Int J Adv Manuf Technol (2002) 19:501–509
Ownership and Copyright

The International Journal of
Advanced
Manufacturing
Technology

Fixture Configuration Design for Sheet Metal Assembly with Laser Welding: A Case Study

B. Li, B. W. Shiu and K. J. Lau

Department of Mechanical Engineering, Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

The role of assembly fixtures is gaining importance in order to meet the special requirement of metal fit-up for sheet metal assembly with laser welding. Fixture configuration methodologies based on a new proposed locating scheme have been developed. In order to demonstrate the feasibility of the proposed fixture design principles in industrial applications, an industrial case study with cross-members assembly is presented. In order to obtain a physical model with the actual tolerances, reverse engineering technologies are employed for geometric modelling of the assembled parts. For achieving modelling accuracy a CMM-based finite-element model is produced and performance characteristics of the 3D features obtained. In the case study, the assembly weld patterns are designed first, to determine the weld locations. Then the general design, the deterministic optimisation and the robust design of the fixture configuration are carried out sequentially. The results of the case study show that the proposed fixturing principles are applicable and effective.

Keywords: Fixture design; Laser welding; Measurement; Sheet metal assembly

1. Introduction

Fixturing is an important manufacturing activity. When fixtures are applied in different manufacturing processes, the functions they play are varied. In sheet metal assembly with resistance spot welding, fixtures are mainly used to control the assembly variation of the whole assembly. In this case, the weld gun produces heat and high local weld tip pressure which are important factors for controlling the implementation of the welding process. However, in the assembly process with sheet metal laser welding, fixtures not only function to control the assembly variation, but also to maintain an intimate fit-up between the assembled parts, the latter is the key factor in ensuring satisfactory implementation of laser welding and the improvement of weld quality [1]. Computer-aided fixture design has been rapidly developed to reduce the lead time involved in manufacturing planning. Recently, most of the workers on fixture design have focused on machining processes [2–4], but a few reported on the sheet metal assembly process [5,6]. As shown in Fig. 1, the fixture design cycle of a typical manufacturing system includes three major aspects: set-up planning, fixture planning, and fixture configuration design [2]. Set-up planning is aimed at determining the number of set-ups and the position and orientation of the workpiece in each set-up. The flange edges or the weld areas in each set-up are determined in this stage. Fixture planning mainly determines the locating and clamping points on the workpiece surfaces. The objective of fixture configuration design is to select fixture components and place them into a final configuration to fulfil the functions of locating and clamping the workpiece. In sheet metal laser welding, the assembly fixtures are also configured to satisfy the metal fit-up requirements.

The degree of metal fit-up (DMF) with (0.1–0.15) IMT (impact metal thickness) is the important specification that laser welding requires. Owing to the flexible nature of sheet metal parts, the stamping process cannot meet this specification. In this context, fixture design for laser welding is case-dependent. Thus, a problem arises, for the same assembly, the resultant fixturing schemes for different cases may be different.

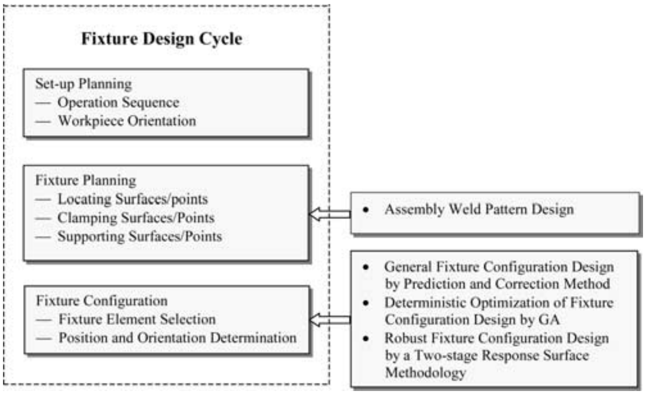

Fig. 1. A general fixture design cycle and the work done for assembly fixture design.

Correspondence and offprint requests to: Dr B. Li, Department of Mechanical Engineering, Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong. E-mail: b.li@polyu.edu.hk

With the introduction of optical coordinate measuring machines (OCMMs) and the application of flexible fixtures, the in-process fixture configuration design for sheet metal laser welding becomes possible. Figure 2 shows the logical structure of the sheet metal laser welding cycle. The variational information of the locating areas on the parts of an assembly can be obtained by an OCMM. This information can be fed into the in-process fixture design module. The new fixturing scheme can be applied for the assembly by using flexible fixtures, so that differences of the fixture configuration required for different cases can be accommodated by the adjustments of flexible fixtures.

Li et al. [7–9] were the first to address the in-process fixturing issues relating to sheet metal assembly with laser welding. The work related to fixture design for sheet metal laser welding is shown in Fig. 1. The assembly weld pattern design, which is presented in a separate paper, is within the scope of fixture planning. The fixture configuration design includes: general fixture configuration design by a proposed prediction and correction method, deterministic optimisation of fixture configuration design by a genetic algorithm, and a robust fixture configuration design by a two-stage response surface methodology. The objective of this paper is to carry out a case study in which the proposed fixturing principles are applied to an actual automotive body assembly. To realise this objective, measurement is necessary to implement the CAD modelling for the experimental case study. The paper is organised as follows. In Section 2 a brief review of the fixture configuration design principles for sheet metal assembly with laser welding is given. The CMM-based finite-element modelling is described in Section 3, where the CAD model representation based on the measurement data is given. The design results and a summary are given in Sections 4 and 5.

