The dimensional quality of sheet metal assembly with welding-induced internal stress

B W Shiu[1]*, J Shi[2] and K H Tse[1]
[1]Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hong Kong
[2]Department of Industrial Operations Engineering, The University of Michigan, Ann Arbor, Michigan, USA

Abstract: The present paper is the first to propose a minimum stress criterion for the minimum dimensional variation during sheet metal assembly. The weld sequence affects the dimensional variation owing to the welding process. A case study illustrates the minimum stress criterion on dimensional variation. This paper proposes a generic design criterion for sheet metal products and processes that would produce minimal stress-induced dimensional variation for spot-welded sheet metal assemblies. The process design proposes a minimum stress build-up by using the 'sheet metal ironing welding technique' in the weld sequencing design. The product design proposes a minimum stress build-up design criterion to manage the accumulation of stress. The proposed product and process design methods enable automotive body design engineers to create a quality product with minimum dimensional variation caused by the manufacturing stress within the body-in-white structure. Moreover, this facilitates the industry's objective of building a high quality automotive body with minimum stress. This is an important factor in contributing to the superior quality of the body panel fits. It also helps to reduce the quality-related warranty costs.

This paper primarily focuses on the development of a joint design guideline by exploring the relationship between the dimensional variation and the stress build-up. First, the automotive assembly process design will be introduced. A simple analysis of a one-dimensional assembly is produced. A three-dimensional structural analysis of a box assembly is investigated for the effect of stress build-up within a structure on the dimensional instability or variation. Then a three-dimensional finite element analysis of an assembly with weld sequencing of two imaginary parts is produced. An experimental industrial trial has confirmed the validity of the simulation methodology. Then a welding sequence design guideline is produced based on the previous simulation result, followed by a joint design guideline to help improve the design of dimensionally robust design.

Keywords: stress analysis, sheet metal assembly, process design, product design

NOTATION

A	cross-sectional area of the beam
E	Young's modulus
$[\mathbf{k}]_{ij}$	directional matrix of the same member
$[\mathbf{K}]$	structural stiffness matrix
K_a, Δl_a	spring constant and deflection after the assembly
K_1, Δl_1	spring constant and deflection of the upper beam
K_2, Δl_2	spring constant and deflection of the lower beam
l	length of the sample structure
Δl	overlap–mismatched length between the two lengths of the structure
Δl_t	equivalent distance caused by the tool error in the y direction
L	length of the cantilever beam
n	sample size
$\{P\}$	applied forces on the structure
Δt	tooling variation induced by the welding processes
x	values of the group of samples
$[\boldsymbol{\beta}]_{ij}$	member structural stiffness matrix
$\{\delta\}_{ij}$	fabrication errors at the ith join and affecting the jth join
$\{\delta\}_{ji}$	fabrication errors at the jth join and affecting the ith join

The MS was received on 3 September 1999 and was accepted after revision for publication on 17 November 1999.

**Corresponding author: Department of Mechanical Engineering, The Hong Kong Polytechnic University, FG627, Hung Hom, Kowloon, Hong Kong.*

$\{\Delta\}$	displacement of the structure
θ	angle of deflection of the beam caused by the tooling error in the y direction
μ	mean of the sample
σ_s	stress build-up in an assembly

1 INTRODUCTION

The dimensional quality of an automotive body greatly affects the overall quality performance, such as wind noise created by poorly fitted panels and water leakage created by non-conforming body dimensions. These quality problems, together with the warranty costs, are overwhelming automotive manufacturers. In today's high demand for product quality, manufacturing quality control (on-line process control) does not satisfy stringent requirements [**1**]. According to a recent study of the final product quality related to manufacturing process and product design, 80 per cent of the overall quality is contributed by the design decision and only 20 per cent of the manufacturing variability contributes to the overall quality characteristics [**2**]. Design in quality is receiving a renewed interest.

Increasing quality and increasing productivity are two major goals in today's automotive industry. The welding process contributes a large percentage of the cost of an automotive body. The dimensional stability increases the productivity and reduces quality-related problems. Welding process failure and dimensional variation are major factors in decreasing productivity (e.g. corrective adjustment of weld gun pressure and location, and assembly fitting with the closure panels such as doors, fenders and hoods). Statistical process control (SPC) became the standard method used to control the process and maintain a high dimensional quality of the product [**3**]. However, these approaches address the after-the-fact problem and do not address the problem of identifying the proper sheet metal product and process design. A proper design guideline based on the accumulation of internal stress is inadequate in the current sheet metal automotive body design. The dimensional stability increases the productivity and reduces quality-related problems.

1.1 Literature review

Ceglarek and Shi [**1**] presented a design evaluation of sheet metal joints with the emphasis on the interaction between the assembly components for the final assembly of the full automotive body and its final effect on the final dimensional integrity of the key product characteristics. Liu and Hu [**4**] presented variation characteristics for the joint configurations regarding the effect of each type of typical joint on the final dimensional tolerance of the sheet metal product. These methods are based on design rules and quantitative measures of the dimensional effects of each type of joint interaction and the propagation of the dimensional variation. They further describe the effect of the assembly mechanics based on each of the joint characteristics that are found in a typical automotive body. Shiu *et al.* [**5**] described modelling methodologies using the structure analysis method for dimensional control. Furthermore, a recent development uses the knowledge-based and model-based diagnostics technique in identifying sources of assembly error [**1**, **4**, **6**]. Tolerance analysis based on a mechanistic model has been researched [**4**, **6**].

Recent research has claimed that overall assembly variation is contributed by the component variation stack-up [**3**, **5**]. These methods are based on the rigid and machined components and are not applicable to flexible sheet metal parts. The flexibility of assembly stack-up has been proposed [**2**, **7**, **8**]. These methods are more representative of the actual assembly mechanics. However, they only consider the flexibility of the localized parts and neglect the internal stress factor in the dimensional stability as well as the spread of the internal stress into other flexible assemblies.

1.2 Automotive sheet metal assembly process design

Automotive body manufacturing is a complicated sheet metal process because of the complex body structure as shown in Fig. 1.

