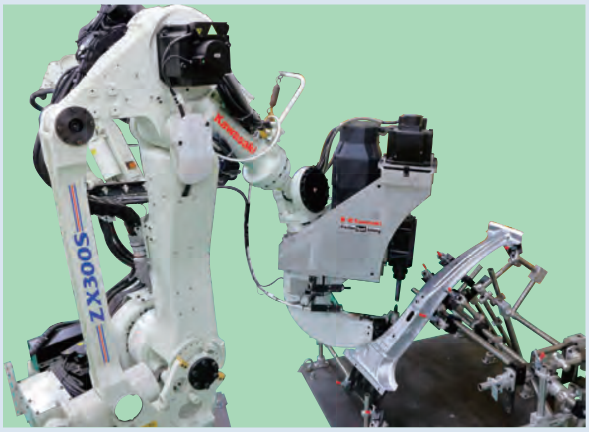
Application of Friction Spot Joining Technology to High Strength Steel: FSJ Robot System for Steel



One of the main application areas of industrial robots is spot joining in the assembly process for car bodies. We are selling resistance spot welding robots. In addition, friction spot joining (FSJ) robots that include our unique technology are already being offered on the market. The FSJ is used for joining of aluminum alloys in the field of manufacturing.

We are currently developing a "FSJ system for steel," with the aim of applying it to ultra-high-strength steel, whose utilization in car bodies has been increasing.

Introduction

It has been a while since global warming first started gaining prominent attention as a social issue. Regulations on greenhouse gases such as CO_2 have been getting stricter globally, affecting cars, which already number in the millions in advanced countries and are increasing in developing countries year by year.

1 Background

To meet the strict CO_2 emission control regulations for cars in recent years, it is required to improve the fuel efficiency of cars, and thus, car manufacturers are focusing on improvement of transmission efficiency, reduction of air resistance, and making car bodies weigh less. Luxury cars manufactured in Europe and the U.S. are currently in the process of replacing the materials they use for car bodies with aluminum, CFRP (Carbon Fiber Reinforced Plastic), or other lightweight materials, while Japanese manufacturers, etc. are also promoting the use of steels as much as possible, which are advantageous cost-wise. Steel has a wide range of strengths, so various types of steel materials are available. For example, soft steels with a tensile strength of 270 MPa are used for external panels, and hard steels with a strength of 1500 MPa are used for car body frame members such as pillars. In particular, applications of ultra-high-strength steels with strengths of 780 MPa or higher have been increasing rapidly (**Fig. 1**).

However, such ultra-high-strength steels are becoming harder to weld with the resistance spot welding method alone, which is currently the main method used for car body welding. This is because the ultra-high-strength steel contains a lot of added elements, which help improve hardenability and increase the tensile strength, and thus, when the steel is melted and then quickly cooled during welding, the welded part is noticeably harder. Therefore, the joint strengths, especially the peel strength, are likely to vary. It is also difficult to obtain adequate strengths, which is an important issue to resolve if one is to use steels as much as possible.

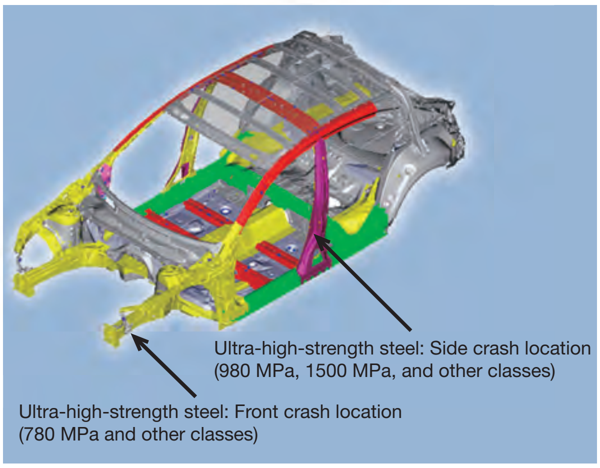


Fig. 1 High-strength steel applied to car bodies

In these circumstances we are developing friction spot joining (FSJ), which applies friction stir joining (joining materials by using heat caused by friction and plastic flow) to spot joining, and a "FSJ robot system." They are increasingly being applied to car parts made of aluminum alloys.

2 Overview of the FSJ robot system

Figure 2 shows the fundamental process of FSJ. In this joining method, a rotating joining tool is pushed against the workpiece to generate frictional heat and the heat softens the workpiece. A pin at the tip is then inserted into the workpiece to generate plastic flow around it to unify them.