2. Review of Fixturing Principles for Sheet Metal Assembly with Laser Welding

2.1 Assembly Weld Pattern Design

Before fixture configuration design is carried out, assembly weld patterns (weld location and weld length, etc.) have to be determined. The traditional experience-based determination of weld locations is not very reliable, so a scientific design approach to the weld patterns is developed. First, the candidate weld locations and the corresponding weld lengths are determined based on the geometrical information of the CAD model of the assembled parts. According to the related strength criterion, the total weld length on the weld area can be estimated and will be allocated to the weld location candidates with adequate safety considerations. Thus the assembly weld pattern can be determined.

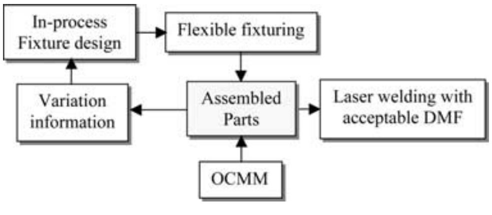

Fig. 2. Logical structure of sheet metal laser weld cycle.

2.2 New Locating Scheme and Finite-Element Modelling

Current stamping processes cannot meet the required degree of metal fit-up which is crucial for implementing the laser weld operation. For poor stamping quality panels, laser welding can be carried out only with the aid of complex fixtures which is expensive and lacks flexibility. A new locating scheme with both total locating and direct locating on welds is proposed. The total locating scheme is used to locate the entire assembly, and the direct locating scheme is used to locate the weld joints to meet the metal fit-up requirement. The geometric model is a surface with normal-distributed source variation. In the finite-element (FE) model, a 4-way pin and a 2-way pin are regarded as a two-direction constraint and a one-direction constraint. The locator is modelled as an enforced displacement in the MSC/NASTRAN program. The two panels of the assembly are connected by gap elements with appropriate stiffness settings. The application of gap elements can reflect the DMF status of the weld area better. When the gap is closed the two mating nodes will move together.

2.3 Prediction and Correction Method

A prediction and correction method is developed for configuring the direct locators of the sheet metal assembly applied with a specified total locating scheme. First, the nodes on the weld stitch are set to the nominal values. By finite-element analysis (FEA), a nodal variation graph (NVG) which includes the nodal variation of the direct locating area around the weld stitch can be obtained. Then the locating nodes can be grouped by setting the different variational threshold values. In this way, a hierarchy level chart (HLC) can be extracted from the NVG. Secondly, a prediction step is carried out by setting the direct locators based on a certain level from the HLC. Then a correction step is carried out by FEA. If the metal fit-up requirement cannot be met, more locators corresponding to a new level from the HLC are applied. Using several prediction and correction cycles, we can find a final suitable locating scheme for the assembly.

2.4 Deterministic Optimum Model

By fixing the location of the “2–1” pins, the fixtures configure the locators used for total locating and the locators for direct locating for welds. Both the number and the location of the locators are set as design targets. In the optimisation of the fixture configuration design, a genetic algorithm (GA) is employed with an integer number as an encoding string. The case control feature of MSC/NASTRAN is used to improve the search efficiency of the GA, thus the population evaluation of one evolution generation only requires one run of FEA. A fuzzy synthesis evaluation method is used for determining the metal fit-up criterion since the DMF can be within 0.1–0.15 IMT. The new DMF criterion is determined by considering a specified factor set, of weld speed, material type, weld bead width and the degree of penetration into the lower layer panel. Owing to the auxiliary effect of direct locators on total locating, the total locating scheme need not be a "3–2–1" locating scheme, it can be, for example, a "2–2–1" or "1–2–1", or even a "2–1" locating scheme may be enough. A developed pattern-sorting method is used to determine the number of total locators. The minimised objective function is the maximum DMF of weld joint nodes. Interface programming is used to connect FEA and the GA.

2.5 Robust Design Model

In robust fixture configuration design, the performance characteristic of the sheet metal laser welding is the degree of the metal fit-up along the weld joint. The control variables are the locations of the designed locators. The noise variable in this study is set as the movement of the two-way pin along the x-direction. Response surface methodology (RSM) is employed as a robust design approach to evaluate the interactions between control variables and between control and noise variables. When using RSM, the design variables should change within a relatively small region of interest of the independent variable space [10]. A two-stage RSM is developed. The first stage of the methodology is to find the small region of interest which is defined as the robust design space (RDS). In this stage, the design variables are assumed to be independent. In the second stage, a response surface model is set up based on the resulting small region. In order to form a second-order model of the response surfaces, a 3^k fractional factorial design (such as a Box–Behnken design) is employed. The response value is the degree of metal fit-up. The minimised objective function which connects the robustness and the performance with the weighted factors ω_1 and ω_2 is used for determining the RDS as shown in Eq. (1).

$$\text{Minimise } F_c(x) \qquad (1)$$
$$= \omega_1 \left(\frac{K}{\|h\|^2} \sum_{i=1}^{N_T} \|f_{i+1} - f_{i-1}\|^2 \right) + \omega_2 (f_i - \alpha \text{ IMT})$$

where f_{i-1}, f_i, f_{i+1} refer to the performance function of the node i and its two neighbouring nodes; h represents mesh size; K is a coefficient to balance the magnitude; N_T refers to the number of design locators for both the total locating scheme and the direct locating scheme; α is a coefficient of quality specification (the range of α can be 0.1–0.15). By using robust fixture configuration design, the resulting design scheme is less sensitive to the location uncertainty of the input variables produced by manufacturing and assembly errors. The influential design locators can also be detected by tests on individual regression coefficients of the fitted response model.

