# Development of a Friction Spot Joining Tool for 980 MPa Tensile Strength Steels Joining

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Car manufacturers have been increasing the use of ultra-high tensile strength steels with strengths exceeding 980 MPa. This is to improve collision safety and reduce vehicle weight, thereby reducing $CO_2$ emissions. Due to their high carbon content, these steels cannot achieve sufficient joining strength when joined using the current resistance spot welding technology. To achieve high joining strength in high-carbon content steels, we focused on the friction spot joining (FSJ) method, a solid-phase joining method that employs the frictional heat of the joining tool to soften and ultimately join the sheets through a plastic flow process. FSJ has already been commercialized for the joining of aluminum sheets, but its poor tool life has prevented its application to steel sheet joining. In order to make the FSJ method practically applicable to steel joining, we developed a cemented carbide tool base material with good resistance to breakage, plastic deformation and thermal cracking, a PVD coating that provides hardness and oxidation resistance, as well as a tool geometry. We also determined appropriate joining conditions to reduce tool wear. By integrating all these elements, we have successfully developed an FSJ tool with superior tool life (7,000 spots) for ultra-high tensile strength steel joining.

Keywords: friction spot joining (FSJ), friction stir welding (FSW), ultra-high tensile strength steel sheets, resistance spot welding (RSW)

## 1. Introduction

Given the growing focus on global warming in recent years, reducing the weight of vehicles to cut $CO_2$ emissions while at the same time improving collision safety has been a critical issue for auto manufacturers, and this has accelerated the adoption of ultra-high tensile strength steel sheets with a tensile strength of 980 MPa or higher. For joining these automobile steel sheets, resistance spot welding (RSW)*1 and laser beam welding*2 are currently the mainstream techniques. However, to increase the tensile strength of the steel sheets a higher carbon content is required. The currently used methods have the drawback of being difficult in achieving sufficient joining strength in precisely these high carbon content steels. The reason is that an embrittlement phase (martensite phase) forms in the weld during fusion joining, something that hardens the material, resulting in breakage.(1) As higher tensile strength steel sheets with higher carbon content are required in the future, it will therefore become increasingly difficult to join them using RSW.

In contrast, as it is a non-fusion joining technique, friction spot joining (FSJ) has recently been attracting attention as a method for joining two high-carbon steel materials or sheets of two different materials. However, since the tools used for joining steel sheets by FSJ have a limited tool life, the method has not yet been put into practice. With the goal of realizing FSJ tools for ultra-high tensile strength steel sheets, by using the technology we have accumulated in manufacturing cemented carbide*3 cutting tools, which are our mainstream products, and by cooperating with Kawasaki Heavy Industries, Ltd., a FSJ machine manufacturer, we have developed a tool with long tool life for joining 980 MPa-class ultra-high tensile strength steel sheets.

## 2. Friction Spot Joining Technology

FSJ is a new solid phase joining technique developed in 1991 by The Welding Institute (TWI), a research organization in the UK.(2) It is a non-fusion joining technique that relies on frictional heat generated by letting a tool, with a protrusion called a probe, rotating at high speeds and then pressing the tool against the sheets to be joined. This will soften the work material and join the sheets through a plastic flow process. The joining method is called friction stir welding (FSW) if performed by linearly moving the tool while pressing it against the materials to be joined, or FSJ if the materials are joined in spots. FSJ is an improved and more developed version of FSW, which was realized in 2004 through joint development by Kawasaki Heavy Industries, Ltd. and Mazda Motor Corporation.(3) **Photo 1** shows external views of the FSJ robot system and the joining tool that is attached to the end of the joining gun. **Figure 1** is a schematic representation of the FSJ process, and **Photo 2** is an exterior view of the two 980 MPa-class ultra-high tensile strength steel sheets joined using FSJ.

While FSJ uses a robot system similar to that used in RSW, it does not, however, require auxiliary equipment such as the water cooling system and the resistance welding machine that accompanies RSW, thus reducing facility and running costs. The main energy-consuming parts in FSJ are only two motors that drive the joining tool. Thus, FSJ is an energy-efficient technique compared with RSW. Moreover, in contrast to RSW that generates both fumes and expulsion, it is possible to maintain a clean working environment during joining using FSJ joining.

