sheet metal assembly with laser welding. Part 1: Finite-element modeling and a prediction and correction method", *International Journal of Advanced Manufacturing Technology*, Vol. 18, No. 4, pp. 266-275 (2001a)

Li, B., and Shiu, B.W., "Principle and simulation of fixture configuration design for sheet metal assembly with laser welding. Part 2: Optimal configuration design with the genetic algorithm", *International Journal of Advanced Manufacturing Technology*, Vol. 18, No. 4, pp. 276-284 (2001b)

Li, B., Shiu, B.W., and Lau, K.J., "Fixture configuration design for sheet metal assembly with laser welding: A case study", *International Journal of Advanced Manufacturing*

Technology, Vol. 19, No. 7, pp. 501-509 (2002)

Li, B., Shiu, B.W., and Lau, K.J., "Robust fixture configuration design for sheet metal assembly with laser welding", *Journal of Manufacturing Science and Engineering, Transactions of the ASME*, Vol. 125, No. 1, February, pp. 120-127 (2003)

Lian, J., Lin, Z.Q, Yao, F.S. and Lai, X.M., "Analysis of nonlinear variation accumulation in auto-body assembly process", *Proceedings of IMECE2002, ASME international Mechanical Engineering Congress & Exposition*, Nov.17-22, New Orleans, Louisiana, USA, Paper Number: IMECE2002-32339 (2002)

Liao, Y.G., "A genetic algorithms-based fixture locating positions and clamping schemes optimization", *Proceeding of Institution of Mechanical Engineering, Part B: Journal of Engineering Manufacturing*, Vol. 217, pp. 1075-1083 (2002)

Liao, X.Y., Lei, W.Y., "The geometric precision and performance analysis for machining surface based on fractals", *Journal of Chongqing University*, Vol. 22, No. 1, pp. 18-23 (1999)

Lin, Z.Q., Hu, M., Mi, X.M., Chen, G.L., "FEM analysis of spot welding process in autobody manufacturing", *Transactions of the China Welding Institution*, Vol. 22, No. 1, February, pp. 36-40 (2001)

Liu, Y.G., and Hu, S. J., "Assembly fixture fault diagnosis using designated component analysis", *ASME Journal of Manufacturing Science and Engineering*, Vol.127, pp. 358-368 (2005)

Liu, S. C., Hu, S. J., "Offset finite element model and its applications in predicting sheet metal assembly variation", *International Journal of Machine Tools & Manufacture*, Vol. 35, No. 11, Nov, pp. 1545 (1995a)

Liu, S.C., and Hu, S. J, "Spot welding sequence in sheet metal assembly, its analysis and synthesis", *ASME Manufacturing Science and Engineering*, MED-Vol.2-2, pp.1145-1156 (1995b)

Liu, S.C., Hu, S. J, and Woo, T. C., "Tolerance analysis for sheet metal assemblies", *ASME Journal of Mechanical Design*, Vol. 118, No. 1, pp. 62-67 (1996)

Liu, S. C., and Hu, S. J., "Parametric study of joint performance in sheet metal assembly", *International Journal of Machine Tools & Manufacture*, Vol. 37, No. 6, pp. 873-884 (1997a)

Liu, S.C., and Hu, S.J., "Variation simulation for deformable sheet metal assembly using finite element methods", *ASME Journal of Manufacturing Science and Engineering*, Vol. 119, pp. 368-374 (1997b)

Liu, S.C, and Hu, S.J., "Sheet metal joint configurations and their variation characteristics", *ASME Journal of Manufacturing Science and Engineering*, Vol. 120, No. 2, May, pp. 461-462 (1998)

Long, Y. and Hu, S.J., "A unified model for variation simulation of sheet metal assemblies", in *Geometric Design Tolerancing: Theories, Standards and Application*, Ed. Dr. Hoda A ElMaraghy, London: Chapman & Hall, pp.208-219 (1998)

Liu, Y.G., and Hu, S.J. "Assembly fixture fault diagnosis using designated component analysis", *ASME Journal of Manufacturing Science and Engineering*, Vol. 127, No, 2, May, pp. 358-368 (2005)

Majumdar, A., and Tien, C.L., "Fractal charaterisation and simulation of rough surface", *Wear*, Vol. 136, pp. 313-327 (1990)