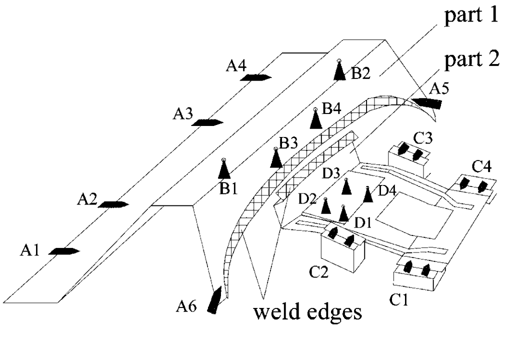

Fig. 3. Measuring fixture scheme for cross-member assembly.

3. CMM-Based Finite-Element Modelling

3.1 Selection of the Experimental Assembly

There are several potential production applications of sheet metal laser welding in automotive industry, e.g. door inners, motor compartment rails, A-pillars, body sides, bumpers, B-pillars, floor pans, lift gates and wheelhouses. In North America, such other applications as seat reinforcements, cross-beam members, dash panels and seat risers are being examined [11]. The selection of the experimental assembly depends mainly on two factors:

1. The parts must be suitable for laser welding.
2. The dimensions of the parts should be relatively small for easily shipping to the laboratory and also for ease of measurement under laboratory conditions.

In this study, the cross-members assembly of BIW (body-in-white) is used in the measuring experiment. As shown in Fig. 3, the assembly includes two parts, a large part with dimensions of 1200 × 180 × 120 mm^3 and a small part with dimensions of 360 × 180 × 80 mm^3. The material of the two panels is mild steel with Young's modulus E = 207000 N mm^{-2} and

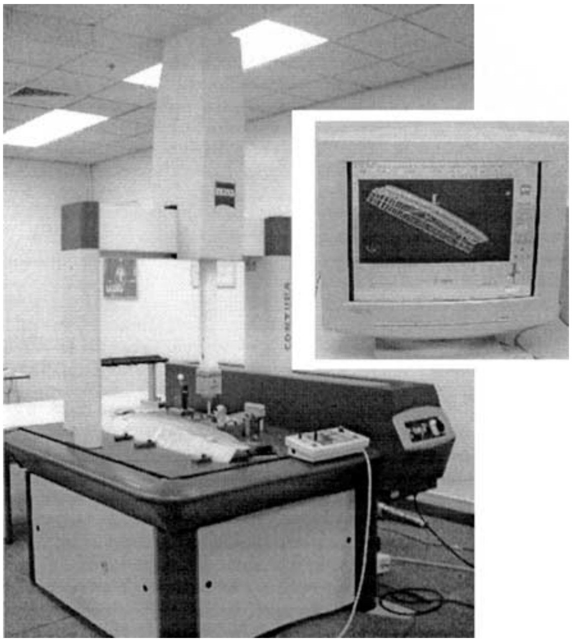

Fig. 4. Digitised measurement by CMM.

Table 1. Design results of weld location (WL) candidates.

Total patch number on weld area 28 WL configuration number	Included patch number per weld 7 Maximum angles (deg.)		Total number of WL configuration 22 WL candidates	
	Part 1	Part 2	Part 1	Part 2
1	0.0937374	1.548441	P1	
2	0.000000	1.758605	P2	
3	0.765278	1.786967	P3	
4	0.000000	1.707148	P4	
5	0.000000	1.194342	P5	
6	0.000000	0.895913	P6	P6
7	0.669191	0.641160	P7	P7
8	0.000000	0.641160	P8	P8
9	0.000000	0.814675	P9	P9
10	0.000000	0.801145	P10	P10
11	0.980947	0.958530	P11	P11
12	0.998246	0.958530	P12	P12
13	1.300194	0.998350	P13	P13
14	1.657047	0.757643	P14	P14
15	1.481659	0.847940	P15	P15
16	1.969000	1.168268	P16	P16
17	2.457149	1.545972	P17	P17
18	2.340084	1.655090	P18	P18
19	2.901358	2.105234	P19	P19
20	2.577895	1.891445	P20	P20
21	1.748533	1.725405	P21	P21
22	1.565100	1.338755		
Boundary angle	$\theta_0 = 1.5°$	$\theta_0 = 1.0°$	21 patches	16 patches
WL candidates for assembly (weld length = 80 mm)				
Patch number	P6, P7, P8, P9, P10, P11, P12, P13, P14, P15, P16, P17, P18, P19, P20, P21			
Designed two welds	P6, P7, P8, P9, P10, P11, P12 P15, P16, P17, P18, P19, P20, P21		Weld length = 35 mm Weld length = 35 mm	

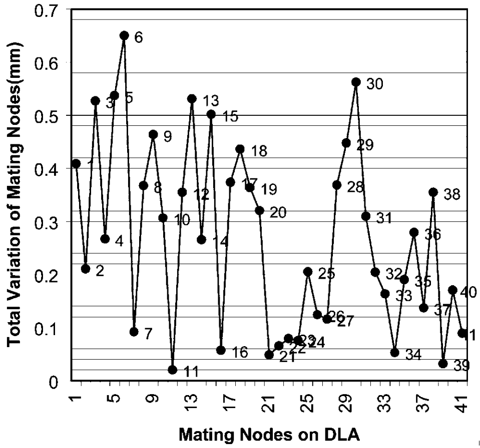

Fig. 5. NVG for general fixture design.

