Development of One-side Plasma Arc Spot Welding System

Yoshitaka Niigaki
Toshiya Shintani
Yousuke Imai
Iwao Kurokawa
Tooru Shiina

Among various matters required of automobiles, reduction in exhaust gas, lighter auto-body weight for reduction in fuel consumption, and increase in auto-body rigidity to secure safety in an automobile collision need to be carried out immediately. To meet the requests for lightening auto-body weight and increasing in the auto-body (rigidity which are contrary to each other), the auto-body structure must be given a higher degree of freedom at which the manufacturing conditions are eliminated as many as possible.

To increase the degree of freedom of the auto-body structure and reduce the cost by eliminating the restrictive conditions and enabling closed-section structures, we developed a core wire-fed plasma welding system which was a one-side welding system in cooperation with Toyota Auto Body Co., Ltd. and introduced it in the auto-body welding line of the New Estima in January 2000.

This technology was realized by fusing the high-grade plasma arc generation and control technology developed in the Research Division of Komatsu and the latest manufacturing technology of Toyota Auto Body Co., Ltd.

We will introduce this welding system below.

Key Words: *One-side, Plasma Arc, Spot Welding, Auto-body, Toyota Body, Estima, Welding System*

1. Introduction

The Research Division started the basic research into plasma arc technology in the mid-1980s and established the leading plasma control technology unique to Komatsu. Since then, Komatsu has been developing fine plasma cutting machines which have working performance as high as the laser cutting machines in accuracy and quality and which are equipped with consumable parts (electrode and nozzle) featuring longer lives than those based on the conventional technologies, and have been putting them on the market faster than our competitors.

Those fine plasma cutting machines have evolved into the "Twister Fine Plasma" series which is one of the core products of the fabricating machinery business of Komatsu Industries Corp. and which is spreading all over the world. Komatsu Engineering Corp. is developing the business of 3-dimensional plasma cutting robot system.

The Research Division also started the research by itself into possibility of plasma spot welding to expand the plasma business from cutting to welding. The main target of this research was auto-body for the following reasons; if the plasma spot welding was available, the degree of freedom of the auto-body design would be increased and the weight and total cost of the auto-body would be reduced. In addition, there was a great demand for the one-side welding and the plasma spot welding would spread in future as a partial substitute for the resistance spot welding which was the main welding method.

The largest technological problem was to control the incidence of explosions which is unique to zinc-plated steel sheet (a phenomenon where zinc is gasified suddenly and that gas causes welding defects when the molten metal touches the zinc plate layer) and secure the quality reliability as high as that of the resistance spot welding (99.99%).

No one had made plasma spot welding practical because of the difficulty of tendency for the zinc to explode when heated. Knowing this fact, we, as engineers, took up the challenge to develop a plasma spot welding system.

After many attemps, we established our unique plasma control technology that featured a hole on the top sheet to discharge the zinc gas and then refill the hole. In the summer of 1995, we introduced the first practical plasma spot welding system in the auto-body welding line (Granvia) of Inabe Plant of Toyota Auto Body Co., Ltd. This first system operated up to the summer of 2001 and proved that it was able to be used on an auto body manufacturing line where very high reliability was required.

This technology (of the first generation) had a severe limitation that the applicable clearance between metal sheets to be welded was limited to 0 – 0.2 mm. If the clearance was 0.3 mm or more, the hole made for welding could not be refilled. Since it was difficult in many cases to control the clearance between the sheets of the auto-bodies to 0 – 0.2 mm for one-side welding in the manufacturing plant, we had to develop a technology to secure the welding quality in a wider clearance range between the sheets (0 – 2 mm).

To solve the problem that the hole made for welding could not be refilled when the clearance between the sheets was large, we developed a technology to supply a core wire between the sheets to make up for the lack of molten metal and started improving this technology (of the second generation) in cooperation with Toyota Auto Body Co., Ltd. in 1996. In the second generation, we also developed the technologies to lengthen the lives of consumable parts, shorten the welding time (0.8 t + 0.8 t: Maximum two seconds) for higher productivity, increase the thickness of sheet assembly to be welded (Total thickness: 4.6 t), and increase the applicable welding positions (addition of horizontal position).

As a result, multiple one-side plasma spot welding systems of the second generation were introduced for the body of car type D in the autumn of 1998 and for the body of the Estima in January of 2001, and they took the first practical step.

The outline and features of the plasma spot welding system of the second generation and its application to the Estima line are explained below.

2. Principle of plasma welding

The basic principle of plasma welding is shown in **Fig. 1**. If a high voltage is applied between the electrode and the workpiece while the plasma gas is flowing, the gas is ionized and becomes conductive, then a plasma arc is generated. Since the plasma arc is restricted by the nozzle, it had higher energy density, compared to MAG and TIG and can be used as a heat source of ultra high temperature (above 20,000°C) having high heat concentrating performance.

If the plasma current, gas composition, gas flow rate, etc. are controlled selectively, this arc can be used for boring (cutting) and refilling (welding) easily and the cost is less than the laser. These features are basis of the welding system we have developed.

For the concrete welding process of the one-side plasma spot welding, see Fig. 5.