A typical automotive body has about 4000–5000 weld spots. These resistance weld spots not only join more than 200 sheet metal parts together but also increase the internal stress in these flexible sheet metal parts. The welding process uses high pressure to join the sheet metal together at the weld point. Typically, each joint is designed with a sheet metal design gap. The design gap at the joint surface is designed to accommodate the sheet metal assembly process variation. This is widely practised in today's automotive body design. However, in today's automotive plants, not only the design gap but also the manufacturing variation constitute the joint gap of the automotive body. One of the major sources of sheet metal assembly variation comes from the internal stress caused by the welding process. The pressure and heat exerted by the spot welding equipment tend to distort and deform the sheet metal to form the assembly joint. Resistance spot welding requires a large weld tip pressure to ensure proper panel fit during the welding process. The high-pressure welding process generates stress not only close to the weld location but also far into the structure of the assembly. The induced stress will be minimized by equalizing the induced stress into the less stressed area of the body. The internal stress built up by the welding process increases the dimensional variation in the automobile body. This

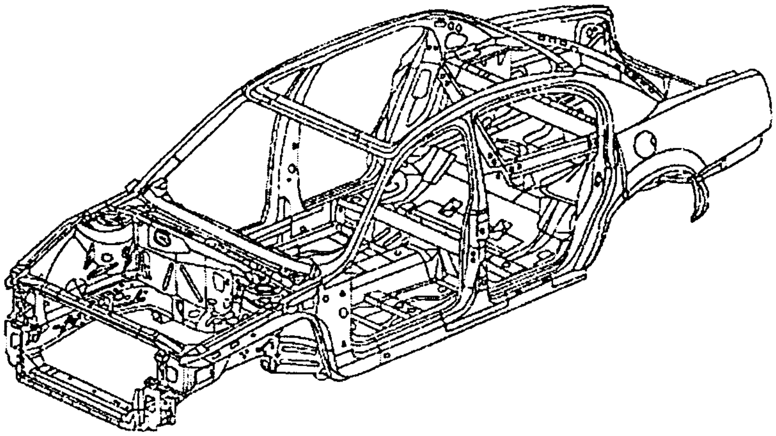


Fig. 1 A typical automotive body structure

stress tends to minimize itself inside the body structure and thus creates a deformation that changes the dimensions of the final autobody.

The weld tip pressure will distort the metal at the joint. This will generate a small and localized distortion in the structure if the metal gap at the joint is small. However, distortion of sheet metal will become a structural effect when the metal gap becomes large, for example 2 mm and up. The distortion will become even more severe when the structural sheet metal parts are welded. The metal gap becomes very sensitive to the dimensional stability. The dimensional accuracy and stability are compromised by the flexibility of the vehicle body structure. The internal stress that is built up by the welding process increases the dimensional variation in the automobile body. The induced stress tends to distribute itself inside the autobody structure. Concurrently, a deformation of the final body dimensions is likely because of the distribution of the internal stress. Furthermore, the direct relationship between the dimensional variation and the internal stress suggests the joint design criteria as well as the process design characteristics.

2 SHEET METAL ASSEMBLY MODELLING

The sheet metal assembly process with appropriate design and manufacturing gap at the joint surfaces will be modelled in this section. Firstly, one-dimensional beam assembly analysis will be used to explore the gapping effect on dimensional variability. Secondly, the dimensional variability will be simulated using structural frame analysis. Thirdly, a three-dimensional assembly analysis will be conducted using the finite element approach. All these analysis techniques will be used to confirm the minimum-stress assembly criterion in the sheet metal assembly.

2.1 One-dimensional beam assembly model

A one-dimensional beam model is used to visualize such an assembly process. This model can be used to generalize the internal stress build-up within a beam-based welding model. The dimensional variation level depends on the level of the stress built up within the assembly. The stress build-up is considered as a function of the weld sequence strategy [7] which is related to the internal stress level. This illustration uses a welding sequence between two simple beams to represent the welding stress build-up in a simple structure (Fig. 2). There are four equally distanced welds in the beam assembly. This one-dimensional beam model illustrates the weld stress build-up in a straightforward example of the direct relationship between the stress level and the dimensional variation.

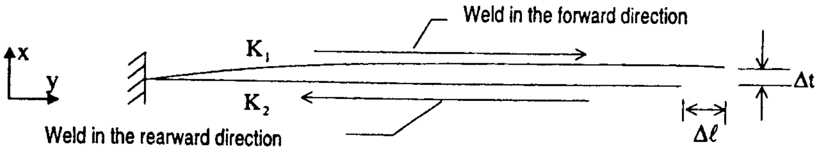


Fig. 2 One-dimensional welding of two sheet metal parts

The analysis model is based on earlier work where welding operations in sheet metal assembly are considered [5, 7]. According to Hooke's law, a linear model of a cantilevered beam acts as a spring and a force F causes a deflection Δl in the y direction:

$$F = K\Delta l \tag{1}$$

where $K = EA/L$ is the spring constant (coefficient of stiffness), E is the Young's modulus, L is the length of the cantilever beam and A is the cross-sectional area of the beam. Since equal and opposite forces act on each cantilever beam, the indeterministic forces can be rewritten twice and equal to each other as in equation (1). Thus, the final deflection can be expressed as

$$\Delta l_a = \frac{K_1}{K_a}\Delta l_1 + \frac{K_2}{K_a}\Delta l_2 \tag{2}$$

where K_a and Δl_a are the spring constant and deflection after the assembly, K_1 and Δl_1 are those of the upper beam and $K - 2$ and Δl_2 are those of the lower beam. The simple model below has perfect parts on the lower beam; thus Δl_2 is zero. The stiffness of the assembly is usually higher than that of the individual beams [8], and thus the final deflection is less than that before assembly and the final deflection is proportional to the initial error:

$$\Delta l_a \propto \Delta l_1 \tag{3}$$

According to Hooke's law, the stress can be expressed as follows:

$$\sigma_s = \frac{F}{A} \propto \Delta l_a \propto \Delta l_1 \tag{4}$$

Thus, the stress induced is proportional to the mismatch of the two assemblies in one weld operation. The welding operation, on the other hand, will induce a variability in the x direction Δt which compounds the internal stress caused by the mismatch. Since it is in the x direction, the equivalent displacement in the y direction is going to be