The FSJ robot system is used to produce car hoods and doors made of aluminum alloy and over 300 systems have already been introduced in the production lines of car manufacturers.

Currently, in order to apply this system to ultra-high-strength steels, we are developing an "FSJ robot system for steel."

3 Application to ultra-high-strength steels

Since ultra-high-strength steels are harder and have a higher softening temperature than those made of aluminum alloy, it has been difficult to apply FSJ to them. In particular, when compared with resistance spot welding, it was very difficult to extend the life of the joining tool, which corresponds to the electrode tip of the resistance spot welding, and secure an adequate joint strength. Therefore, we have carried out the development focusing on making a "practical high-durability joining tool" and "FSJ joining process that is suitable for ultra-high-strength steels" (**Fig. 3**).

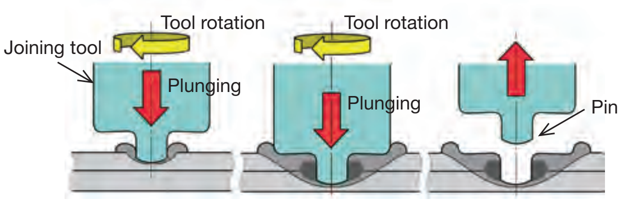


Fig. 2 Fundamental process of FSJ

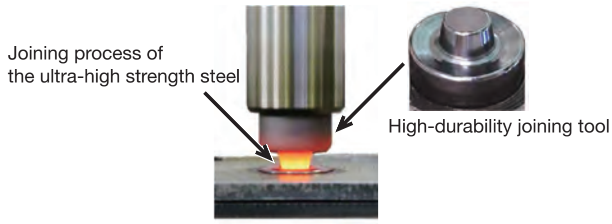


Fig. 3 Development theme

(1) Development of a practical high-durability joining tool

(i) Materials of the joining tool

One of the basic requirements for the development of a long-life and inexpensive tool is to have a cycle time that is equivalent to that of the resistance spot welding currently being used, especially in the automotive industry, while maintaining a similar joint cost.

The following lists the main characteristics of the materials required for the joining tool.

① Ability to withstand a rapid heat cycle that reaches over 1,000°C from room temperature in several seconds
② Low responsiveness with the materials of the object being joined to
③ Superior oxidation resistance
④ Stable organization even at high temperatures with sufficient strength, hardness, and toughness

When joining ultra-high-strength steel, a large axial load of 20 kN or more may be applied to the tool. Therefore, the steel must withstand a high axial force and torsional stress in temperatures from room temperature to high temperatures. In addition, since ultra-high-strength steel used as a material of the object to be joined to is harder than aluminum alloy even at high temperatures, the tool wears easily and it is also important to secure wear resistance.

Candidates for the tool material include cemented carbide mainly consisting of tungsten carbide (WC), ceramic such as silicone nitride (Si_3N_4), and PCBN (Polycrystalline Cubic Boron Nitride) made of sintered cubic boron nitride particles. During the development, in order to make the tool industrially acceptable, we set the first goals for its life when used for joining ultra-high-strength steels to be approximately 5,000 joints and the cost for each joint to be 1 yen or less. In addition, for joining using robots, a joining gun that is as compact and lightweight as possible is desired because there are limitations on the weight capacity, operation speed, etc. Therefore, we also considered the selection of the coefficient of friction and thermal conductivity to be an important point so that even small axial loads can generate sufficient frictional heat.

(ii) Evaluation system for tool durability

When developing a tool, tool durability must be evaluated. In the tool durability evaluation, it is required to not only implement a continuous joining test, but also to observe in detail and record the dimensions, the profile, and the external appearance of the tool, which change during the test. It is also required to periodically obtain the transition of the joint strength as the tool dimensions change. If a human being carried out such evaluation work, he could only make about 1,500 joints a day maximum. To promote tool evaluation and development efficiently, we developed an evaluation system for tool durability testing using three robots, as shown in **Fig. 4**. This system automated a series of tasks and data collection, ranging from supply of test pieces to the joining jig and their removal after joining, to monitoring of the joining status, dimension measurement and taking photos of the tool and test pieces, and implementation of the tensile test. This allowed 10,000 joints to be made in the continuous joining test in a day at maximum, which enabled accelerated tool development.