Poisson's ratio $\gamma = 0.3$. In this experiment, one selected set of the cross-members assembly of good manufacturing quality is used.

3.2 CAD Model Representation Based on Measuring Data

Both weld pattern design and fixture configuration design are carried out based on the finite-element model. In order to obtain the finite-element model, geometric modelling must be carried out first. The experimental parts in this study are obtained from the automotive workshop, but CAD models of the parts are not available. Even if the CAD models were available, it would still be impossible to apply them directly for fixture design since we need a model with tolerances, whereas the CAD model is only a nominal model without tolerances. It is thus necessary to create a CAD representation from the actual model. In this context, reverse engineering methodology [12] is employed to solve this problem. Reverse engineering is based on techniques for measuring the shape of physical models and data processing techniques for constructing CAD models from the measured data. Currently, there are many different kinds of digitising technologies available, ranging from manual touch-probe devices and coordinate measuring machines (CMMs) to laser scanning systems and industrial CT scanners. Each technology has its own strengths and limitations. As high accuracy is required in this study, a CMM is employed to measure the auto-body parts, and the measuring data will be used for finite-element modelling.

In this measuring experiment, a "CONTURA" CMM with a moving bridge configuration is employed, and the corresponding supporting software packages are Calypso and Holos. Calypso software is used for probe calibration and the definition of base alignment of the measurement system. Holos software is used for digitisation of the physical surfaces of the parts. The first step in the measurement is the division of the digitised surface. Based on the geometrical features of the digitised surface, the workpiece surface will be divided into more patches. In order to make it easier to probe the boundaries of the surface, the division mesh is marked with a marker pen. Since in this case the weld areas are distributed on the flange area of the assembly, the measuring points with high density are set on the flange area. The other important factor which must be considered in this step is that the design of the surface division should be convenient for constructing the surface. The second step is the set-up of the measuring fixtures. The fixture requirements for measurement purposes are quite different from those for welding. The main role of the measuring fixtures is to keep the dimension of the parts stable. The fixturing scheme in this case is not necessarily limited to a "3–2–1" or "4–2–1" locating scheme, additional clamps and supporting poles are required. In industrial applications a popular checking fixture is often a die base with some clamps applied. However, in the laboratory the use of a die base is not cost-justifiable, so clamps and supporting poles are employed. The automotive parts are freeform parts; the measuring fixture elements are used to clamp the sheet metal parts onto the worktable of the CMM. If necessary, a measuring datum is provided for base alignment. Figure 3 shows the fixturing scheme for measurement. Clamps A1, A2, …, A6 and supporting poles B1, B2, B3, B4 are used to locate part 1; locating blocks C1, C2, C3, C4 and the supporting poles D1, D2, D3, D4 are used to locate part 2. The base alignment is defined on part 1, a 2D

Table 2. HLC for general fixture design.

Level i	V_i (mm)	Number of applied locators	Nodal ID number
1	0.54	3	5, 6, 30
2	0.5	6	5, 6, 30, 3, 13, 15,
3	0.42	9	5, 6, 30, 3, 13, 15, 9, 18, 29
4	0.37	11	5, 6, 30, 3, 13, 15, 9, 18, 29, 1, 17
5	0.36	14	5, 6, 30, 3, 13, 15, 9, 18, 29, 1, 17, 8, 19, 28
6	0.34	16	5, 6, 30, 3, 13, 15, 9, 18, 29, 1, 17, 8, 19, 28, 12, 38
7	0.30	19	5, 6, 30, 3, 13, 15, 9, 18, 29, 1, 17, 8, 19, 28, 12, 38, 10, 20, 31
8	0.26	22	5, 6, 30, 3, 13, 15, 9, 18, 29, 1, 17, 8, 19, 28, 12, 38, 10, 20, 31, 4, 14, 36
9	0.2	25	5, 6, 30, 3, 13, 15, 9, 18, 29, 1, 17, 8, 19, 28, 12, 38, 10, 20, 31, 4, 14, 36, 2, 25, 32
10	0.16	28	5, 6, 30, 3, 13, 15, 9, 18, 29, 1, 17, 8, 19, 28, 12, 38, 10, 20, 31, 4, 14, 36, 2, 25, 32, 33, 35, 40
11	0.11	31	5, 6, 30, 3, 13, 15, 9, 18, 29, 1, 17, 8, 19, 28, 12, 38, 10, 20, 31, 4, 14, 36, 2, 25, 32, 33, 35, 40, 26, 27, 37
12	0.08	33	5, 6, 30, 3, 13, 15, 9, 18, 29, 1, 17, 8, 19, 28, 12, 38, 10, 20, 31, 4, 14, 36, 2, 25, 32, 33, 35, 40, 26, 27, 37, 7, 41
13	0.06	36	5, 6, 30, 3, 13, 15, 9, 18, 29, 1, 17, 8, 19, 28, 12, 38, 10, 20, 31, 4, 14, 36, 2, 25, 32, 33, 35, 40, 26, 27, 37, 7, 41, 22, 23, 24
14	0.04	39	5, 6, 30, 3, 13, 15, 9, 18, 29, 1, 17, 8, 19, 28, 12, 38, 10, 20, 31, 4, 14, 36, 2, 25, 32, 33, 35, 40, 26, 27, 37, 7, 41, 22, 23, 24, 16, 21, 24
15	0	41	5, 6, 30, 3, 13, 15, 9, 18, 29, 1, 17, 8, 19, 28, 12, 38, 10, 20, 31, 4, 14, 36, 2, 25, 32, 33, 35, 40, 26, 27, 37, 7, 41, 22, 23, 24, 16, 21, 24, 11, 39