$$\Delta l_1 \propto \Delta t\theta = \frac{\Delta t^2}{l} \tag{5}$$

where Δl_1 is the equivalent distance caused by the tool error in the y direction, l is the length from the fixed end to the welding point and θ is the angle of deflection of the beam caused by the tooling error in the y direction. Tables 1 and 2 show the weld sequences and the weld-induced stresses based on the mismatches created from the manufacturing defects and the weld tool variabilities, where Δt is the tooling variation induced from the welding processes, l is the whole length of the cantilever beam structure and σ_s is the stress build-up due to the difference in length when two beams are joined together caused by the tooling and material variations. The magnitude of tooling variation varies vertically in the direction of the welding process. This gives the physical variability of the tooling in determining the final location of such processes. Thus, the total stress build-up is the sum of all stresses built up from the entire weld sequence which, for the case in Table 1, is

$$\sigma_s \propto 16\frac{\Delta t^2}{l} \tag{6}$$

This gives the relationship between the internal stress and the weld process and tooling-induced variation. By taking the variance of the equation, it is possible to estimate the dimensional variation as a function of the tooling assembly variation:

$$\mathrm{var}(\sigma_s) \propto \frac{16}{l}\,\mathrm{var}^2(\Delta t) \tag{7}$$

The internal stress is a linear function of the welding and tooling variation. The level of dimensional variation,

Table 1 The direction of welding sequence is from the fixed to the free end

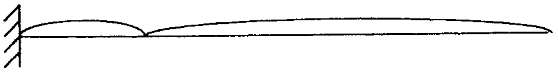
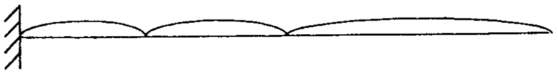
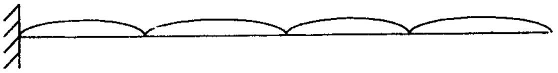
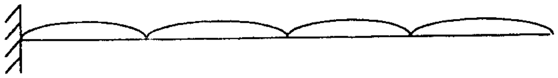
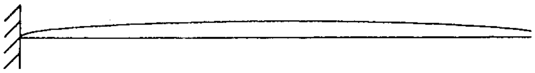
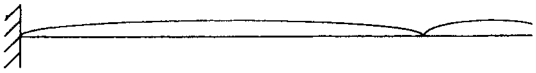
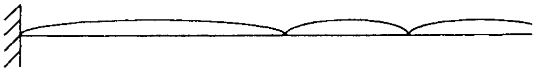
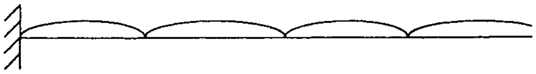
Weld number	Stress build-up	Weld sequence
First weld starting from the fixed point	$\sigma_s \propto \frac{\Delta t^2}{l/4}$	
Second weld	$\sigma_s \propto \frac{\Delta t^2}{l/4}$	
Third weld	$\sigma_s \propto \frac{\Delta t^2}{l/4}$	
Fourth weld	$\sigma_s \propto \frac{\Delta t^2}{l/4}$	

Table 2 The weld sequence direction is from the free to the fixed end

Weld number	Stress build-up	Weld sequence
First weld from the free end	$\sigma_s \propto \Delta l + \frac{\Delta t^2}{l}$	
Second weld	$\sigma_s \propto \frac{3}{4}\left(\Delta l + \frac{\Delta t^2}{l}\right) + \frac{\Delta t^2}{3l/4}$	
Third weld	$\sigma_s \propto \frac{1}{3}\left(\frac{3}{4}\Delta l + \frac{25}{12}\frac{\Delta t^2}{l}\right) + \frac{\Delta t^2}{l/2}$	
Fourth weld	$\sigma_s \propto \frac{1}{2}\left(\frac{1}{4}\Delta l + \frac{97}{36}\frac{\Delta t^2}{l}\right) + \frac{\Delta t^2}{l/2}$	

$\text{var}(\Delta t)$, is directly affected by the internal stress generated, $\text{var}(\sigma_s)$.

At the first weld of the case in Table 2, an extra length of material from the beam structure is welded into the length of the second beam. Assume that Δl is the overlap–mismatched length between the two lengths of the structure. This creates a stress build-up within the assembly. Thus, the total stress build-up is the sum of all stresses built up from the entire weld sequence:

$$\sigma_s \propto \frac{17}{8}\Delta l + \frac{89}{8}\frac{\Delta t^2}{l} \tag{8}$$

This gives the relationship between the internal stress and the weld process and tooling-induced variation. By taking the variance of the equation, it is possible to estimate the variation versus the tooling variation:

$$\text{var}(\sigma_s) \propto \frac{17}{8}\text{var}(\Delta l) + \frac{89}{8l}\text{var}^2(\Delta t) \tag{9}$$

The internal stress is a linear function of the welding and tooling variation and the mismatch between the two pieces of material when they are first welded together at the freed end. The level of the dimensional relationship is directly affected by the internal stress generated:

$$\frac{17}{8}\text{var}(\Delta l) + \frac{89}{8l}\text{var}^2(\Delta t) \gg \frac{16}{l}\text{var}^2(\Delta t) \tag{10}$$

The total variation is significantly larger in the left-hand side than in the right-hand side. Thus, the variation level shows that the mismatch of the panel assembly is more significant than that of the tooling variation coming from the weld process. This simple beam formulation demonstrates the direct relationship between the stress build-up and the variability of the assembly of flexible beams. Furthermore, a better representation of the body assembly is obtained in two parts. The first is the structural effect in structural analysis where the automotive body is considered as a frame. The second is the effect of parts in a more detailed simulation with smaller parts where stress and deformation are simulated.