(iii) High-durability joining tool

Using the evaluation system for tool durability, we carried out performance evaluation of a huge number of prototype tools. The material used for the tools was PCBN, ceramic, and cemented carbide with coating as shown in **Table 1**. PCBN is very hard and has superior wear resistance. It also showed a relatively long life of 7,000 joints as a result of the test using 980 MPa class ultra-high-strength steel. However, PCBN is a very expensive material. Ceramic can be mass-produced at a lower cost, but has some issues such as the necessity to take countermeasures against breakage due to low toughness. The life of cemented carbide needs to be extended by

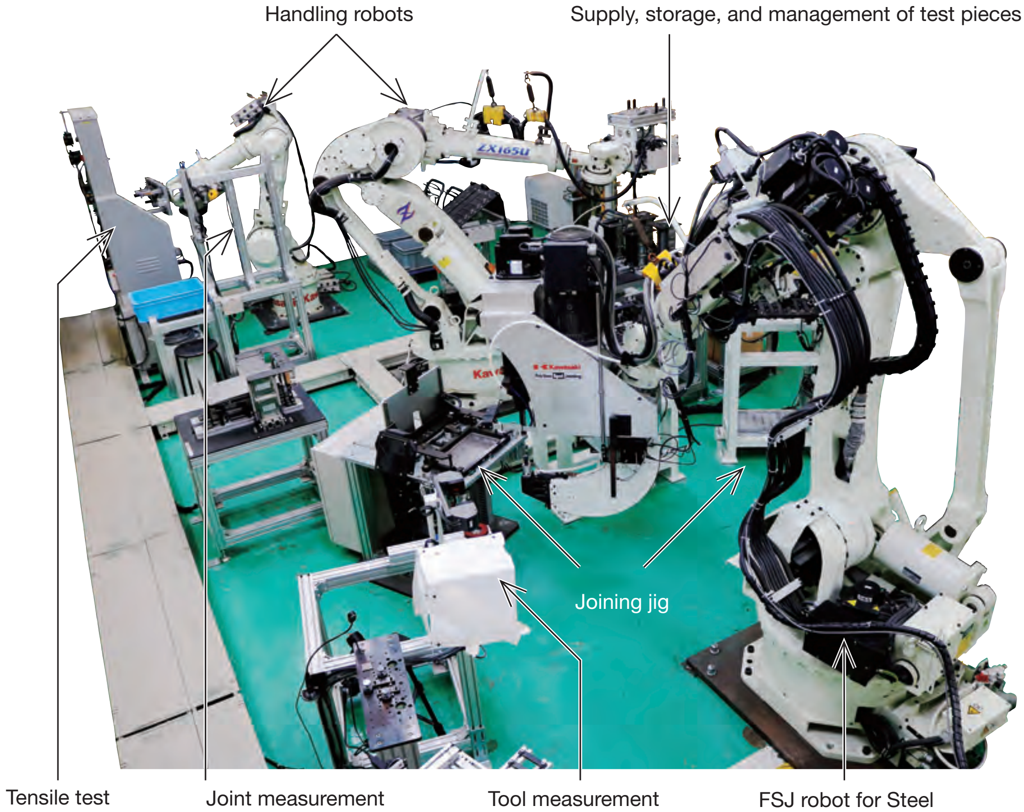


Fig. 4 Evaluation system for tool durability

Table 1 Example of prototype tool

	PCBN	Ceramic	Cemented carbide
External appearance			
Durability	○	△	○
Manufacturing cost	×	○	○
Joint cost	×	○	○
Total evaluation	△	○	◎

using refined materials and coatings, but it has a good balance between durability and cost.

We looked into this cemented carbide and advanced the development of a tool made of it in cooperation with Sumitomo Electric Industries, Ltd. During this development, we refined the material and coating and optimized the joining process in order to improve the plastic deformation resistance, defect resistance, wear resistance, and other properties of the tool.

Figure 5 shows the changes in the pin diameter and tensile shear strength of the joint during the continuous joining test. As the number of joints increased, the pin diameter decreased because the edge of the pin tip was worn. Although the tensile shear strength gradually decreased accordingly, it was still higher than the minimum value for Class A of the JIS standard for spot welding (Z3140), which was our criteria, and durability of at least 13,000 joints was confirmed.

At the beginning of the development, the tool was judged to reach its life when no more than 2,000 joints were carried out because the pin of the tool was worn, which lowered the joint strength. However, by developing a tool made of improved materials and a joining process that reduces loads to the tool, the amount of wear reduced and the joint strength defined in JIS was satisfied even after 13,000 joints, which results in a lifespan six times the first tool or longer. Considering that it is said that the electrode tip used for resistance spot welding is to be replaced after approximately 10,000 joints, the tool has a life that is equivalent to that electrode tip, and we can say that the tool has made progress toward practical realization.