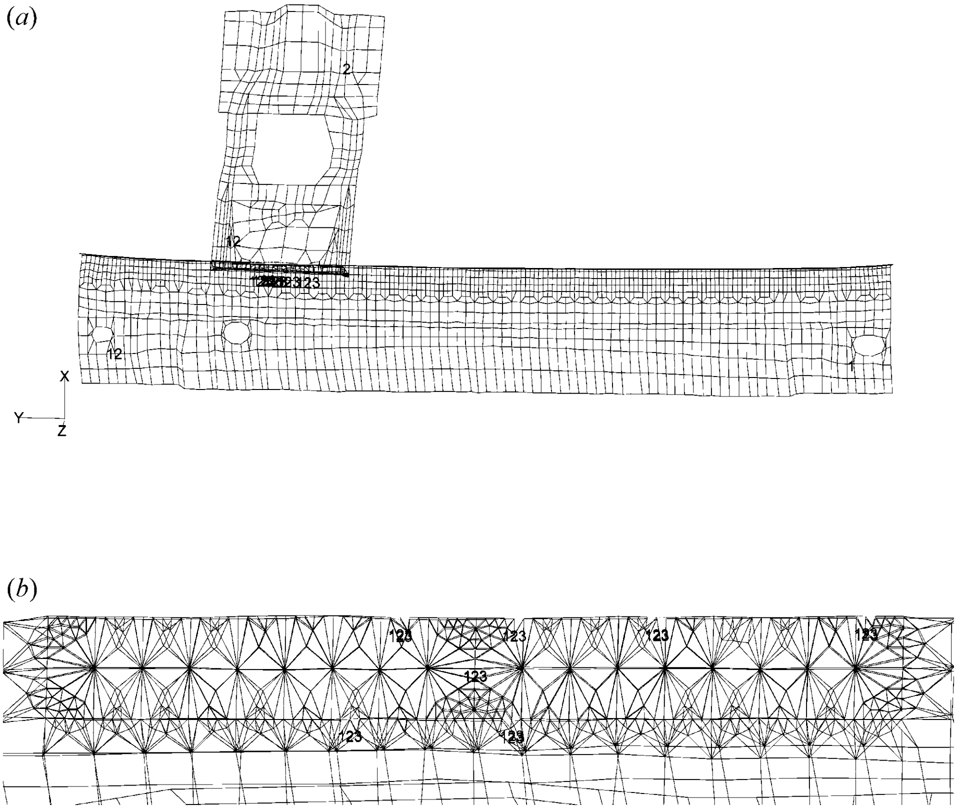

Fig. 6. Finite-element model. (*a*) Whole model. (*b*) Local fine mesh on weld location.

line connecting the centre-points of the locating hole and locating slot, and a point on the side plane of part 1 is also defined. Subsequent to the measuring operation based on the division mesh, the approximation of the surface segments can be obtained. Then by constructing surfaces from the measured patches, the CAD representation of the two parts can be obtained. The digitised measurement by the CMM is shown in Fig. 4.

Table 3. Design results of the case study.

"2–1" pins	Node number	Part 1: 1257 Part 2: 2422	Part 1: 1100 Part 2: 2655
	Restrained direction	(*X*, *Y*)	(*X*)
Total locating scheme	Part 1: "4–2–1" Part 2: "4–2–1"	Part 1: "2–1" Part 2: "2–1"	
DMF (mm)	0.102564	0.103837	
Number of direct locators	General fixture design: 9	Optimal design: 7	

Designed locators with "2–1" total locating scheme

	Initial scheme		Optimal scheme		Robust design			
					Mean of RDS ($\omega_1 = 0.7$, $\omega_2 = 0.3$)		Robust scheme	
	Part 1	Part 2	Part 1	Part 2	Part 1	Part 2	Part 1	Part 2
Node number	2115	2748	2863	3241	2848	3220	2847	3221
	2118	2745	2932	3315	2119	2744	2119	2744
	2112	2741	3648	3388	3017	3443	3016	3444
	2129	2734	3101	3540	3052	3480	2127	2736
	2155	2764	3061	3489	3156	3559	3155	3558
	2156	2763	3010	3432	3061	3489	2152	2765
	2104	2774	2960	3344	2970	3380	2100	2762
DMF (mm)	0.09187		0.08504		0.12509		0.11806	

