8

Development of digital laser welding system for car side panels

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1. Introduction

Because of the extremely globalized competition, all manufacturing enterprises not only have to decrease the product development time and reduce manufacturing cost, but also develop new technologies. Automotive enterprises are facing to two market requirements such as the increment in demand for improvement of safety and the reduction of fuel consumption. From the design point of view, the improvement of safety means high strength of car body while the reduction of fuel consumption is treated to light car body. Because car body consists of panels, the improvement of strength can be treated as material property and welding structure. Welding structure is considered as an important factor in case of car body strength. Also, as a part of efforts to lighten car body in automotive enterprises, they try to make car body using new technologies such as TWB(Tailor Welded Blank) (Ku et al., 2004; Zhang, 2006) or hydro forming (Gao et al., 2006; Park et al., 2002; Saito et al., 2006; Suh et al., 2006) which can minimize the overlapping areas of welding. At the same time, they attempt to lighten car body by substituting the existing steel–oriented panel with new materials such as aluminum or magnesium.

The existing spot welding is not anymore appropriate for strength of welding structure and new materials. In order to overcome these problems, laser welding is studied and carried out for car body welding instead of spot welding. Because laser welding has so many advantages such as good accessibility, fast welding speed and good welding quality, the automotive enterprises try to develop and apply laser welding technology. BMW and Volkswagen try to design two layer structures for application of Nd:YAG laser which increase greatly the flexibility of welding process. And AUDI used seam tracking system to perform laser welding without jig/fixture (Emmelmann, 2000; Koerber et al., 2001; Sasabe et al., 2003) (Fig. 1). In case of Korean automotive enterprises, laser welding is still not activated so that just some parts of car body are welded by laser welding (Jung et al., 2002). But they began to recognize the necessity of laser welding and then carry out many experiments and researches for the extensive application. In spite of the high performance of laser welding, it is currently used in only a few area of the theoretically possible application. This is due to the fact that a lot of companies, owing to the complex, time-consuming and cost intensive planning of the laser welding cell, exercise restraint when it comes to entering the field of laser material processing, such inhibitions can be eliminated by providing application specific solution, i.e. a reasonable planning method when planning complex system like a laser welding cell.

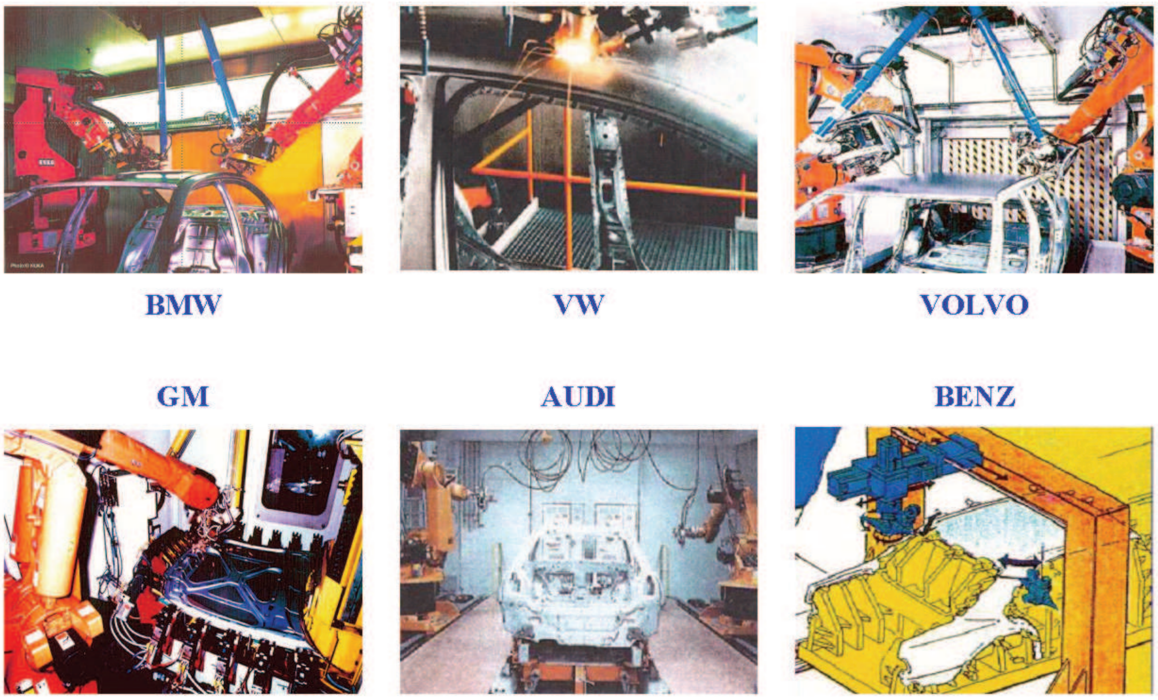

BMW VW VOLVO
GM AUDI BENZ

Fig. 1. Application of laser welding in car body assembly

The objective of this paper therefore is to conceive a method of the planning of laser welding cell and its implementation with digital manufacturing.

For the implementation of the laser welding cell as planning object, this means that it should be followed the systematic planning procedure(Fig. 2).