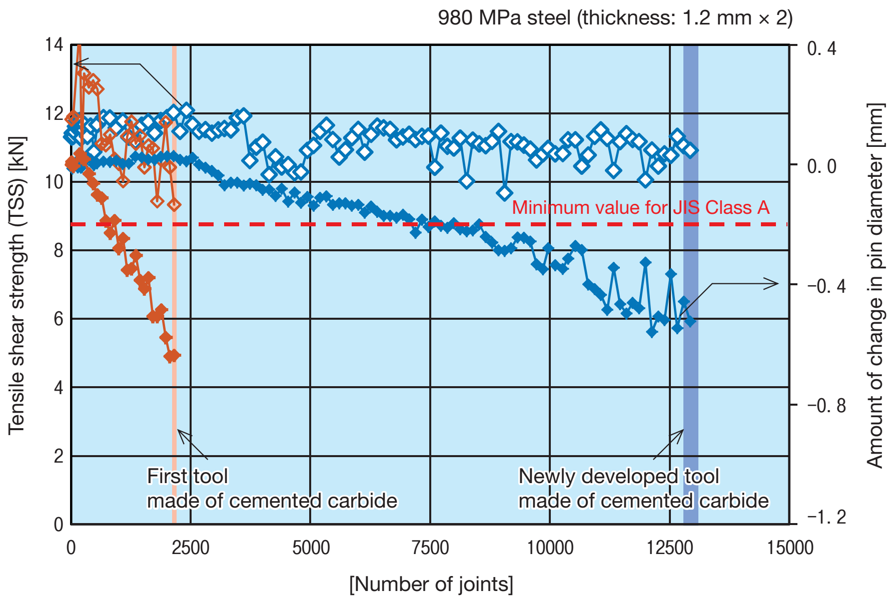


Fig. 5 Test results of continuous joining

We will continue to implement durability evaluations using even higher strength steels and review the stability of the tool quality and cost savings.

(2) Development of a joining process suitable for ultra-high-strength steels

Carbon is used to increase the strength of steels. Ultra-high-strength steels contain an especially large amount of carbon. In addition, to improve the hardenability, some elements such as manganese are added. Although the amount is set in consideration of weldability, the weld strength varies in reality and it is difficult to secure the joint strength itself. This is a welding issue that is specific to ultra-high-strength steels, and its solution is an important key to using steel materials as much as possible.

In welding methods known as fusion welding such as resistance spot welding, since the steel materials are heated up to the melting point or higher, the welded part is hardened during cooling and embrittlement occurs. Therefore, the hardened welded part is heated up again in the same or a different process to temper it and recover its toughness. However, it requires careful heat input control because the characteristics vary depending on the hardening that occurred after welding, the heating method, and the heating temperature and time.

On the other hand, FSJ does not melt the steel materials but joins them in the solid state by using plastic flow. Therefore, the highest temperature during joining can be kept below the hardening temperature, and it may be possible to realize joining without hardening the joint. This