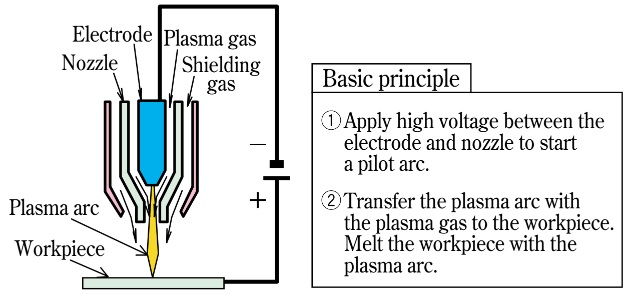


Fig. 1 Basic principle of plasma welding

3. Configuration of welding system

The configuration of the plasma welding system is shown in **Fig. 2**. The automatic welding system we developed is mounted on a robot.

This system consists of the plasma power supply unit to supply a current to the plasma torch installed to the end of the robot arm, gas unit to set the flow rate of the supplied gases (two systems of the plasma gas and shielding gas), cooling water unit to cool the consumable parts (electrode and nozzle) at the end of the plasma torch, wire feeder to feed the core wire (filler wire), and welding controller to set and control the welding condition.

The torch pressing assembly is installed to the end of the robot. It contains the air cylinder to press the welded part (workpiece) with air pressure, mechanism to open and close the torch end cap (used to replace the parts and remove the spatters), gas changeover box to change the gas flow rate, and pull motor function to feed the wire stably.

The welding controller sets all welding condition parameters such as the welding current, timing to change the gas, timing and speed to feed the core wire (filler wire), etc. and detects the clearance between the sheets to be welded. The plasma power supply unit outputs the welding current according to the commands from the welding controller and can save up to 32 welding conditions. It carries out welding automatically from starting of a plasma arc to completion of welding according to the robot controller.

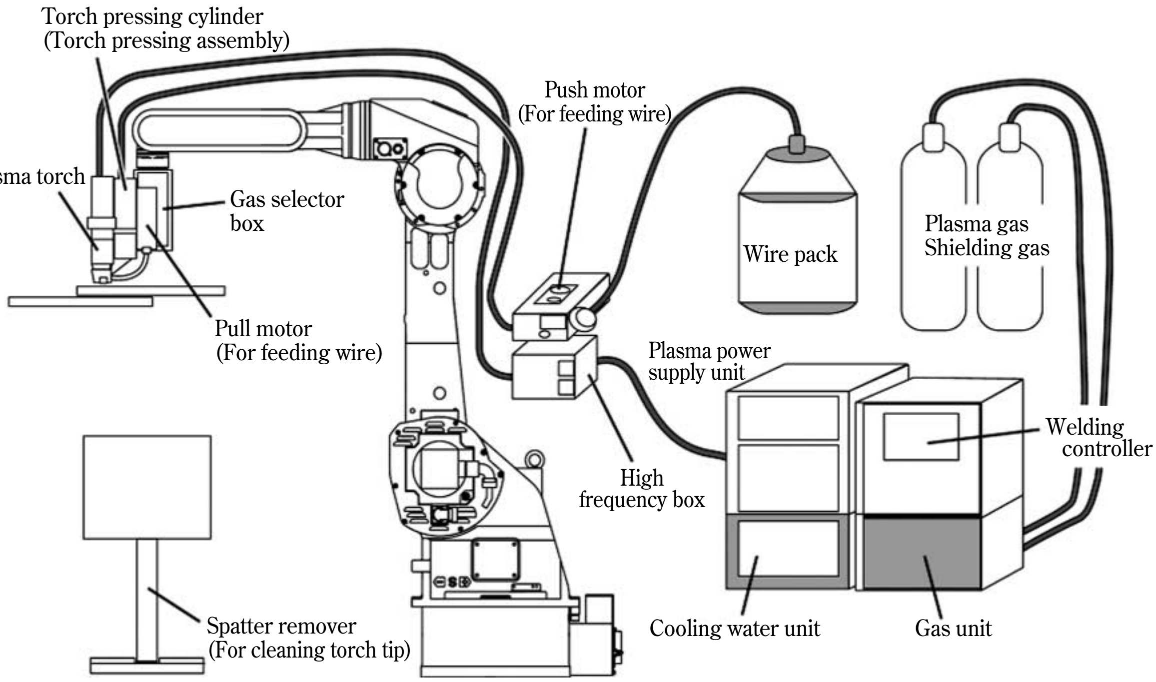


Fig. 2 System configuration of plasma welding system

The structure of the torch end is shown in **Fig. 3**. The basic specifications and welding capacity of the torch are shown in **Table 1** and **Table 2** respectively. The torch is made of concentric cylinders. The center of those cylinders is the roughly cylindrical electrode. The roughly cylindrical nozzle is installed on the outside of the electrode. The cooling cap and shielding cap are installed on the outside of the nozzle.

The welding system forms a DC circuit, where the electrode is negative and the welded part (workpiece) is positive. The plasma power supply unit is a DC power supply unit having the rated output current of DC 120 A.

Generally, inert gas (Ar + 7% of H_2) is used as the plasma gas. The shielding gas supplied to surround the plasma gas is selected according to the material of the welded part. When the welded part is zinc-plated sheet, oxidizing gas (Ar + 50% of O_2) is used to prevent explosion.