The characteristics of RSW, laser beam welding, and FSJ are summarized in **Table 1**. As FSJ is a non-

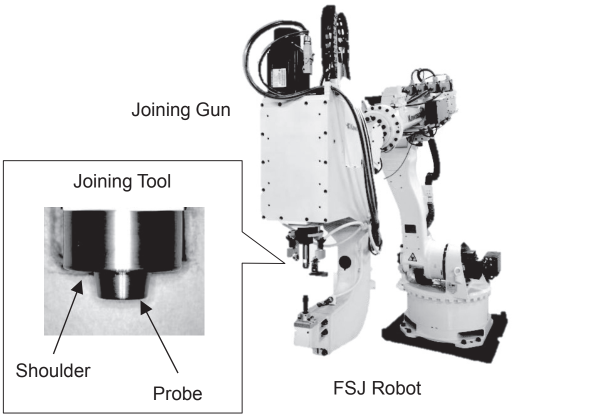



**Photo 1.** External views of the FSJ robot system and joining tool

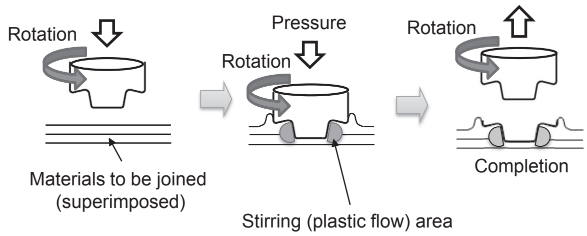



**Fig. 1.** Schematic representation of the FSJ process

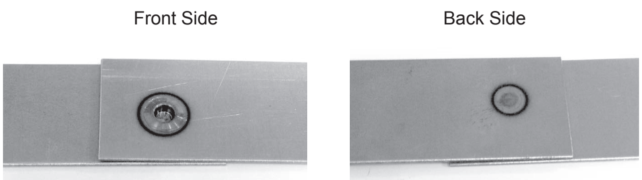



**Photo 2**. External views of an FSJ joint (980 MPa-class ultra-high tensile strength steel sheets)

**Table 1.** A comparison of different joining methods

| | Resistance Spot Welding (RSW) | Laser beam Welding | Friction Spot Joining (FSJ) |
|---|---|---|---|
| Joining method | Fusion joining | Fusion joining | Sold phase joining |
| Joining different materials | Not possible | Not possible | Possible |
| Joining medium and high carbon steel | Not possible | Not possible | Possible |
| Power consumption | Medium | Medium | Low |
| Working environment | Not good (Fume and expulsion) | Not good (Spatter and fume) | Good |
| Joining cost | Low | High (Equipment cost) | High (Tool cost) |

fusion joining (solid phase joining) technique, it is possible to join two high-carbon steel materials or two entirely different materials. However, the method has not been put into practice due to its problems of short tool life. Joining aluminum has already been realized using tools made of tool steel*4 as the tool temperature during joining is low, only 400 to 500°C. In the case of joining steel, however, the tool temperature reaches around 1,000°C, and this results in a much shorter tool life. It is against this background that we started developing a tool with long tool life using cemented carbide.

## 3. FSJ Joint Strength

In aluminum FSJ, the probe of the tool is threaded to promote plastic flow by stirring. However, in the case of joining ultra-high tensile strength steel, the stirring effect from the thread is smaller than when joining aluminum, and the threaded probe is easily chipped. Therefore, we optimized the diameter and length of the probe instead of threading it, and found conditions under which a high joint strength (tensile shear strength) that exceeds the JIS-A-class average can be obtained. A simple circular truncated conical probe is less likely to wear away and be chipped and also has the added advantage of reducing machining costs (**Photo 3**).

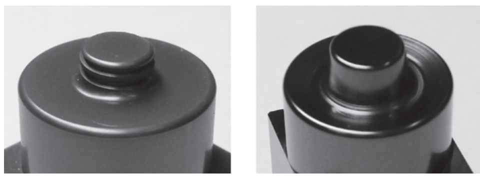
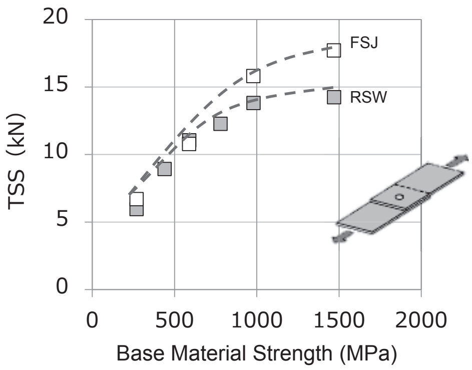
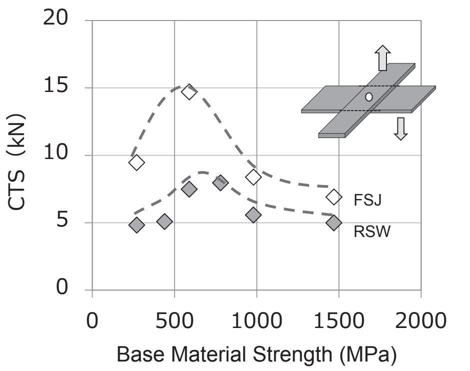