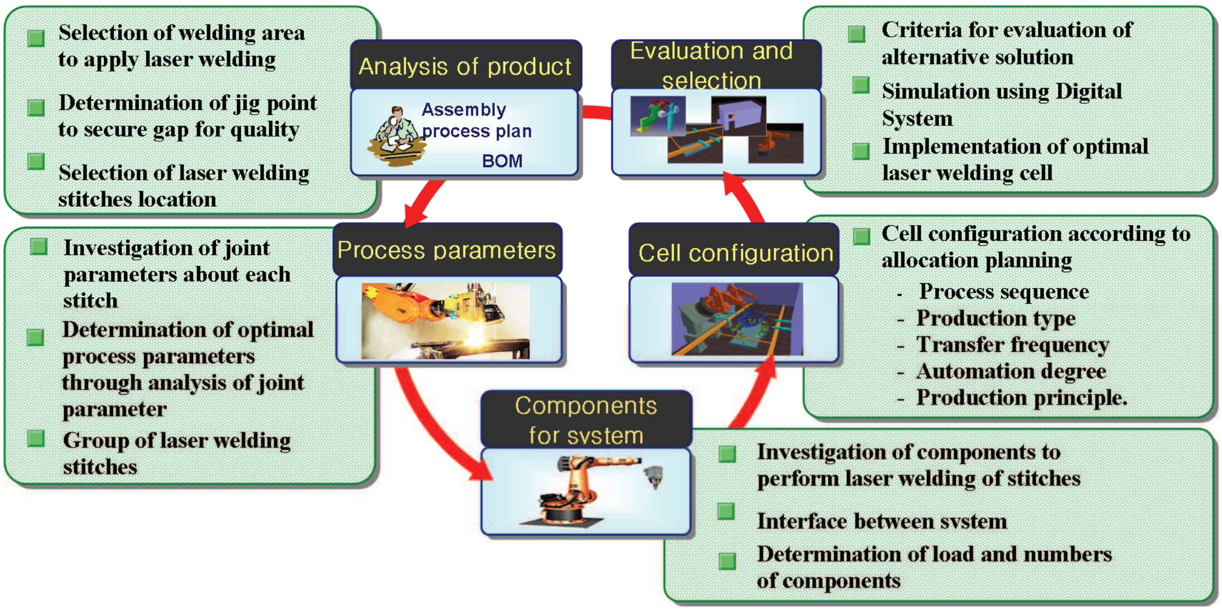


Fig. 2. Systematic procedure for planning laser welding cell

Through the analysis of product as the first step the requirements for executing a welding process and configuring a welding cell are grasped. Based on the these information, the process parameters guaranteeing the welding quality are chosen and grouped for planning the welding sequence and for deriving the needed characteristics of the cell components. To execute the appropriate components are determined through the comparison between the requirement profiles of them and the ability of the commercial products. With the selected components, the cell configurations are generated and evaluated using digital manufacturing.

2. Characteristics of laser welding

2.1 Advantages of laser welding compared spot welding

Most automotive enterprises have assembled car body using spot welding. With this technology, spot guns are big, heavy and have to take lots of direction change to perform the welding task. These problems lead to decrease the flexibility of system and tool accessibility. As a result, the number of cell to perform the welding task increases. However, laser welding using laser beam radiated from optic head can weld, even if accessibility of optic head is allowed at only one side. As laser welding is applied, it offers greatly flexibility of product design and tool accessibility and dramatically decreases welding time than the existing spot welding. In addition, laser welding is expected to improve the welding strength, to prevent from car body deformation as well as to have better quality. Also, we can make the lighter car body through benefits of laser welding such as elimination of redundant reinforcements, minimization of part numbers and overlapping areas of panels.

2.2 Influential factors and process parameters of laser welding

For laser welding, heat conduction welding and deep penetration welding can be distinguished (Dawes, 1992; William, 2001). In the heat conduction welding method, the material melts due to the absorption and thermal conduction of laser beam radiated from optic head. This method has fast welding speed but has low penetration depth because of insufficient thermal energy. The other is deep penetration welding or keyhole welding method, which is normally used for welding car body to ensure reliability of quality and to be easy to exhaust fusion vapor of material. Because of diffused reflection of laser beam in keyhole, welding depth is deep and welding speed is fast.

In order to perform laser welding effectively, process planning should be generated after a examining factors that influence to the laser welding process. The first important factor was gap between panels which was recognized through lots of experiments with the different combination of materials(Fig. 3).

The results of the experiments carried out with the different materials and gaps show that in case of gap greater than 0.2 mm the laser beam cannot penetrate the panels at all combinations. At the first- and second combination, the welding quality was satisfied when welding with the given range of the gap, i.e., $0.0 \leq \text{gap} \leq 0.2$ mm. In the last two case, the welding failures such as sinking, protrusion, etc. occurred by welding without a gap.

In case of galvanized steel usually used for car body, if there is no exit for evaporated zinc vapor, it may permeate into the inside of welding area because the evaporation point of zinc coated layer is lower than the melting point of steel (1320°C) and could be the main reason of poor welding. Thus, gap between panels should satisfy the gap between 0.1 mm to 0.2

mm and jig was used to keep the suitable gap. As the results of the experiments, a jointing area with more than 4 layers or high reflexibility also produced poor welding because of insufficient thermal energy.