The core wire (filler wire) is fed to the torch end from the side without contacting the welded part to prevent it from being welded.

The maximum weldable thickness is 4.6 mm. The number of the sheets welded at a time is two or three (If three sheets are welded, the clearance detecting function is not available, however). The applicable clearance between the sheets to be welded is 0 – 2 mm. The allowable welding angle is 0° (Horizontal and flat positions) – 100° (Horizontal position). The welding time is about two second when the total thickness of the welded sheets is 2 mm. We are working now to shorten the welding time to a half.

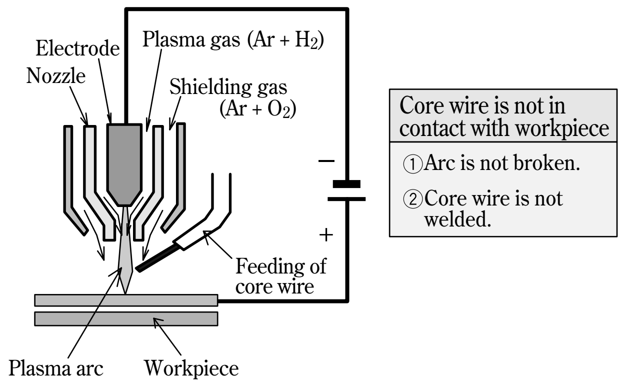


Fig. 3 Structure of torch tip

Table 1 Basic specifications of plasma welding system

Unit	Item	Specification
Power supply unit	Rated input voltage	3-phase 200 V
	Rated input power	Approx. 32 kVA
	Rated output current	DC120 A
Torch unit	Electrode	Embedded tungsten
	Nozzle	Inside diameter: ϕ2.2
	Cooling method	Cooling with water

Table 2 Capacity of plasma welding system

Item	Capacity
Applicable thickness	Max. 4.6 mm
Applicable clearance between sheets	0 – 2.0 mm
Welding speed	2.0 sec (When thickness is 2.0 mm)
Allowable welding angle	0 (Horizontal) – 100°

4. Conventional problems and technological features of solution of them

This one-side plasma spot welding system has the following technological features to solve the conventional problems.

(1) Application to sheets having clearance of 0 – 2 mm between them

When the clearance between the welded sheets is large (e.g. 0.3 mm or more), if spot welding is executed with only the plasma arc, the molten metal flows between the sheets and a hole is made easily on the upper sheet and the reliability of the welding quality is greatly lowered, thus the system cannot be used as it is (**Fig. 4**).

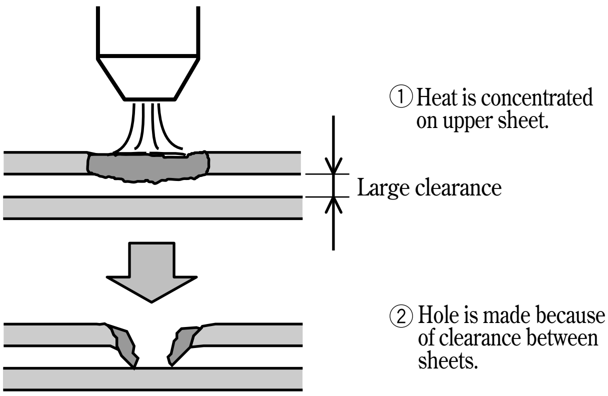


Fig. 4 Mechanism of boring in upper sheet (When core wire is not fed)

We developed a core wire feeding system to supply molten metal between the sheets and solve the above hole problem. If the core wire was fed simply, however, the heat was transferred to only the core wire and upper sheet and was not dispersed into the lower sheet. As a result, it was difficult to obtain sufficient welding strength stably.

Then, we made holes (key holes) on both upper and lower sheets with only the plasma current and fed the core wire in those holes and flatten the surface with only the current. By supplying the current in the three steps, the welding process was so controlled that the plasma arc heat would be dispersed securely to the core wire and both sheets. With this 3-step current method, it became possible to stabilize the welding strength of the sheets having a clearance of 0 – 2 mm between them (**Fig. 5**).

The welding strength (monoaxial shearing tensile strength) of the sheets welded by this method is equivalent to or larger than that of the sheets welded by the resistance spot welding. The fatigue strength is equivalent to that obtained by the resistance spot welding.

(2) Automatic detection of clearance between sheets

This welding system has a function to detect the clearance between the welded sheets momentarily from the change of the arc voltage when it makes holes. It can feed the core wire automatically to fill the holes according to the change of the clearance. With this function, the welding strength can be stabilized, even if the clearance between the sheets varies in the manufacturing plant. Accordingly, the clearance does not need to be controlled severely in the manufacturing plant as for the laser welding and the manufacturing cost can be reduced.

(3) Application of thickly zinc-plated steel sheet

If a thickly zinc-plated steel sheet is welded by plasma welding, the zinc is gasified in the molten metal and the gas pressure blows off the molten metal (explosion). As a result, the molten metal of the upper sheet is broken partly. A photo of an explosion taken with a high-speed video camera is shown in **Fig. 6**.