2.2 Structural beam analysis of the assembly simulation

This section illustrates the same phenomenon used in a three-dimensional structure analysis with fabrication error analysis [9]. A structural analysis where the automotive body is considered as a frame is applied. The result shows a very similar conclusion to that of the above analysis. The following example is illustrated by a beam structure analysis. The Monte Carlo [7] simulation method is used with a given set of normally distributed fabrication error. This is used as the means to introduce internal stress. The structure simulation is given in Fig. 3 with the solid frame as the design of the product dimensions and the dashed frame as the assembled product which illustrates the internally stressed assembly. The frame structure of an automobile is also illustrated in Fig 3. The components with fabrication error are manufactured away from the nominal design. When these oversized or undersized parts are assembled into the structure, the whole structure, which is forced to accommodate these non-conformed parts, deforms dimensionally and induces an internal stress. Thus, the relationship of the stress level and dimensional variation can be obtained from classical frame structure analysis. The stress level is caused by the fabrication error induced within the assembly. The fabrication error or the internal induced stresses displace the final assembled frame and thus it forms the dimensional variation of the assembly.

The stiffness matrix can be constructed with reference to Shiu *et al.* [4]. The fabrication error is used as the source of the stress build-up with the final assembly of

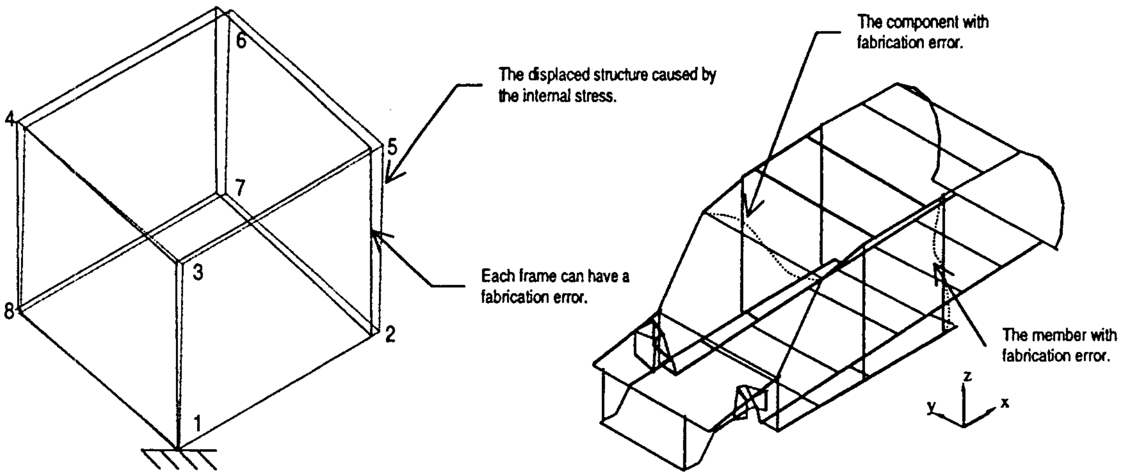


Fig. 3 Frame structure analysis of the sheet metal parts

the above structure. A particularly small deviation from the nominal design causes the structure to deflect as in Fig. 3. The dashed line represents the structure deformation under both the fabrication error and the stress build-up within the final assembly. Fabrication errors include the lengths of erroneously manufactured structure members, distortions from the design values and the non-conformance of each of the subassemblies. These fabrication errors are very likely in most assembly and manufacturing processes. Moreover, in order to manufacture the whole assembly from the erroneously manufactured parts, the manufacturing processes stress up the individual parts in order to assemble them together. The following equation indicates the fabrication error on each of the joins at sheet metal assembly:

$$\{\delta\}_{ij}^{\mathrm{T}} = [\delta_1 \quad \delta_2 \quad \delta_3 \quad \delta_4 \quad \delta_5 \quad \delta_6]_{ij} \tag{11}$$

Thus, the manufacturing stress is induced and built in the final assemblies. These final assemblies are produced with stress built in. $\{\delta\}_{ij}$ and $\{\delta\}_{ji}$ are the deflections of each end of the members of the final structure (Fig. 4): $\{\delta\}_{ij}$ represents the fabrication errors at the ith join and affecting the jth join and $\{\delta\}_{ji}$ represents the fabrication errors at the jth join and affecting the ith join.

Each member will have a fabrication error with six components, the three translations and three rotations of the fabrication error. These fabrication errors will introduce a force compensation into the structure in order to eliminate the fabrication error effect on the structure. These compensation forces are the sources of stress build-up within the system (structure). In order to accommodate the fabrication error of the structure, internal stresses are inevitable. The structure then has to absorb the compensation forces in order to minimize the effect of the induced stress. On the basis of traditional structure analysis [9], the displacement of the structure is caused by the force applied to the structure:

$$\{\boldsymbol{P}\} = [\mathbf{K}]\{\varDelta\} \tag{12}$$

where $\{\boldsymbol{P}\}$ is the applied forces on the structure with components corresponding to each node, $\{\varDelta\}$ is the displacement of the structure and $[\mathbf{K}]$ is the total structural stiffness matrix. The equation can be expanded and expressed as a matrix equation based on the structure design:

$$\begin{bmatrix} \{\boldsymbol{P}\}_2 \\ \{\boldsymbol{P}\}_3 \\ \{\boldsymbol{P}\}_4 \\ \{\boldsymbol{P}\}_5 \\ \{\boldsymbol{P}\}_6 \\ \{\boldsymbol{P}\}_7 \\ \{\boldsymbol{P}\}_8 \end{bmatrix} = \begin{bmatrix} [\mathbf{k}]_{22} & 0 & 0 & [\mathbf{k}]_{15} & 0 & 0 & 0 \\ 0 & [\mathbf{k}]_{33} & 0 & [\mathbf{k}]_{35} & 0 & 0 & 0 \\ 0 & 0 & [\mathbf{k}]_{44} & 0 & [\mathbf{k}]_{46} & 0 & [\mathbf{k}]_{48} \\ [\mathbf{k}]_{51} & [\mathbf{k}]_{53} & 0 & [\mathbf{k}]_{55} & [\mathbf{k}]_{56} & 0 & 0 \\ 0 & 0 & [\mathbf{k}]_{64} & [\mathbf{k}]_{65} & [\mathbf{k}]_{66} & [\mathbf{k}]_{67} & 0 \\ 0 & 0 & 0 & 0 & [\mathbf{k}]_{76} & [\mathbf{k}]_{77} & [\mathbf{k}]_{78} \\ 0 & 0 & [\mathbf{k}]_{84} & 0 & 0 & [\mathbf{k}]_{87} & [\mathbf{k}]_{88} \end{bmatrix} \begin{bmatrix} \{\varDelta\}_2 \\ \{\varDelta\}_3 \\ \{\varDelta\}_4 \\ \{\varDelta\}_5 \\ \{\varDelta\}_6 \\ \{\varDelta\}_7 \\ \{\varDelta\}_8 \end{bmatrix} \tag{13}$$