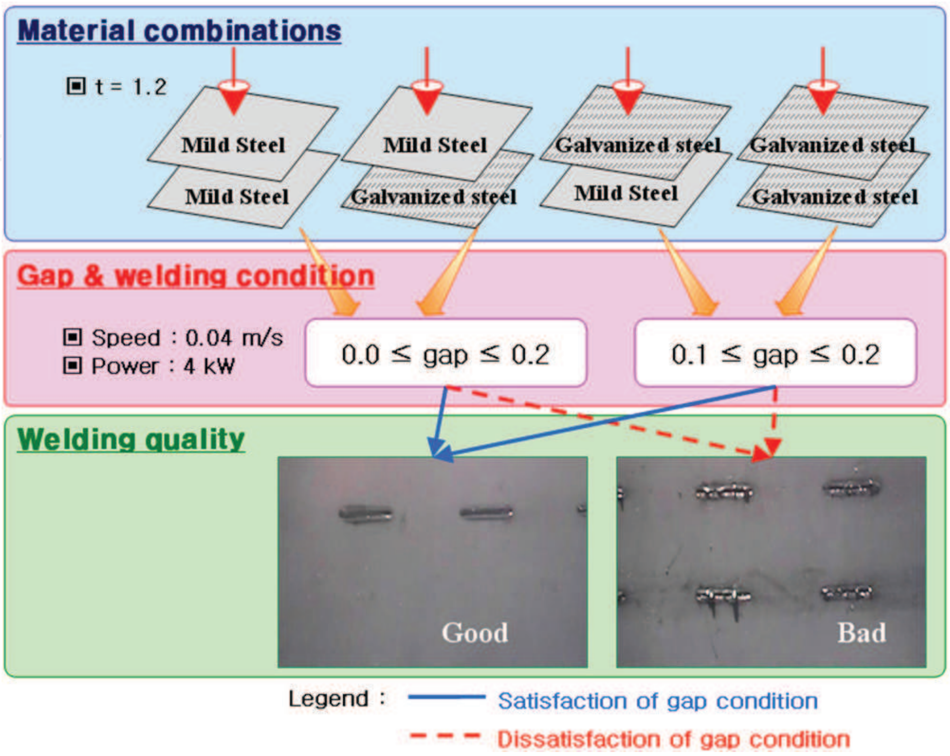


Fig. 3. Welding quality according to material combination and gap condition.

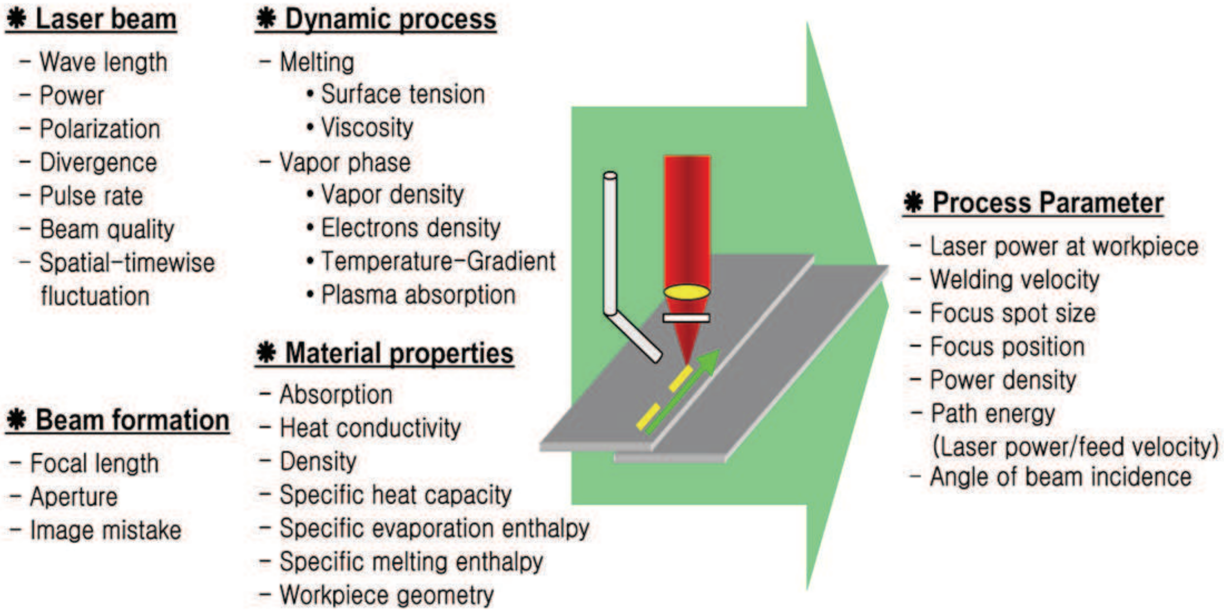


Fig. 4. Important influential variables of laser welding process.

Contrary to spot welding, laser welding has various lengths of welding lines called stitch i.e. the unit length of laser welding path. Fig. 4 presents some influential process variables obtained from laser welding experiments. Because it was impossible to consider all of the influential variables to control welding process, angle of beam incidence, laser power, welding speed, welding depth and stitch path were chosen as the most important process variables for laser welding.