To be concrete, when a base metal is plated with a material having a boiling point lower than the melting point of the base metal as in the zinc-plated steel sheet, if the very hot molten metal touches the plating material, the plating material evaporates instantaneously. At this time, the explosive inflation of the plating material can blow off a part of the molten metal. Since forecasting this explosion is very difficult, controlling it has been impossible.

While we were analyzing the mechanism of the explosion by observing it through the video camera, we repeated many ideas by a trial-and-error method. As a result, we found that oxygen in the shield gas increased the molten metal temperature, reduced the viscosity of the molten metal, reduced the zinc gas bubbles in size, and helped the gas escape (**Fig. 7**).

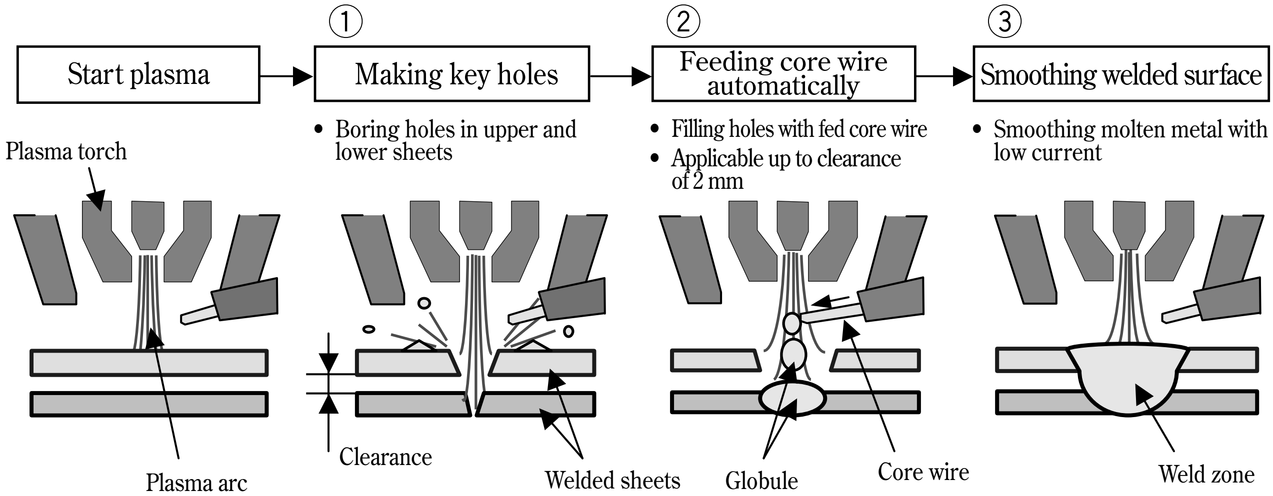


Fig. 5 Welding process (3-step current method)

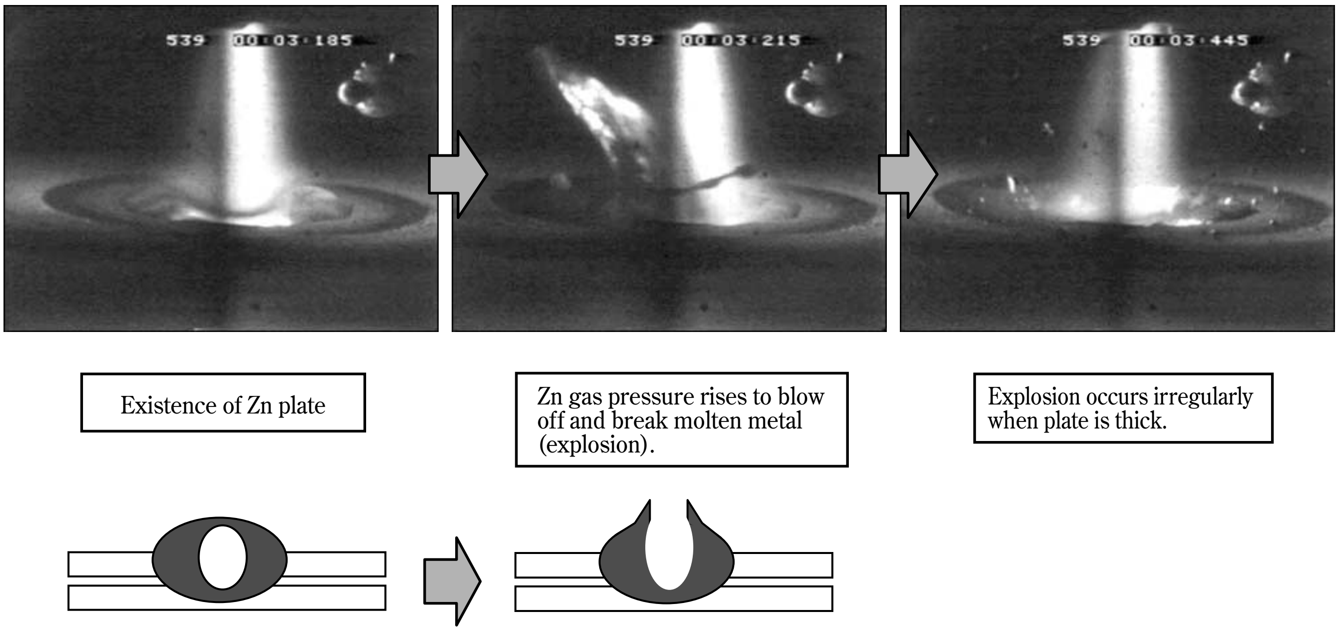


Fig. 6 Mechanism of explosion (Observation through video camera)