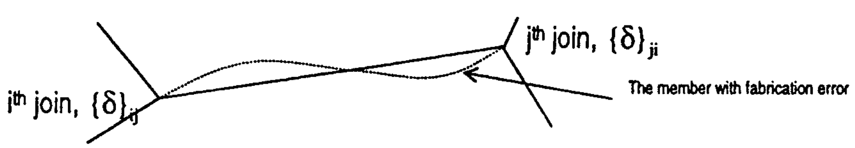


Fig. 4 A member of the structure

where $[\mathbf{k}]_{ij}$ is the member stiffness matrix with six degrees of freedom for each joint of the structure. The equation above is a 48 × 48 matrix equation. The fabrication error replaces the applied force on the structure:

$$\{\boldsymbol{P}\}_i = -\sum_j [\boldsymbol{\beta}]_{ij}^{\mathrm{T}}(-[\mathbf{k}]_{ii}^{j}\{\boldsymbol{\delta}\}_{ij}) \tag{14}$$

where $[\boldsymbol{\beta}]_{ij}$ is the member structural stiffness matrix and $[\mathbf{k}]_{ij}$ is the directional matrix of the same member. The final structural displacement can be rewritten as a simple equation:

$$[\mathbf{K}]\{\Delta\} = -\sum_j [\boldsymbol{\beta}]_{ij}^{\mathrm{T}}(-[\mathbf{k}]_{ii}^{j}\{\boldsymbol{\delta}\}_{ij}) \tag{15}$$

After the total stiffness matrix construction, the left-hand side and the right-hand side of the equation can be constructed. The inverse of the structural matrix, $[\mathbf{K}]$, can be calculated after the matrix construction. A simplified version of the relationship between the final deformation of the overall structure and the fabrication error can be written as follows:

$$\{\Delta\} = -f(\{\delta\}) \tag{16}$$

The above equation, which is a system of 48 equations, can be further expressed in the relationship between the stress level and the variation level of the assembly, where f is the function representing the relationship between the two variables. A set of randomly generated fabrication errors, which are within the specified distribution, is used to calculate the stresses within the structure. The fabrication errors create the stress within the structure. The final deflection of the structure or system can be calculated with the equation above. The final deflection of the whole system is used to generate the final variation level of the structure using the Monte Carlo simulation technique [7]. A group of distributed fabrication errors is introduced into the model; the deflection of the structure is then calculated and grouped into a distribution of dimensional variation as shown in Fig. 5. The dimensional variation of each point with 6σ (where σ is the variance) distribution is calculated from the following equation where 99.8 per cent of the total distribution of the variability is within the 6σ distribution:

$$6\sigma = 6\sqrt{\frac{1}{n-1}\sum_n (\mu - x)^2} \tag{17}$$

where n is the sample size, μ is the mean of the sample and x represents the values of the group of samples derived from the deflections of the Monte Carlo simulation. Figure 5 shows the total variation based on the final deflection of the above structure versus total stress build-up within the structure based on the combinations of the fabrication errors of each of the structure members.

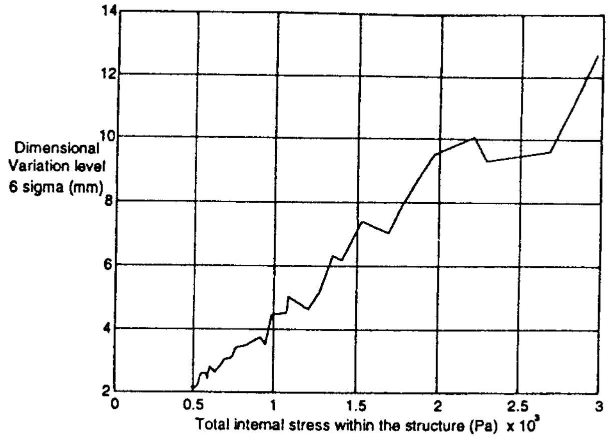


Fig. 5 Simulation results for the dimensional variation and internal stress

As shown in Fig. 5, the higher is the stress build-up within the structure, the higher the dimensional variation of the assembled structure is. Every point on the figure represents the total stress level and dimensional variability within a structure with a given level of fabrication error. This confirms the one-dimensional study. Next, a detailed part assembly effect in a more detailed simulation with smaller parts using finite element modelling shows the validity of the above minimum stress assembly criterion.

2.3 Finite element simulation of the assembly analysis

The overall stress on a structure is revealed by the above structure analysis. However, the local stress levels are not clear as to their relationship between the detailed part and the weld spot. In order to illustrate the stress-induced dimensional variation, a realistic assembly model with a finite element modelling technique is used in combination with a statistical method, namely Monte Carlo simulation. This section develops a generic modelling technique for sheet metal assembly that applies to most subassembly operations. This is a localized model assembly in a typical section of the automotive pillars. The same modelling methodology applies to a larger assembly such as the body side assembly or the automotive body frame. The compression of a weld flange is used as the cause of internal stress, which is very likely in sheet metal parts production. As shown in Figs 6 and 7, the simulation illustrates the stress build-up at the weld joint. Two flexible parts are welded along the edges. In this assembly, stresses are accumulated; however, if this assembly is connected to other parts, stress is relieved and spread. Thus, clamping and