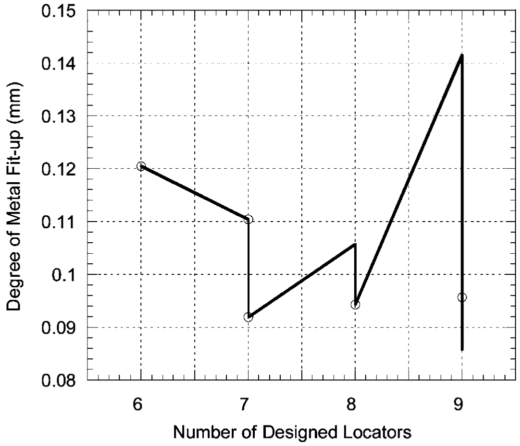

Fig. 7. Optimisation of the number of designed locators.

3.3 Finite-Element Modelling

The digitised surface model obtained from the CMM can be imported to the NASTRAN software. The imported surface must be cleaned and some small features which are not important to the FEA must be deleted to improve analysis efficiency, then the finite-element model can be generated. Based on this FE model, the assembly weld pattern design and the fixture configuration design can be carried out.

In the fixture configuration design, we are concerned with whether the DMF of the weld can meet the laser welding specification. It is very important that the FE model, in particular, the weld area on the model, can reflect the real-life manufacturing quality. The best measurement operation is thus one based on the actual assembled location of the two parts. However, in this way, the measuring fixture will be very complicated in order to keep the two flange edges of the assembly in intimate fit-up, since we do not have any physical information available at this stage. As some manufacturing datum for each part exists, if these datums are set as measuring datums, the measurement fixture will be greatly simplified. So, in this study, we measure the two assembled parts separately. In order to connect the two parts in the MSC/NASTRAN software, three mating points on each part must be recognised. Then, based on the point information, the align and rotate operations in MSC/NASTRAN are carried out. The final model for analysis is thus obtained.

In this paper, the mesh density of the FE model along the flange edge is 5 mm. If the length of the flange edge is L, the number of element edges along the flange edge is $N = L/5$. Thus, the weld area of interest can be set as 3 rows × $N+1$ columns. However, the probe stylus will touch the outer surface of the panel, while the FE modelling is along the mid-plane of the panel. In order to avoid the metal thickness problem involved, we take the measured surface as the required mid-plane. For complicated 3D sheet metal shapes, the DMF is calculated in the following way. Assuming the nodal coordinates of two mating weld joint nodes from the CMM are (x_1, y_1, z_1) and (x_2, y_2, z_2) and when a certain fixture scheme is set in position, the corresponding deformations after FEA are (Δx_1, Δy_1, Δz_1) and (Δx_2, Δy_2, Δz_2); the DMF is then evaluated by the 3D distance between the two mating nodes on the weld area, as shown in Eq. (2).

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

Table 4. Analysis and test of the second-order response model.

Analysis of variance

Source of variance	Sum of Squares	DOF	Mean square	F-ratio	$F_{0.05,\,n1,\,n2}$
Regression	3.0671×10^{-4}	35	8.763217×10^{-6}	7.512	1.915
Residual	2.7997×10^{-5}	24	1.166564×10^{-6}		
Lack of fit	2.3857×10^{-5}	21	1.136030×10^{-6}	0.823	8.655
Pure error	4.1409×10^{-6}	3	1.380308×10^{-6}		
Total	3.347×10^{-4}	59	R-square = 0.9087		
Mean response	0.12457		RootMSE:		0.00108

Test on individual regression coefficients

Variable	Coefficient Estimate	t for H_0 (coeff. = 0)	$t_{0.025,24}$: 2.0639
intercept	0.12577250	232.8956	+
X1	–0.00049778	–2.111473	+
X2	0.00002812	0.117465	–
X3	–0.00001075	–0.048760	–
X4	0.00092008	4.173289	+
X5	–0.00089274	–3.993961	+
X6	0.00139358	6.320977	+
X7	0.00202291	9.050120	+
X1 × X1	0.00017767	0.568850	–
X2 × X2	–0.00063972	–2.037592	–
X3 × X3	–0.00058420	–1.870445	–
X4 × X4	–0.00189833	–6.077879	+
X5 × X5	–0.00003184	–0.101422	–
X6 × X6	0.00016167	0.517622	–
X7 × X7	–0.00020109	–0.640508	–
X1 × X2	–0.0000174	–0.045500	–
X1 × X3	0.00003213	0.084126	–
X1 × X4	0.00025731	0.513628	–
X1 × X5	0.00025038	0.655664	–
X1 × X6	–0.00024300	–0.636351	–
X1 × X7	–0.00085275	–2.233122	+
X2 × X3	–0.00000275	–0.007202	–
X2 × X4	–0.00011228	–0.245861	–
X2 × X5	–0.00011661	–0.263927	–
X2 × X6	–0.00000125	–0.003273	–
X2 × X7	0.00002342	0.058870	–
X3 × X4	0.00112188	2.937887	+
X3 × X5	0.00001788	0.046810	–
X3 × X6	–0.00001775	–0.046482	–
X3 × X7	–0.00094463	–2.473717	+
X4 × X5	–0.00014825	–0.388227	–
X4 × X6	0.00026650	0.697891	–
X4 × X7	0.00046438	1.216073	–
X5 × X6	–0.00026975	–0.706402	–
X5 × X7	–0.00027860	–0.700844	–
X6 × X7	0.00033100	0.866799	–