The values of these process variables were determined by the state of the joint variables such as the location and shape of stitch and material. Joint variables were also divided into the geometrical and the technical variables concerning to shape and material of welding area respectively. The geometrical variables include joint type, location of welding area, curvature in the normal direction and tangential direction and stitch path. The technical variables are represented by material, thickness, panel layers, gap, surface condition and surface coating condition. In order to find out the correlation between the process variables and the joint variables, matrix shown at Fig. 5 was developed based on the analysis of the results of the experiments to determine relevant process variables corresponding to joint variables of each stitch.

		Joint variables										
		Geometrical variables					Technical variables					
		Joint type	Location of welding area	Curvature about normal direction	Curvature about tangential direction	Starting – and ending point of stitch	Material	Thickness	Layer	Gap	Surface condition	Coating
Process variables	Angle of beam incidence	⦿	⦿									
	Laser power						⦿	⦿			⦿	⦿
	Welding speed						⦿	⦿			⦿	⦿
	Welding depth							⦿	⦿	⦿		
	Teaching points			⦿	⦿	⦿						

Fig. 5. Relationship of the process variables and the joint variables.

3.Concept for implementation of laser welding system

3.1 Generation of stitch through product analysis

The conventional assembly method of side panel is spot welding, which is formed by about 250 spot points. In order to change it to laser welding, the possibility of laser welding application and its requirements have to be surveyed through the exact analysis of product. For the flawless generation of welding stitch that is the basic element of laser welding, first of all, the gap between panels must fulfill the condition for quality assurance, i.e, 0.1 ≤ gap

≤ 0.2 mm. This is accomplished by jig for fixing locations. With the condition that the key points and the inapplicable and inappropriate points for laser welding are performed by spot welding, the determination of jig locations is carried out. The key points are the welding points for forming shape of a module of car body at the beginning stage of welding. The inapplicable points can't be welded with today's laser welding technology. That is, Nd:YAG laser which is popular for welding car body in automobile industry can't penetrate 4 layers welding structure. With regard to the inappropriate points, many jig points are normally needed in corner area for securing of the gap. Some of them can be replaced with spot points to reduce the number of jigs. In Fig. 6, the jig points for the laser welding of side panel are presented considering only the secure of gap.

Since the left part of side panel has a little unevenness, jig point was created with comparatively regular interval. But in case of right rear side due to 4 layers structure or panel combination having severe unevenness, jig points exist close each other shown at Fig. 6.

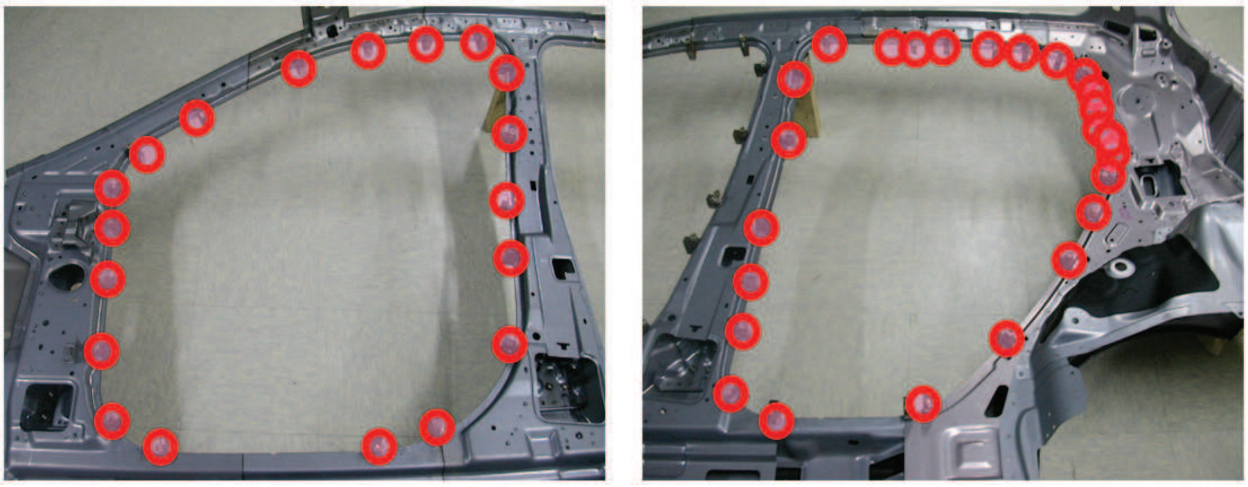


Fig. 6. Jig points of side panel

There are some parts where the application of laser welding is not easy because the existing car body is oriented to spot welding. This leads that it is difficult or impossible to use only laser welding for side panel assembly. Also laser welding results in more unnecessary jigs than that of the existing spot welding.

The side panel has some structures where laser welding is not acceptable such as 4 layers, high reflexibility and so on. For solving these problems, spot welding is applied to the inapplicable points. This contributes to assure quality and reduce whole assembly time by decreasing set up time. After determination of jig points and spot welding points, laser welding stitches are generated between jig points and spot welding points.

The path of stitches is intended to have shape of straight line to make robot teaching easily. The stitch length of 20-30 mm is found on the basis of the experiment results and references. The interval of stitches is set to be greater than 10 mm regarding strength and thermal stress. As a result, 92 stitches are generated on the side panel. Jig points, spot welding points and laser welding stitches generated on the side panel are shown in Fig. 7.