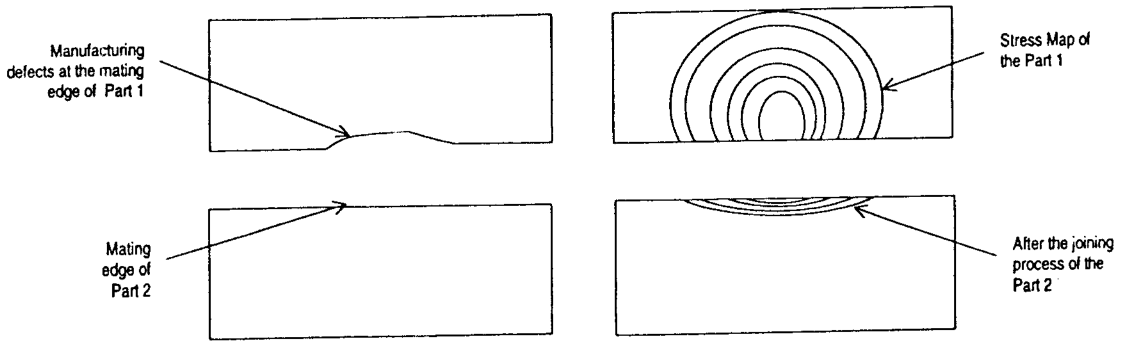


Fig. 6 Manufacturing defects at the mating surface of an assembly

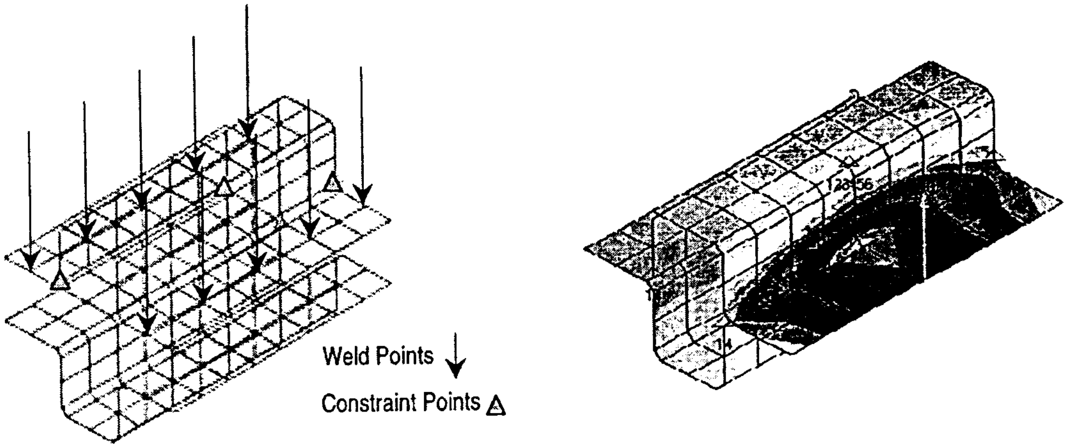


Fig. 7 The assembly model of sheet metal welding and the resulting stress

compression of the edges during the welding operation cause the internal stress as shown in Fig. 7.

Before the assembly process, the parts have no induced internal stress. Each individual part is free of any stress concentration. Manufacturing defects are common under imperfect manufacturing conditions. Even if there is imperfection in the detail of the parts, the manufacturing process has to assemble the parts, regardless of the gap width. The welding equipment simply forces the mating surfaces to match during the welding process or the manufacturing process. Thus, the stress distribution due to the manufacturing process is shown in Figs 6 and 7. The part is forcibly deformed to meet the mating surfaces of the other part of the assembly material. The force or stress at the interface is created at the join and in the surrounding material. These stresses deform the final assembly into different dimensions to the original design.

The simulation uses a more realistic example. The part is a typical tunnel section that exists in many automotive body structures, and manufacturing defects are located at the welding edge. These manufacturing defects are very common in the sheet metal stamping process. The welding process then joins the two defective parts together with the blunt force of the weld tip pressure. The weld point, which simulates the welding process, is represented by merging the neighbouring nodes in the model. The parts are then assembled with a weld sequence similar to that of a typical welding process. In the case of manufacturing defects such as an open gap between two surfaces, the surfaces are joined with enforced displacements to close the gap of two flexible parts. The stresses are indeterminate from the assembly of the sheet metal joint yet equal in magnitude between the top and bottom parts. Once the gaps are closed, the stress cannot be relieved because those two surfaces are not perfectly matched. Internal stresses are induced when those imperfect faces are welded or joined. The locating scheme as well as the constraint method are the same, which presents the actual assembly environment. The 3–2–1 constraint method which represents the six-degree-of-freedom constraint in three different directions is used for locating both parts. Similarly to the above examples, the joints are joined with the forces and constraints to combine both edges together. There are about 30 samples in each of the simulations for a given level of the manufacturing defect: this typically represents 99.7 per cent of the normal distribution

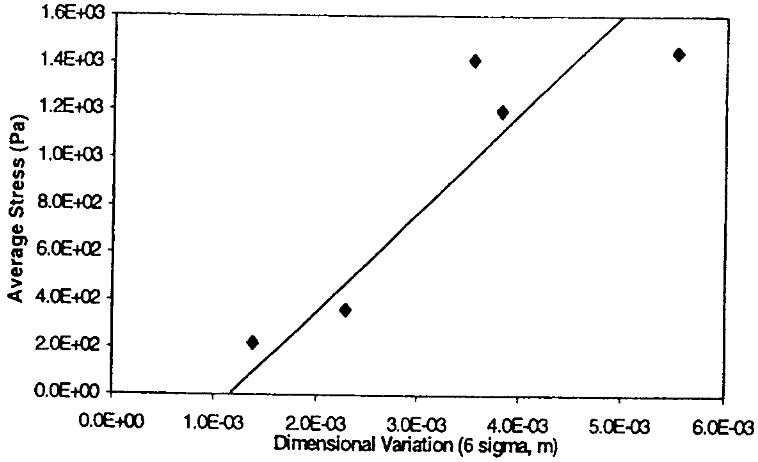


Fig. 8 Simulated dimensional variation and the induced internal stress

of the whole assembly process. Figure 8 presents the variation of simulated stress level with the dimensional instability of the total assembly after all the stresses have built up inside the assembly.