Mallat, S.G., "A wavelet tour of signal processing", *San Diego: Academic Press* (1998)

Mandelbrot, B.B., "The fractal geometry of nature", *San Francisco: W.H. Freeman* (1983)

Mandelbrot, B.B., "Stochastic models for the earth's relief, the shape and the fractal dimension of the coastlines, and the number-area rule for islands", *Proceedings of Nature Academic Science* USA, Vol. 72, pp. 3825-3828 (1975)

Math Works, "Signal processing tools box for us with MATLAB: user's guide", version 5 (2002)

Mattikalli, R., Mahanian, S., Jones A, and Clark G., "Modeling compliant part assembly: mechanics of deformation and contact", *Proceedings of the 2000 ASME Design Engineering Technical Conferences*, Sept.10-13, Baltimore, Maryland, USA, Paper Number: DETC2002/DFM-14036 (2000)

Menassa, R., and DeVries, W., "Optimization methods applied to selecting support positions in fixture design", *ASME Journal of Engineering for industry*, Vol.113, pp. 412-418 (1991)

Mijar, A.R., and Arora, J.S., "Review of formulations for elastostatic frictional contact problems", *Structure Multidiscipline Optimization*, Vol. 20, pp. 167-189 (2000)

Paulo, S.R., Diniz, Eduardo A.B. Da Silva, and Sergio L. Netto, "Digital signal processing: system analysis and design", *New York: Cambridge University Press* (2002)

Rao, S.S., "The finite element method in engineering", the third edition, *Woburn, MA: Butterworth-Heinemann* (1999)

Rearick, M., Hu, S.J., and Wu, S.M., "Optimal fixture design for deformable sheet metal workpieces", *Transaction of NAMRI/SME*, Vol. 21, pp. 407-412 (1993)

Sellem, E. and Riviere, A., "Tolerance analysis of deformable assemblies", *Proceedings of the 1998 ASME Design Engineering Technical Conferences*, Sept. 13-16, Atlanta, GA, USA, Paper Number: DETC98-DAC5571 (1998)

Shan, S., and Wang, G. G., "An efficient pareto set identification approach for multi-objective optimization on black-box functions", *ASME Journal of Mechanical Design,* Vol. 127, No. 5, pp. 866-874 (2005)

Shiu,B.W., Ceglarek, D., and Shi, J., "Multi-station sheet metal assembly modeling and diagnostics", *Transactions of NAMRI/SME*, Vol. 24, pp.199-204 (1996)

Shui,B., Ceglarek, D., and Shi, J., "Flexible beam-based modeling of sheet metal assembly for dimensional control", *Transaction of NAMRI/SME*, Vol. 25, pp 49-54 (1997)

Shiu, B.W., Shi, J., and Tse, K.H., "Dimensional quality of sheet metal assembly with welding-induced internal stress", *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, Vol. 214, No. 7, pp. 693-704 (2000)

Shiu, B.W., Apley, D., Ceglarek, D., Shi, J., "Tolerance allocation for sheet metal assembly using beam-based model", *Trans. of IIE, Design and Manufacturing,* Vol. 35, No. 4, pp. 329-342 (2003)

Stavroulaki, M.E., and Stavroulakis, G.E., "Unilateral contact application using FEA software", *International Journal of Applied Mathematical Computation Science*, Vol. 12, No. 1, pp. 115-125 (2002)

Stout, J. B. "Geometric covariance in compliant assembly tolerance analysis", *M.S. Thesis, Mechanical Engineering Department, Brigham Young University* (2000)

Takezawa, N., "An improved method for establishing the process wise quality standard", *Report of statistical and applied research, Japanese Union of Scientists and Engineering (JUSE)*, Vol. 27, No. 3, September, pp. 63-76 (1980)

Wang, L., Shan, S., and Wang, G. G., "Mode-pursuing sampling method for global optimization on expensive black-box functions", *Journal of Engineering Optimization*, Vol. 36, No. 4, pp. 419-438 (2004)

Zhang, Y. and Taylor, D., "Optimization of spot-welded structures", *Finite Elements in Analysis and Design*, Vol. 37, pp. 1013-1022 (2001)