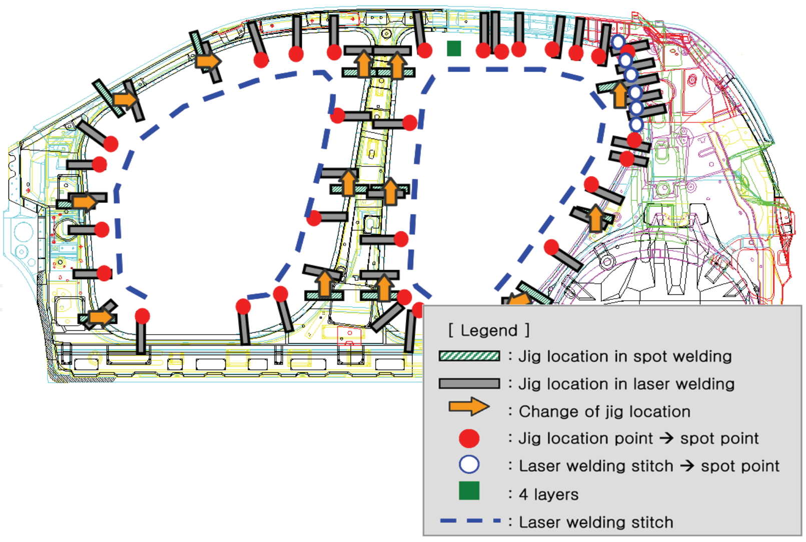
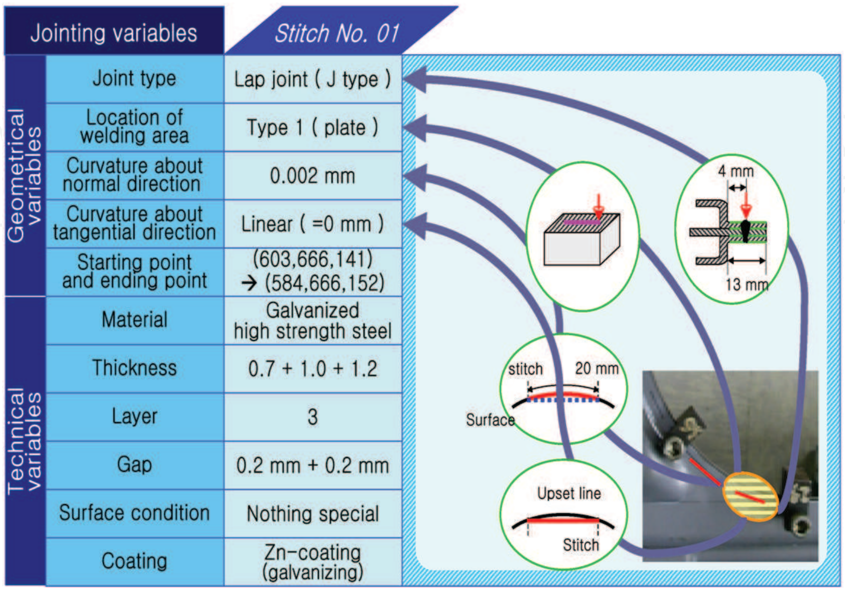


Fig. 7. Determination of jig points, spot welding points and laser welding stitches.

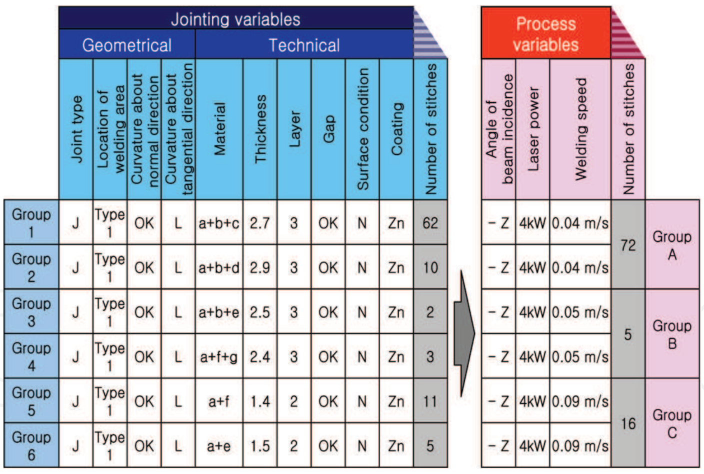
3.2 Derivation of process parameters

In order to ensure the quality in carrying out laser welding for the generated stitches, process parameters should be determined. As explained in section 2, process parameters are determined by analyzing joint variables of each stitch. Joint variables were investigated from the analysis of BOM, process plan, 3D modeling files and measuring data of the side panel in a real car. Fig. 8 shows joint parameters acquired from stitch No. 01. After the investigation of all 92 stitches, stitches having same joint parameters were grouped and 6 groups were generated. According to the data acquired by various welding experiments, process parameters are determined to perform optimal laser welding of each group. The group A including stitch No.1 shown in Fig. 7 is welded in vertical direction (-Z) and velocity of 0.04 m/sec at Nd:YAG laser 4kW, the best welding quality is gained as shown in Fig. 9. The 6 groups of the jointing parameters in Fig. 9 are combined into 3 groups in terms of process parameters.