4. Design Results

The first step in fixturing design is weld design. The weld areas in this assembly are the flange edge of the small part and the corresponding mating area of the long part. The assembled weld design shown in Section 2.1 is carried out, and the weld location candidates are given in Table 1. The loading status of this assembly, when being assembled into the BIW frame, is very complicated. Based on experience, assuming the average shear load applied in this assembly is 1.8 kN. The thickness of the panel is 1 mm and the allowed boundary strength $[\tau_e]$ is 30 MPa. Thus, the minimum total length of the weld can be obtained, which is 60 mm. From consideration of the distribution of the original DMF, two welds each of 35 mm can be determined. The patch number of the two welds is listed in Table 1. The second step of this design is fixture configuration design. General fixture design is carried out based on the "4–2–1" locating scheme for the two assembled parts. The nodal variation graph and the hierarchy level chart for general fixture design is shown in Fig. 5 and Table 2. Using the prediction and correction method, 9

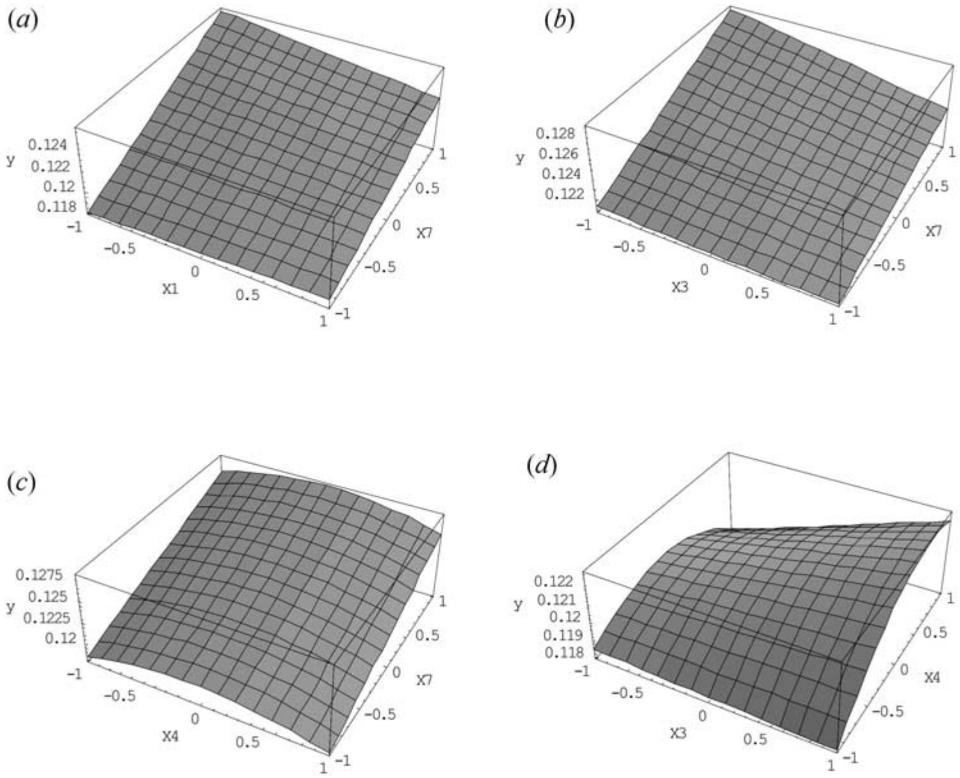

Fig. 8. Response surfaces for the main designed locators.

direct locators are required to achieve a DMF of 0.102564 mm (the allowed DMF limit is set at 0.13 mm). Testing with different total locating schemes, from "4–2–1" to "2–1", the DMFs are almost unchanged. This is because the weld type of this assembly is a butt weld, so the total locating direction is different from the variational direction of the weld lines, moreover, the part dimension is large. Thus, for an optimal and robust fixture design, only direct locators are taken as designed locators when the "2–1" total locating scheme is applied. The finite-element model of this case study is shown in Fig. 6.

The fixture design results of this case study are presented in Table 3. In the optimisation of fixture design, the number of locators is treated as a design variable and is optimised first, based on a coarse mesh size; results show 7 direct locators are enough to achieve a DMF of 0.09187 mm. The optimisation process is shown in Fig. 7. The optimal result based on a fine mesh with 7 locators shows that the DMF in this case can be 0.9187 mm. Taking the result of the determination of robust design space as the centre-point a ±1 mm variation in the robust design space is determined. The control variables are designed locators (D*1*, D*2*, …, D*7*) and a 3^k fractional factorial BBD is carried out. The analysis of variance and the test for independent variables in the response model are shown in Table 4. From the table, we can see the influential terms of the response model. The approximate response function with influential terms is shown in Eq. (3). The optimal results are: X1 = −1, X3 = −1, X4 = 1, X5 = 1, X6 = −1 and X7 = −1. Thus, the locator D2 can be set at a location X2 = 0. The four response surfaces for locators D1 and D7, D3 and D7, D4 and D7, D3 and D4 are shown in Fig. 8. The robust design results are also given in Table 3.