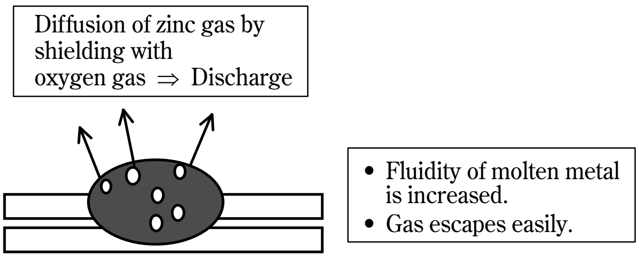


Fig. 7 Discharge of zinc gas by shielding with oxygen gas

With this technology, we succeeded in reducing the occurrence rate of explosion to almost 0% and became able to increase the reliability of the welding quality greatly.

In the past, as welding was repeated, the spatter made when the hole was made on the upper sheet were accumulated on the plasma torch tip and they shortened the insulated parts. As a result, the plasma arc became defective and the welding quality was lowered consequently. This problem was a strong barrier to practical application of the plasma arc welding.

To solve this problem, we changed the shape of the torch tip so that a minimum of spatter would stick to the tip and reinforced the electrical insulation. In addition, we developed a spatter remover and the torch pressing assembly to open and close the torch tip cap to increase the spatter removing efficiency. In the actual Estima manufacturing line, the spatter is removed periodically and automatically.

These devices contributed greatly to increasing the availability of the Estima manufacturing line and securing the reliability of the welding quality.

(4) Lengthening of lives of consumable parts

As the welding is executed, the electrode used for the plasma welding system is worn and the plasma arc characteristics become unstable and the initial welding quality cannot be maintained. That is, the consumable parts must be replaced periodically. This matter has been a large defect of the plasma arc welding. It is a so-called aging problem.

The electrode for the common plasma welding is made of tungsten having a very high melting point. It is embedded in copper having high thermal conductivity and cooled with water by a special means to minimize its wear.

If only this measure is taken, the electrode is worn and the welding quality changes because of aging in about 100 repetitions of welding. Accordingly, the electrode could not be applied to a unmanned welding system mounted on a robot such as one on the auto-body welding line.

To solve this problem, we changed the shapes of the electrode and nozzle so that the electrode will be worn less and developed a torch structure and a welding process to maintain a stable plasma arc and restrict a change of the welding quality until the electrode is worn to a certain degree. With this technology, the lives of the parts were lengthened to several ten times compared to the conventional parts and the stability and reliability of the welding quality were improved. As a result, it became possible to mount the system on the robot for automatic welding.

The actual replacement frequency of the consumable parts is about 5,000 – 8,000 spots (once a day).

(5) Increasing of reliability of welding quality

In addition to the above functions, the system has the function of detecting the following trouble to prevent welding defects and secure the reliability of the welding quality.

① Function of detecting abnormal generation of arc + Automatic retry function
② Function of detecting leak
③ Function of detecting double arc (series arc)
④ Function of detecting explosion
⑤ Function of detecting clogging with core wire (filler wire)

The above functions of detecting defects have been installed to the Estima body manufacturing line and have contributed to increasing the availability of the line and securing the reliability of the welding quality.

These functions of detecting defects are only measures to prevent continuous occurrence of welding defects. It goes without saying, however, that the hardware measures such as the structural improvement of the torch to prevent spatters from sticking, periodical maintenance with the spatter remover, etc. described in (3) above are the basis to secure the reliability.

5. Application to Estima body

(1) Purpose of development

When a closed-section structure was spot-welded, a hole had to be made to insert the gun and a cover was installed after welding was finished. We then eliminated the restrictive condition for spot welding to reduce the parts cost and man-hours (**Fig. 8**).

Since the crushable zone of the Estima body was short, the rigidity of the front side member had to be increased. Accordingly, the size and rigidity of the front side member were reduced and increased respectively as shown in **Fig. 9**.

(2) Selection of one-side welding method

The typical one-side welding methods and their performances are shown in **Table 3**. The arc (MAG) welding is applicable to only fillet welding and it causes large thermal distortion. The YAG laser which seems to be spreading these