Jointing variables		Stitch No. 01
Geometrical variables	Joint type	Lap joint (J type)
	Location of welding area	Type 1 (plate)
	Curvature about normal direction	0.002 mm
	Curvature about tangential direction	Linear (=0 mm)
	Starting point and ending point	(603,666,141) → (584,666,152)
Technical variables	Material	Galvanized high strength steel
	Thickness	0.7 + 1.0 + 1.2
	Layer	3
	Gap	0.2 mm + 0.2 mm
	Surface condition	Nothing special
	Coating	Zn-coating (galvanizing)

Fig. 8. Joint parameters of welding stitches

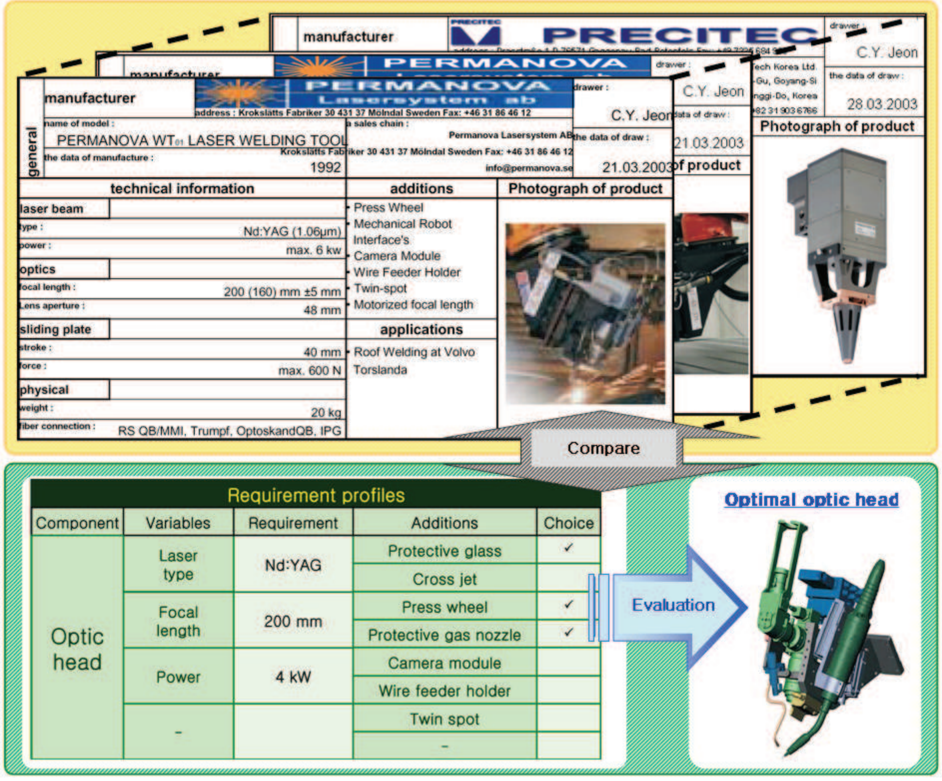


	Jointing variables											Process variables				
	Geometrical				Technical											
	Joint type	Location of welding area	Curvature about normal direction	Curvature about tangential direction	Material	Thickness	Layer	Gap	Surface condition	Coating	Number of stitches	Angle of beam incidence	Laser power	Welding speed	Number of stitches	
Group 1	J	Type 1	OK	L	a+b+c	2.7	3	OK	N	Zn	62	- Z	4kW	0.04 m/s	72	Group A
Group 2	J	Type 1	OK	L	a+b+d	2.9	3	OK	N	Zn	10	- Z	4kW	0.04 m/s		
Group 3	J	Type 1	OK	L	a+b+e	2.5	3	OK	N	Zn	2	- Z	4kW	0.05 m/s	5	Group B
Group 4	J	Type 1	OK	L	a+f+g	2.4	3	OK	N	Zn	3	- Z	4kW	0.05 m/s		
Group 5	J	Type 1	OK	L	a+f	1.4	2	OK	N	Zn	11	- Z	4kW	0.09 m/s	16	Group C
Group 6	J	Type 1	OK	L	a+e	1.5	2	OK	N	Zn	5	- Z	4kW	0.09 m/s		

Fig. 9. Process parameters of laser welding stitches

3.3 Determination of system components

For the configuration of laser welding cell, optimal components should be determined which can effectively perform the required process. Optic head which is one of important equipments to build laser welding cell is a device to focus laser beam on the welding area. Optic heads are offered in variety according to laser type, focal length and existence or nonexistence of injection device of protection gas or filler wire.



general

manufacturer: PERMANOVA Lasersystem ab
address : Krokslatts Fabriker 30 431 37 Mölndal Sweden Fax: +46 31 86 46 12
name of model : PERMANOVA WT01 LASER WELDING TOOL
the data of manufacture : 1992
a sales chain : Permanova Lasersystem AB Krokslatts Fabriker 30 431 37 Mölndal Sweden Fax: +46 31 86 46 12 info@permanova.se
drawer : C.Y. Jeon
the data of draw : 21.03.2003

technical information		additions
laser beam		• Press Wheel • Mechanical Robot Interface's • Camera Module • Wire Feeder Holder • Twin-spot • Motorized focal length
type :	Nd:YAG (1.06μm)	
power :	max. 6 kw	
optics		
focal length :	200 (160) mm ±5 mm	
Lens aperture :	48 mm	
sliding plate		**applications**
stroke :	40 mm	• Roof Welding at Volvo Torslanda
force :	max. 600 N	
physical		
weight :	20 kg	
fiber connection :	RS QB/MMI, Trumpf, OptoskandQB, IPG	

Photograph of product

Requirement profiles

Component	Variables	Requirement	Additions	Choice
Optic head	Laser type	Nd:YAG	Protective glass	✓
			Cross jet	
	Focal length	200 mm	Press wheel	✓
			Protective gas nozzle	✓
	Power	4 kW	Camera module	
			Wire feeder holder	
	-		Twin spot	
			-	

Fig. 10. Selection of optimal components (optic head).