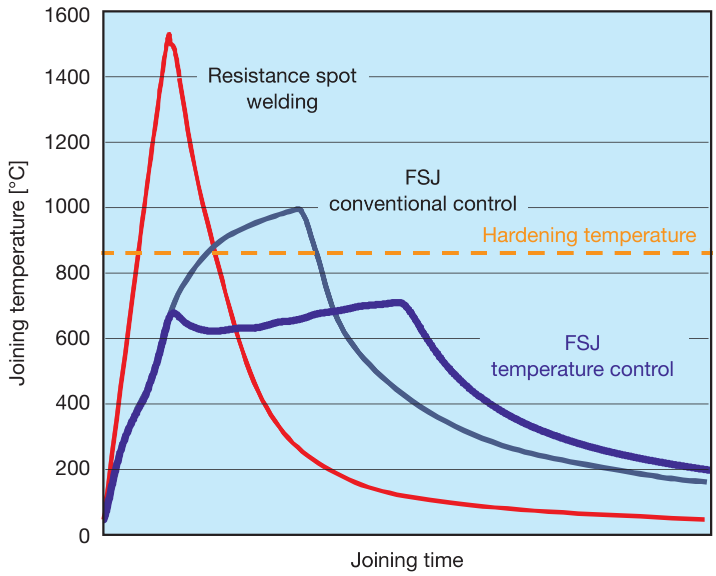


Fig. 6 Thermal history of joint during FSJ

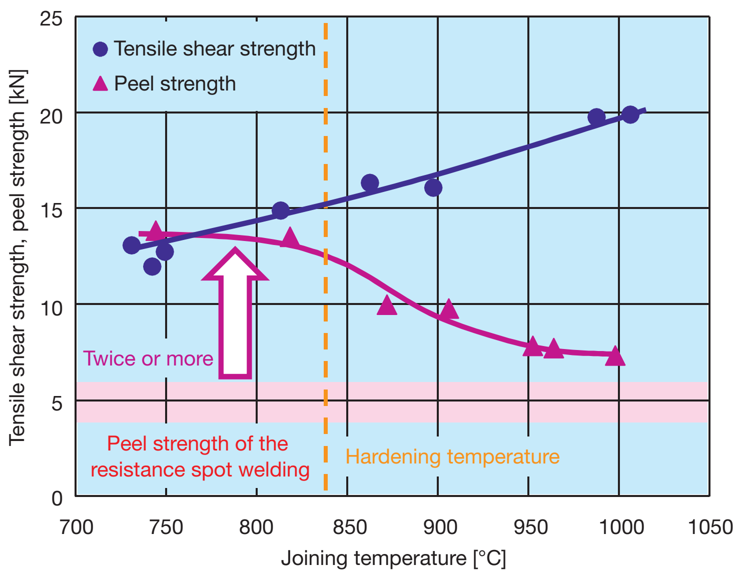


Fig. 7 Joining temperature and joint strength

is a characteristic advantage of FSJ, a form of solid-state joining, and it is an innovative method that makes a clear departure from conventional welding methods.

Focusing on the innovativeness of FSJ, we developed a unique joining temperature control process that monitors the temperature during joining and changes the joining conditions to keep the temperature constant.

The history of the joining temperatures is shown in **Fig. 6**. For comparison, it also schematically shows the temperature histories of resistance spot welding and FSJ using conventional controls. For resistance spot welding, the joining temperature far exceeds the hardening temperature and hardening occurs during cooling, which results in embrittlement. For FSJ using conventional control, the temperature goes above the hardening temperature. On the other hand, for FSJ using the joining temperature control, joining is possible without exceeding the hardening temperature.

Next, **Fig. 7** shows the tensile shear strengths and peel strengths of a joint on 1500 MPa class ultra-high-strength steel (thickness: 1.8 mm) when the joining temperature is changed by the joining temperature control. Both strengths change characteristically depending on the joining temperatures. When the joining temperature is high, the peel strength is low while the tensile shear strength is high. In contrast, when the joining temperature is lower than the hardening temperature, the tensile shear strength is low while the peel strength increases drastically. We confirmed that the peel strength at that time was at least twice that of resistance spot welding.

The tensile shear strength and peel strength have a trade-off relationship. In this way, the desired characteristic can be obtained in each part by controlling the temperature so that the parts that require shear strength are joined at a high temperature and parts that require peel strength are joined at a low temperature.

In addition, use of this joining temperature control enables joining of high-carbon steels, which are considered difficult to weld due to the significant embrittlement, and during dissimilar materials welding, it may be possible to control the thickness of the intermetallic compounds on the joint interface. As described above, FSJ using joining temperature control is a brand-new second-generation FSJ, and an innovative joining method that will dramatically expand the applicable range of the materials that can be joined compared to the conventional welding method.


Takuya Fukuda
System Engineering Department,
Robot Division,
Precision Machinery Company


Kazumi Fukuhara
System Engineering Department,
Robot Division,
Precision Machinery Company


Doctor of Engineering
Ryoji Ohashi
Manufacturing Technology Department,
System Technology Development Center,
Corporate Technology Division


Yoshitaka Kobayashi
Manufacturing Technology Department,
System Technology Development Center,
Corporate Technology Division


Doctor of Engineering
Masahiro Miyake
System Engineering Department,
Robot Division,
Precision Machinery Company

Conclusion

It started to show signs of the practical realization of long tool lifespans, which was the biggest issue for the application of FSJ to steel materials. In addition, we succeeded in the development of our proprietary joining temperature control process that is suitable for joining ultra-high-strength steels. Now, we will focus on the "FSJ robot system for steel" for the production of car bodies, accelerating its development toward practical application.

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