$$
\begin{aligned}
R(X) = {} & 0.1257725 - 0.00049778\ X1 + 0.00092008\ X4 - 0.00089274\ X5 \\
& + 0.00139358\ X6 + 0.00202291\ X7 - 0.00085275\ X1\ X7 \qquad (3) \\
& + 0.00112188\ X3\ X4 - 0.00094463\ X3\ X7 - 0.00189833\ X4^2
\end{aligned}
$$

5. Summary

This paper carries out a case study of automotive assembly by applying the fixture configuration design methodologies developed for sheet metal laser welding. A selected cross-member assembly of BIW is taken as the example. In order to obtain a physical model of the car body parts with actual tolerances, a CMM is employed for the measurement of the parts. A CMM-based finite-element model is then generated. In this case study, the degree of metal fit-up is no longer a 1D variation, but a 3D variation. Thus, the distance between the mating nodes in 3D space is regarded as the performance characteristic of this design.

By using the weld pattern design method, two 35 mm long welds on the flange edges and the weld area and locating area are determined. For general fixture design, additional direct locators are required. In previous design methods the number of these will be used directly in the optimal design, whereas in this paper, the number of direct locators is treated as a design variable. The optimal process is thus a dynamic design process. First, the number of designed locators is optimised on the locating area with a coarse mesh; then, global optimisation is carried out using a fine mesh for the locating area. Robust design is then followed up with the two-stage response surface methodology developed. The influential designed locators are detected and a robust fixturing scheme is obtained.

The optimal design scheme has better performance characteristics, but the robust design scheme is less sensitive to the location variability. From this case study, we can see that the proposed fixture configuration methodologies can effectively meet the requirement for industrial application.

Acknowledgements

The author is grateful to Dr Jan Shi at the Department of Mechanical Engineering, University of Michigan for providing experimental parts. This work is supported by Hong Kong Polytechnic University Research Fund G-V699.

References

1. D. Avilla, Laser Welding Design and Process Fundamentals and Troubleshooting Guideline, Rofin-Sinar, 1996.
2. W. Ma, J. Li and Y. Rong, "Development of automated fixture planning systems", International Journal of Advanced Manufacturing Technology, 15, pp. 171–181, 1999.
3. Y. Rong, X. Liu, J. Zhou and A. Wen, "Computer-aided setup planning and fixture design", International Journal of Intelligent Automation and Soft Computing, 3(3), pp. 191–206, 1997.
4. A. J. C. Trappey and C. R. Liu, "A literature survey of fixture design automation", International Journal of Advanced Manufacturing Technology, 5(3), pp. 240–255, 1990.
5. Mark R. Rearick, S. Jack Hu and S. M. Wu, "Optimal fixture design for deformable sheet metal workpieces", Transactions NAMRI/SME, 21, pp. 407–412, 1993.
6. W. Cai, S. J. Hu, J. X. Yuan, "Deformable sheet metal fixturing: principles, algorithms and simulation", ASME Journal of Manufacturing Science and Engineering, 118, pp. 318–331, 1996.
7. B. Li, B. W. Shiu and K. J. Lau, "Principle and simulation of fixture configuration design for sheet metal assembly with laser welding. Part 1: Finite-element modelling and a prediction and correction method", International Journal of Advanced Manufacturing Technology, 18(4), pp. 266–275, 2001.
8. B. Li and B. W. Shiu, "Principle and simulation of fixture configuration design for sheet metal assembly with laser welding. Part 2: Optimal configuration design with genetic algorithm", International Journal of Advanced Manufacturing Technology, 18(4), pp. 276–285, 2001.
9. B. Li, B. W. Shiu and K. J. Lau, "Fixture configuration design for sheet metal laser welding with a two-stage response surface methodology", ASME Design Engineering Technical Conferences, paper No. DETC 2001/DAC-21096, 2001.
10. D. C. Montgomery, Response Surface Methodology: Process and Product Optimization Using Designed Experiments, John Wiley, New York, 1995.
11. B. Irving, "Automotive engineers plunge into tomorrow's joining problems", Welding Journal, 73(12), pp. 47–50, 1994.
12. A. Hideki and S. Yuu, "Autonomous measurement of physical model shape for reverse engineering", Transaction NAMRI/SME, 27, pp. 251–256, 1999.

Notation

F_c	minimised objective with combination of robustness and performance
f_{i-1}, f_i, f_{i+1}	performance function of the node i and its two neighbour nodes
h	mesh size
K	coefficient to balance the magnitude
N_T	number of design locators for both the total and direct locating scheme
α	coefficient of quality speciation
(x_1, y_1, z_1)	node coordinates of weld joint on part 1
(x_2, y_2, z_2)	node coordinates of weld joint on part 2
$(\Delta x_1, \Delta y_1, \Delta z_1)$	nodal deformation of weld joint on part 1 after FEA
$(\Delta x_2, \Delta y_2, \Delta z_2)$	nodal deformation of weld joint on part 2 after FEA
X1, X2, …, X7	coded variables of the designed locators