In order to select optimal optic head, the ability of optic head was grasped through the developed form for technical profiles(Fig. 10). The requirement profileswere derived from the analysis of welding problem.

In the following step, evaluation for the best applicable optic head was carried out in the consideration of flexibility, availability, price and compatibility with company specific conditions, e.g. mechanics and information interface, and so on. As the result, the optimal optic head emerged for the definite problem.

4. Digital laser welding system

Digital manufacturing is a technology which uses sophisticated computer to model physical and logical schema and behavior of real manufacturing systems including manufacturing resources, environments and products.

Based on these models, digital manufacturing supports decision making and error checking in the entire manufacturing processes (Lin et al., 2001; Park et al., 2004; Zhai et al., 2005). Implementation of digital cell is started from the modeling of the selected components and the processes(Fig. 11).

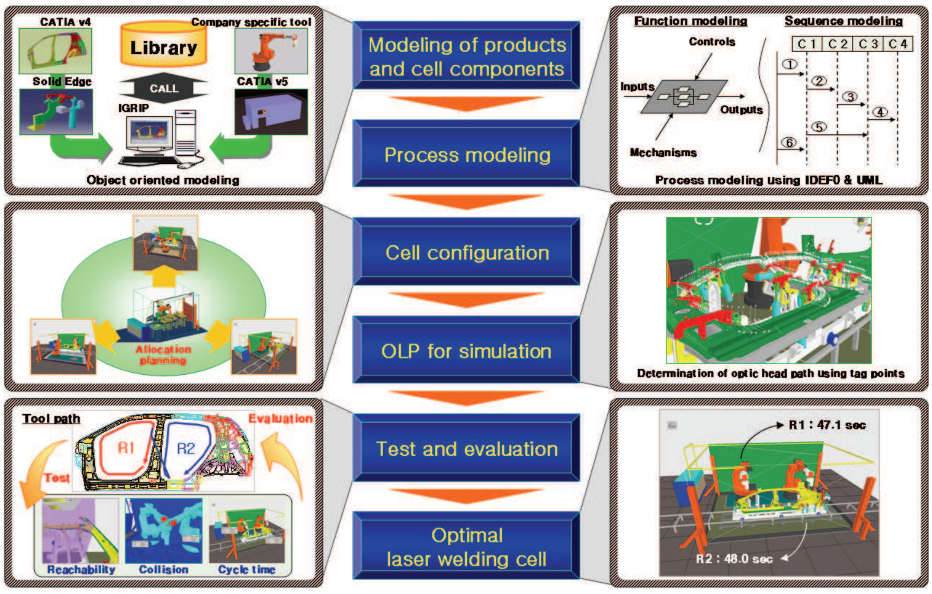


Fig. 11. Procedure for digital laser welding cell

The components are modeled based on object-oriented modeling method by using 3D CAD tools. The models of car body panels, handling devices, transfer devices, jigs and robots modeled from different tools used in virtual environment of the DELMIA's IGRIP tool to layout the workspaces of them and to investigate their kinetic behaviors. For modeling the dynamic components like robot, the kinetic characteristics such as freedom degree, range of motion and angular velocity etc. are assigned to each element of a component according to the design specification of it by using the function of IGRIP "Kinematics", e.g., θ(motion range): $-120° < \theta < 158°$ and ω(angular velocity): $\omega = 140°/s$ for the third axis of the robot used for building the cell. Auxiliary components such as booth, fiber, laser generator and so on, which have variable dimension, are modeled by using CATIA v5 based on dimensional information acquired from field. These 3D models of the components are systematically stored in library by using the function "Catalog" of CATIA v5 and used for new configuration of cells by calling back through a search. After that, the process modeling is performed to define the cell functions and the static and dynamic relationship among the components.

The IDEF0(Integration DEFinition0) model is used for describing those functions and the control mechanism of the cell for executing a welding process. The class diagram and the sequence diagram of UML(Unified Modeling Language) (Martin, 2003; Rosenberg et al., 2001) are used to describe the relationships among the components.

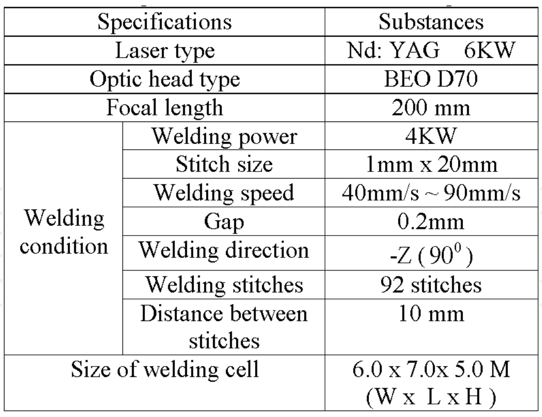
The class diagram defines the static relationships among the components to model the static design view of a system. Laser welding cell consists of two activities, one is a fixing task of components and the other is a welding task. The interfaces and relationships of the components for the cell are grasped with respects to two tasks.