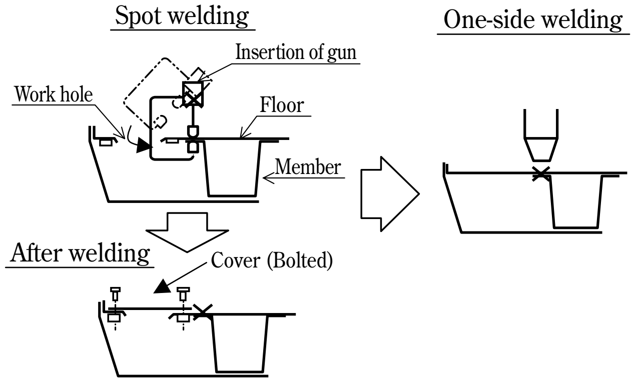


Fig. 8 Welding of closed-section structure

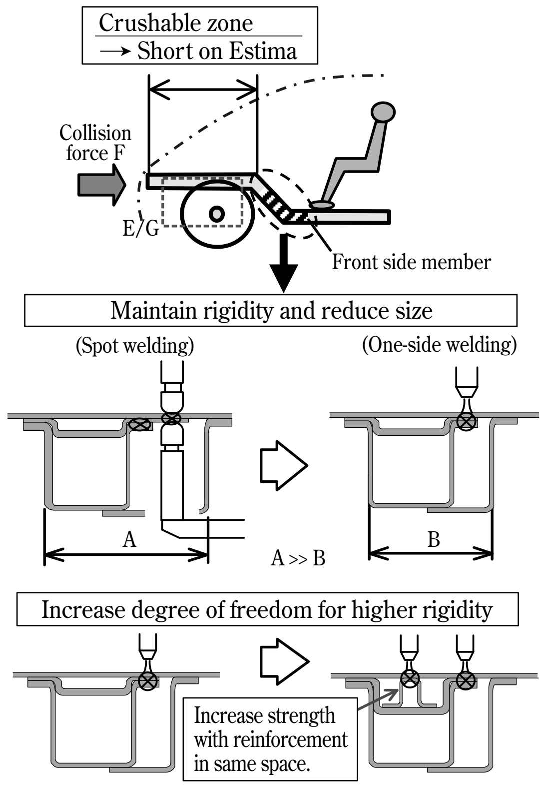


Fig. 9 Closed-section structure having reduced size and increased rigidity

Table 3 Comparison of one-side welding methods and their performances

No.	Evaluation item		Plasma	Arc (MAG)	YAG laser
1	Performance	One-side weldability	◎: Overlapped parts	△: Limited fillet welding	◎: Overlapped parts
2		Applicable clearance between sheets	◎: 0 – 2.0 mm	△: 0 – 1.0 mm	×: Max. 0.2 mm
3		Applicable total thickness of sheets	◎: 1.4 – 4.6 mm	◎: 1.6 –	△: 1.4 – 3.0 mm
4		Strain	○: Strain is little	△: Thermal strain is left	◎: Strain is very little
5		Welding or core wire	◎: Core wire is not welded since it does not contact.	△: Core wire can be welded since it contacts.	◎: Core wire is not welded since it does not contact.
6		Welding strength: JIS Grade A	◎	◎	◎
7		Productivity (Welding time)	△: 1.5 – 3.5 sec/spot	△: 1.5 – 3.5 sec/spot	△: 1.0 – 2.5 sec/spot
8	Cost	Equipment cost (Index)	△: 3.2	○: 1	×: 13.6 – 22.7
9		Running cost (Index)	△: 1.9	○: 1	△: 3.7

days is very expensive and requires very strict control of the clearance between sheets to be welded in the manufacturing plant.

For welding of the Estima body, the plasma spot welding was employed, considering that the objective sheets ① were overlapped, ② varied in thickness, and ③ had various clearances between them and that the cost had to be reduced.

(3) Application to Estima body

The plasma spot welding for the Estima body is applied to 68 points on sheets of 15 types from the minimum of 0.65 mm x 0.7 mm to the maximum of 2.3 mm x 2.3 mm. It is applied to high-tension steel, too.

The objective parts of plasma welding and the closed-section structure are shown in **Fig. 10** and execution of the plasma welding is shown in **Fig. 11**.

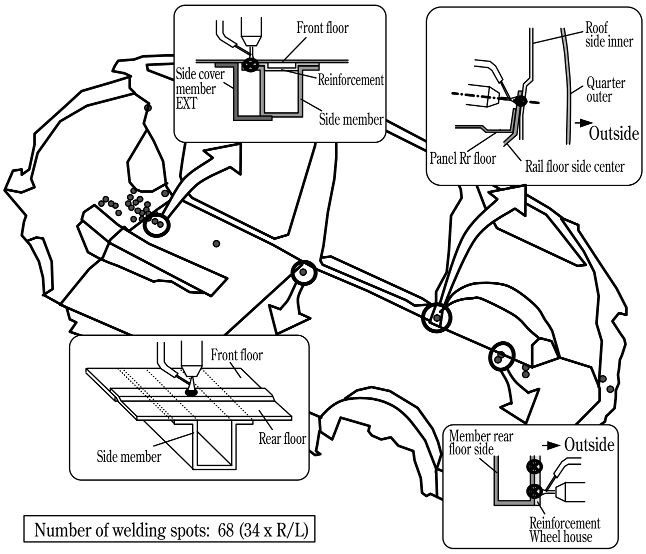


Fig. 10 Plasma welding spots and closed-section structure

(4) Merits of one-side welding

The benefits of the one-side plasma spot welding are shown in **Fig. 12**. If the purposes of increasing of the degree of freedom in design, improvement of weldability, and application of the one-side plasma welding to new materials (high-tension steel) are attained, the additional benefits of lighter weight, reduced number of parts, reduced size, reduced number of welding spots, wide use of the welding equipment, shortening of welding time, etc. are also expected. The one-side plasma spot welding is mainly applied to the under-body parts at present. We expect, however, it will be applied more widely.