Figure 8 illustrates the stress level build-up with the dimensional instability of the sheet metal assembly. This is of critical importance in the design of robust parts for assembly and product variation. The modelling of the assembly uses enforced displacement with non-linear analysis of the indeterminate displacement of the balancing non-conforming dimensions. This is a more accurate estimate of the assembly process. This also indicates the direct relationship between the stress and dimensional instability. It also exhibits the same relationship between the internal stress and the dimensional variation.

3 INDUSTRIAL IMPLEMENTATION OF THE ASSEMBLY STRESS ANALYSIS

This is an industrial example obtained from an actual automotive assembly plant. This example illustrates the minimum stress criterion in sheet metal assembly. The assembly is a typical rear wheelhouse assembly in a high volume production. Because of its high volume production requirement, there are two parallel assembly lines producing the same part. Those parts are produced from a single geometrical assembly station. Thus, the initial geometrical set between the inner part and the outer skin is the same. However, there are significant differences in dimensional quality between the two parallel assembly process. The robotic welders are programmed to have the same welding locations. However, the welding sequences are different. Those products produce different dimensional variation distributions.

After careful investigation, only one welding robot is found to have a different welding direction in comparison with the other parallel robot. As illustrated in Fig. 9, the difference is in the direction of a weld in the same lines of welds. The corresponding dimensional effect is illustrated in Fig. 10. The effect easing the internal stress is shown by the lower curve whereas that accumulating the internal stress is shown by the upper curve. This indicates the true effect of the build-up of internal stress in causing the increase in the dimensional variation of the final assembly.

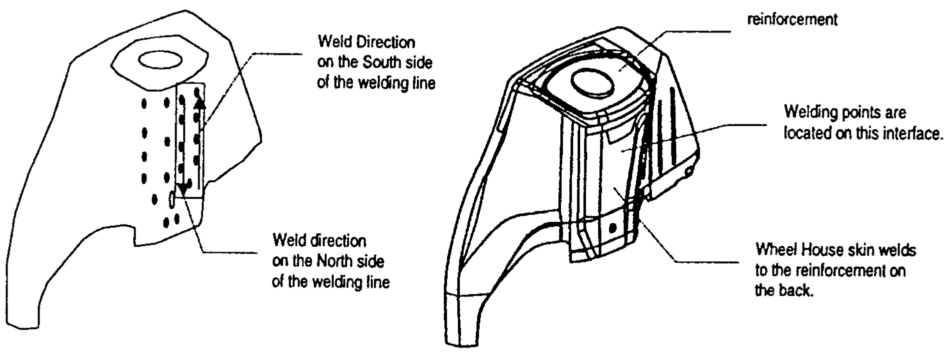


Fig. 9 Industrial example of weld sequencing

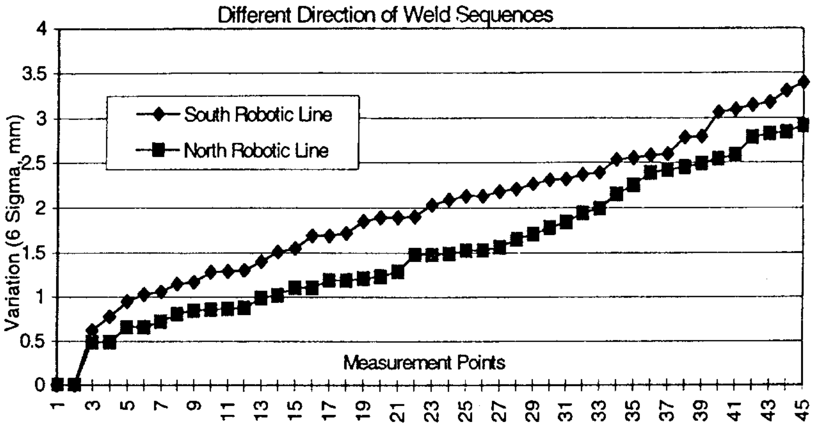


Fig. 10 Industrial example of the dimensional effect of weld direction

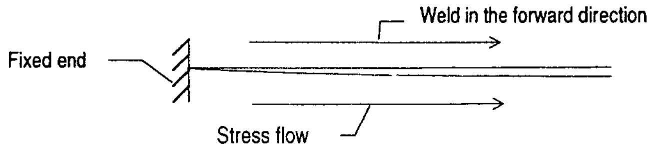
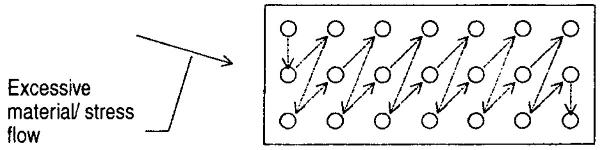
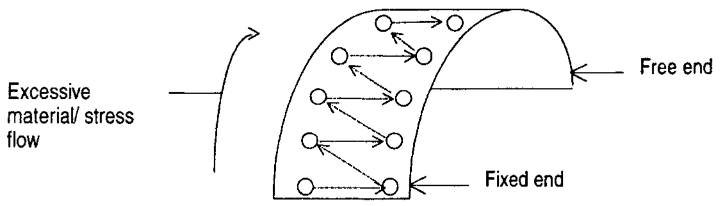
4 PROCESS DESIGN TECHNIQUE FOR SHEET METAL ASSEMBLY

This paper proposes a process design technique to minimize stress build-up within an assembly. The main idea is to allow the flow of material when the welding sequence is going to produce material or stress build-up within the system. These guidelines or procedures are formulated for one-, two- and three-dimensional assembly. It illustrates a simple flow chart of how to do weld sequences. Table 3 illustrates the three different basic improved process design techniques.

One-dimensional process design technique

The one-dimensional example provides the best illustration of the minimum stress build-up conditions. The fixed end as shown in the figure represents the structural beginning where one cannot allow the stress to spread into the fixed end direction. The free end is the end

Table 3 Process design criteria

One-dimensional process design technique	
Two-dimensional process design technique	
Three-dimensional process design technique	

where stress can be freed from constraints. Thus, the weld direction would represent the release in weld-created stress in that direction.

Two-dimensional process design technique

The two-dimensional process design technique produces a flattening of a metal sheet whether the corners of the flat sheet metal are to be fixed or welded first. Stress build-up within the flat sheet metal is obvious when the two parts are not perfectly matched with each other.