Generally, according to the lapse of time, the events of the components proceed in sequence. The sequence diagram, which represents the messages among the components, is used to describe the dynamic relationship among the components. The sequence diagram shows a set of components and the messages sent and received by those components. The dynamic processes described in the sequence diagram are expressed as the movements of the components by the GSL(Graphic Simulation Language) offered from IGRIP. After modeling the components and the processes, it is needed to allocate the components optimally in satisfaction of constraints given for building the cell, e.g. operation sequence, production organization and type, automation degree, allowed space and investment cost etc. The satisfaction of cycle time and minimization of transfer time for material flow are main points because assembly of car body is the typical type of mass production. The cell is configured so that the quality is ensured by executing welding processes properly in considering the management of tool and jig/fixture, the control regulation planned with the sequence diagram and the connection relationship between pre and post cell. Three types of the cell layout are proposed as the result of allocation planning.

To verify the executing capability of processes within three generated cells and to evaluate the complex behavior of them for selecting the optimal one, simulation should be performed in the reality based and computer generated environment.

The geometry information such as the dimension of the cell and the components and the technology information for welding process and material handling are required for OLP (Off Line Programming). For simulating the detailed welding tasks, the OLP of the robot is executed. To generate kinetically correct and collision free robot cell, the tool paths of the robot are planned with tag points in a virtual environment. The robot program is accomplished based on these information by using GSL (Graphic Simulation Language).

After fully examining the accessibility of optic head to all stitches, the collisions with equipments such as jig etc., the welding parameters for the secure of quality, the applicability of sensor to tracing welding path and the operation sequences for preventing from distortion of parts, the program is generated to execute the events offered from the sequence diagram. Three types of the proposed configuration of cell are evaluated through the simulation of laser welding for the side panel with the generated program. The evaluation regarding to technology is done in terms of cycle time related to productivity, minimization shortest moving distance, automation degree, flexibility, available space and possibility of modular system adapting to change of manufacturing environment and so on. From the organization and economy point of view, the terms of expansion ability, control logic, interface between stations and investment and operating cost are chosen for the evaluation. As the result of evaluation, the cell configuration having the parallel arrangement of two robots is selected as optimal due to high score in the load balancing of each robot(the cycle time of each robot is 47.1 sec and 48 sec) and the minimal area required for implementation. The total cycle time for welding the side panel is also saved 3 sec compared to two another cell configurations. In addition, the selected cell has the following technical and geometrical parameters as shown in Table 1.



Specifications		Substances
Laser type		Nd: YAG 6KW
Optic head type		BEO D70
Focal length		200 mm
Welding condition	Welding power	4KW
	Stitch size	1mm x 20mm
	Welding speed	40mm/s ~ 90mm/s
	Gap	0.2mm
	Welding direction	-Z (90^0)
	Welding stitches	92 stitches
	Distance between stitches	10 mm
Size of welding cell		6.0 x 7.0x 5.0 M (W x L x H)

Table 1. The specifications of the laser welding cell

5. Conclusion

The laser as economical and flexible tool has established a solid ground in industrial manufacturing area. Specially at welding BIW (Body In White) in automobile industry, the importance of it has been increased due to the technological characteristics such as high process speed, slim seam and good capability of automation and so on.

For application of laser welding technique, welding principle and influential factors were investigated based on the analysis of laser welding processes. With that, the main process parameters were determined according to the material and shape of the welding area through a lot of experiments. The results show the best quality was gained when welding with the gap (0.2 mm), welding speed (0.04~0.09 m/s) and laser power 4 kW. The correlation matrix between the process variables and joint variables was also developed for forming the welding group to carry out the welding process.

The whole stitches for welding side panels were classified to three groups in terms of the process parameter for executing the welding processes efficiently. And the appropriate equipments were selected through the comparison the requirement profiles with the ability of them.

For the configuration of a laser welding cell, a methodology was pursued, which is based on digital manufacturing technique and the application of model analysis concept to validate the cell's behavior.

First, the model was created for analyzing the static and dynamic behavior of the cell by using the class- and sequence diagram of UML. Based on that, a layout planning were executed for structuring the working area. For the motion simulation process, a technology- and machine-oriented offline programming was carried out to optimize the spatial position of tool path in consideration of the welding process as well as the kinetic properties of the selected equipments.

The results of the layout planning and the simulation were the three laser welding cells. Through the final evaluation, the laser welding cell having the specification shown in table 1 proved to be the best suited one for welding the side panels. The decisive criteria were the required cycle time of the robot and the space requirement.

The presented method of implementing the laser welding cell based on digital manufacturing permits substantially improved applying of laser technology and structuring of manufacturing system.

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Laser Welding

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This book is entitled to laser welding processes. The objective is to introduce relatively established methodologies and techniques which have been studied, developed and applied either in industries or researches. State-of-the art developments aimed at improving or next generation technologies will be presented covering topics such as monitoring, modelling, control, and industrial application. This book is to provide effective solutions to various applications for field engineers and researchers who are interested in laser material processing.

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