(5) Effects of introduction

As a result of the application of one-side plasma spot welding to closed-section structures (which were difficult to weld with a resistance spot welding system), the number of the parts was reduced by 16 and the weight was reduced because of simplification of the structures of the members (by 3 kg) and the total product cost was reduced. **(Fig. 13)**

6. Conclusion

The one-side plasma spot welding system which we developed enabled design of closed-section structures which required one-side welding, and that had the following effects on the Estima body manufacturing line.

① Weight is reduced by reduction in number of the parts and simplification of the structure, and the product cost is reduced consequently.

② Welding quality is stabilized by the core wire feeding system even if there is clearance between the welded sheets.

③ The welding quality is stabilized by using shielding gas of Ar-50%O_2 to prevent explosions on thickly zinc-plated steel sheets.

④ The result of employment of the one-side plasma spot welding system has proved that it can hold sufficient performance and reliability even in operation of an auto-body manufacturing line which requires high reliability.

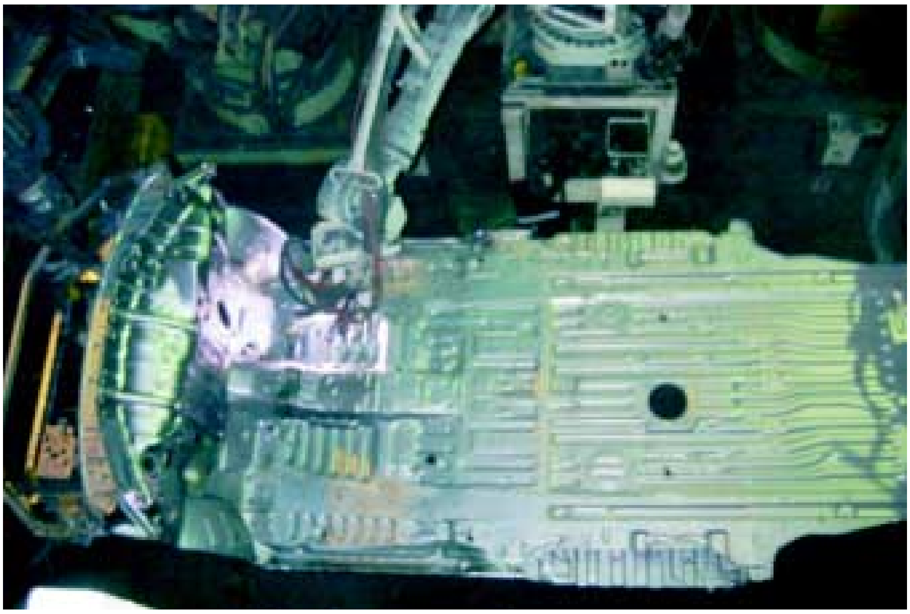


Fig. 11 Execution of plasma welding

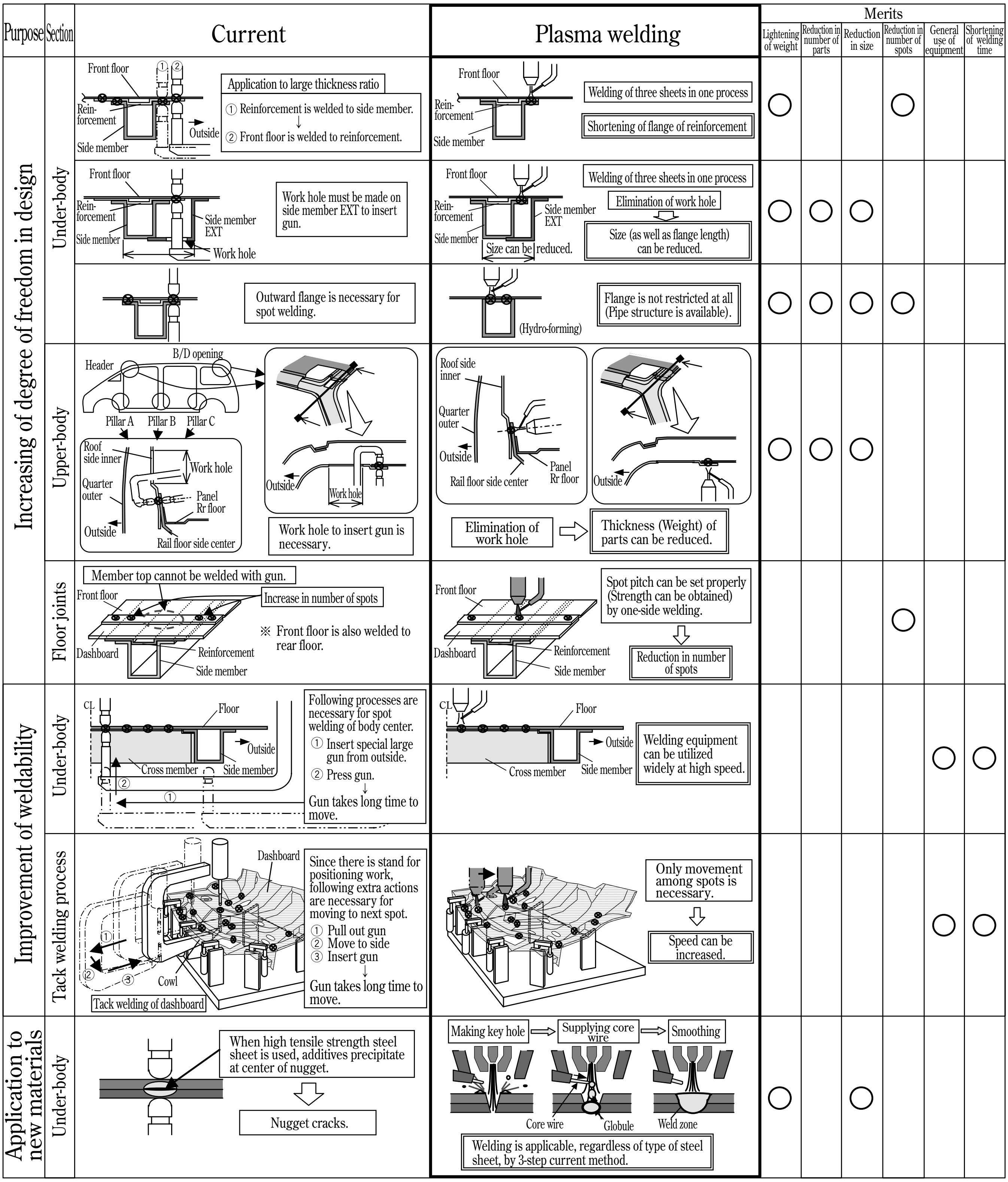


Fig. 12 Merits of one-side plasma spot welding

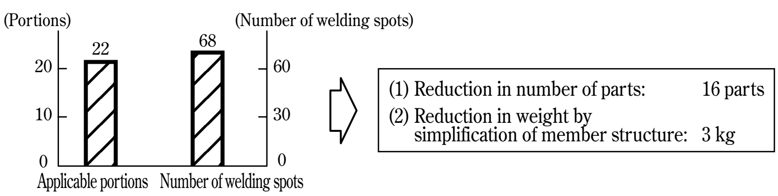


Fig. 13 Number of closed-section portions of Estima to apply one-side plasma spot welding, number of welding spots, and obtained effects

Toyota Auto Body Co., Ltd. has decided to employ the one-side plasma spot welding system for the next model-change cars. We predict that this system will spread gradually.

The business of this technology was transferred to Komatsu Engineering Corp. in October 2000, and the sales department started sales efforts of the system directed mainly toward car manufacturers in Japan since then. Komatsu Engineering Corp. has received some orders and is gradually increasing the sales toward the other industries.

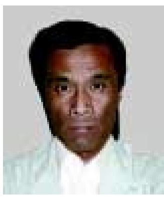
In the future, we will work on increasing the welding speed, increase number of weldable sheets, etc. This will increase the product power of the system while promoting the sales aimed at car manufacturers in Japan and assisting those manufacturers in starting new businesses, in cooperation with Komatsu Engineering Corp.

Introduction of the writers

Yoshitaka Niigaki
Entered Komatsu in 1982.
Currently working in Planning Dept., Research Div.