Three-dimensional process design technique

The three-dimensional ironing technique is a simple extension of the two-dimensional technique where weld stress build-up is released at the free end of the three-dimensional structure.

5 PRODUCT DESIGN GUIDELINES FOR SHEET METAL ASSEMBLY

When designing product joints in automotive body parts, a robust design for reducing body assembly variation will be of critical importance in designing a good and robust joint for the assembly variation to be incorporated into the joint design. A design gap is commonly used in automotive body design to accommodate the variation in the final build of the assembly. Table 4 illustrates the three different basic joint designs in current practice and the improved designs.

Step joint design

A step joint is one of the major areas where stress build-up is very likely to occur. A design allowing stress to flow within the assembly is of critical importance. A notch can be used to allow the stress to be relieved from the metal compression of the joint area.

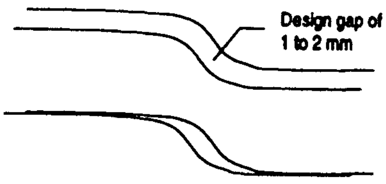
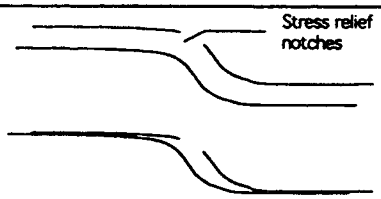
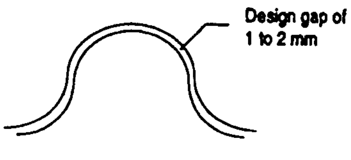
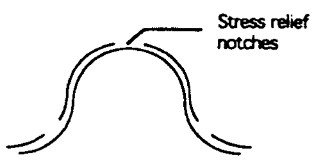
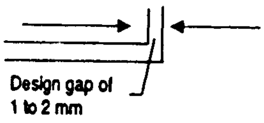
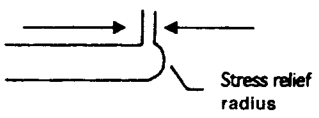
Tunnel design

This is a common design error in many automotive body designs. Tunnel design with the stress relief area is of critical importance because the stress is amplified by the compounded curvature of the tunnel design.

Planar joint design

A planar joint has a typical design that is prone to accumulate the stress throughout sheet metal assembly. In the better design, a stress relief radius is used to prevent the localized stress build-up and to stop the spread of stress to other areas of the system which might affect the dimensional variation of the assembly.

Table 4 Product design criteria

	Design that accumulates stress build up	Design that avoids stress build up
Step Joint Design (design gap of 1 to 2 mm)		
Tunnel Joint Design		
Planar Joint Design		

6 SUMMARY AND CONCLUSIONS

The dimensional integrity of sheet metal assemblies is one of the most important factors in automotive body quality. The autobody affects many downstream processes in the general assembly, wheel alignment, panel fits and warranty cost. Hence, joining more than 200 flexible parts together is both challenging and demanding work for engineers and designers to maintain a good and accurate quality for such high volume production in today's typical automotive manufacturing facilities. The correct and robust design of sheet metal parts is of critical importance to the automotive designers to enable high quality products to be produced early in the design stage. Manufacturing control and statistical process control can only control after-the-fact problems such as the maintenance issue in automotive body manufacturing. They do not address the problem by allowing robust design into complex body design and manufacturing systems.

This paper develops a comprehensive analysis technique and a design criterion for automotive engineers to design better a robust automotive body that is insensitive to manufacturing variability and detail part variability. Thus, improving the overall quality of the body assembly can be achieved early in the design stage. It is widely recognized that a large percentage of manufacturing quality problems are contributed by poor methodology during the design stage. Furthermore, there are difficulties in obtaining good quality when the manufacturing variability and capability are not considered in the product design. A generic method to analyse the internal stress and dimensional variation has been developed. This analysis enables process and product design engineers to consider the internal stress and dimensional instability in their products. This method forms a generic application approach to analyse sheet metal or compliant material assembly processes for improving dimensional accuracy. An industrial case study has also confirmed the simulation technique and the theoretical background of the study. Furthermore, a more practical or generic design guideline has been developed for automotive body designers to improve the product design so that variation and manufacturability can be incorporated into the design. This methodology allows high quality vehicles with much improved dimensional accuracy to be produced.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the reviewers for their diligence in reviewing the current paper. This paper is made possible by the financial support of the Hong Kong University Grant Council.

REFERENCES

1 **Ceglarek, D.** and **Shi, J.** Design evaluation of sheet metal joints for dimensional integrity. *Trans. ASME, J. Mfg Sci. Engng*, May 1998, **120**, 452–460.

2 The engineering process to design-in-quality. In *Robust Engineering Manuals*, 1997 (General Motors Knowledge Center).

3 **Hu, S. X.** and **Wu, S. M.** Identifying sources of variation in automotive body assembly using principal component analysis. *Trans. NAMRI/SME*, 1992, **20**, 311–316.

4 **Liu, S. C.** and **Hu, S. J.** Sheet metal joint configurations and their variation characteristics. *Trans. ASME, J. Mfg Sci. Engng*, 1998, **120**, 461–467.

5 **Shiu, B. W., Ceglarek, D.** and **Shi, J.** Multi-stations sheet metal assembly modeling and diagnostics. *Trans. NAMRI*, 1996, **24**, 199–204.

6 **Shiu, B. W., Apley, D., Ceglarek, D.** and **Shi, J.** Tolerance allocation for sheet metal assembly using beam-based model. *Trans. Inst. Ind. Engr, Des. Mfg*, 1998.

7 **Liu, S. C., Hu, S. J.** and **Woo, T. C.** Tolerance analysis for sheet metal assemblies. *Trans. ASME, J. Mech. Des.*, March 1996, **118**, 62–67.

8 **Liu, S. C., Lee, H. W.** and **Hu, S. J.** Variation simulation for deformable sheet metal assemblies using mechanistic models. *Trans. NAMRI SME*, 1995, **23**, 235–240.

9 **West, H. H.** Stiffness method: general form of equilibrium method. In *Analysis of Structures*, 1989, pp. 589–654 (John Wiley, New York).