Toshiya Shintani
Entered Komatsu in 1984.
Currently working in Thermal Engineering Research Dept., Research Center, Research Div.

Yousuke Imai
Entered Komatsu in 1993.
Currently working in Advanced Research Dept., Research Center, Research Div.



Iwao Kurokawa
Entered Komatsu in 1970.
Currently working in Awazu Plant, Komatsu Engineering Corp.

Tooru Shiina
Entered Komatsu in 1992.
Currently working in Construction Equipment Technical Center 2, Development Div.

[A few words from the writers]

The most vivid about this system is that there were many problems and we were summoned and fully scolded when the New Estima body manufacturing line started in at the beginning of January 2000.

The person in charge of the line said, "The parts will run out soon if the current condition continues. If the parts are not supplied, the manufacturing line will stop. You must take measures immediately."

We chose the measures and schedule to meet the trouble then and there and promised the person in charge that two engineers would stay by the line (one for the day shift and the other for the night shift) until the trouble was repaired.

Our team then worked hard together for some weeks after that. As a result, the problems were repaired and the operation of the manufacturing line was stabilized by the end of January.

One day, the person who had scolded us before gave us some encouraging words. He said, "Oh, you are here today. Thanks to you, the line is operating normally. Thank you very much."

At this moment, we really felt happy about being engineers and having developed this technology. We were very glad that we attained a great success with the efforts and cooperation between the customer and us on a relationship of mutual trust and that the customer recognized it. It is our fortune that we had this wonderful experience.

We believe that we could not put the one-side plasma spot welding system in practice, however, if Toyota Auto Body Co. did not give us much cooperation and did not have a great wish to attain practical use of this system. We are very grateful to Toyota Auto Body Co., Ltd. for the cooperation given to us.

Research and development of the plasma technology were started about 15 years ago in the Research Div. and many engineers have worked on this technology since then. We think that the practical plasma spot welding system was completed as the result of the all efforts of those engineers.

We are proud that we have presented a new welding method to the world and that it is recognized by the world and that it is contributing to production.