**Photo 3**. Threaded probe tool (left) and circular truncated conical probe tool (right)

Using steel sheets with various strengths, the Tensile Shear Strength (TSS) and Cross Tensile Strength (CTS) of the FSJ and RSW[(4)] joints were compared to each other. The results are displayed in **Figure 2**. While the TSS of RSW increases gradually for steel sheets with lower strengths, this increase levels off above 980 MPa. For FSJ, however, the TSS continues to increase even for 1,500 MPa strength steels. The CTS of both RSW and FSJ show similar behaviors, although FSJ displays higher values than RSW. As stated above, RSW, which is a fusion joining method, generate cracks due to embrittlement of the joint that often become the origin of a rupture, and we believe this to be the reason for the higher CTS values of FSJ. Consequently, one must conclude that FSJ is superior to RSW in terms of both TSS and CTS.




(a) Tensile Shear Strength (TSS)




(b) Cross Tensile Strength (CTS)

**Fig. 2**. Tensile shear strength and cross tensile strength of FSJ and RSW

Considering the trend towards higher tensile strength and greater carbon content, FSJ is a promising technology that can be expected to replace RSW in the future.

## 4. Tool Damage Evaluation

There are numerous grades of cemented carbides used for different applications. During the course of this work, we manufactured tools using several typical cemented carbides grades generally used for cutting tools to evaluate the potential of the existing grades. For the evaluation, two 1.2-milimeter-thick sheets of 980 MPa-class ultra-high steel were laid on top of each other and joined using FSJ. The resulting damage to the tool can be classified into (1) to (5) as shown in **Photo 4**. The experiments revealed that it is necessary to achieve high heat crack resistance, high plastic deformation resistance, high chipping resistance, high wear resistance, and high oxidation resistance in order to realize a tool with a long tool life. However, the tools manufactured using the existing cemented carbide grades displayed the damage modes shown in **Photo 4 (1) to (5)** after mere tens to hundreds of tool passes. This demonstrated the difficulty in realizing a tool with a sufficiently long tool life.

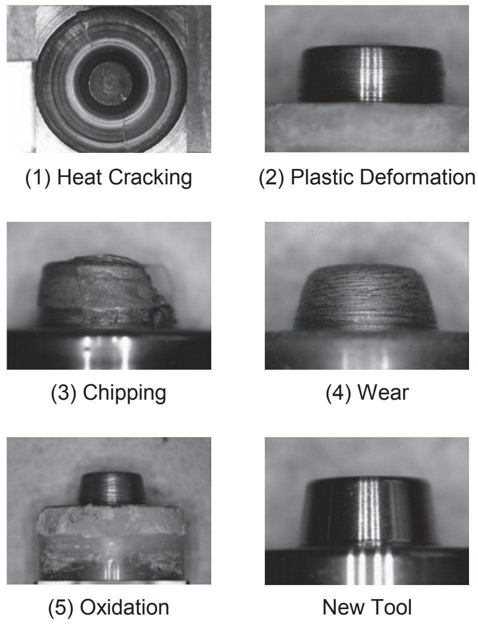



**Photo 4**. Tool damage modes

## 5. Development of a FSJ Tool with Superior Tool Life

As FSJ requires frictional heat to be generated between the tool and the materials to be joined, for efficient joining the base material of the tool should have low thermal conductivity to prevent heat dissipation. However, if the thermal conductivity is too low, the heat cycles during continuous spot joining can cause heat cracking at the tool shoulder. Therefore, it was necessary to optimize the thermal conductivity of the cemented carbide base material.

As the FSJ tool is exposed to heavy loads, it must be hard enough to resist plastic deformation. However, in cemented carbides there is generally a trade-off between the hardness and toughness, thus excessive hardness can result in chipping. It was therefore necessary to develop a base material with a good balance between hardness and toughness appropriate for FSJ.

In addition, since the probe, which is the most important part for maintaining joint strength, during joining will be rotating at high speeds and high temperatures in the materials to be joined, it is subject to aggressive wear, resulting in degradation of the joining strength. Also, as the tool shoulder is repeatedly exposed to high temperatures in the atmosphere, the oxidized base material wears out, resulting in burrs at the joint and leading to a degradation of the joint quality (**Photo 5**).

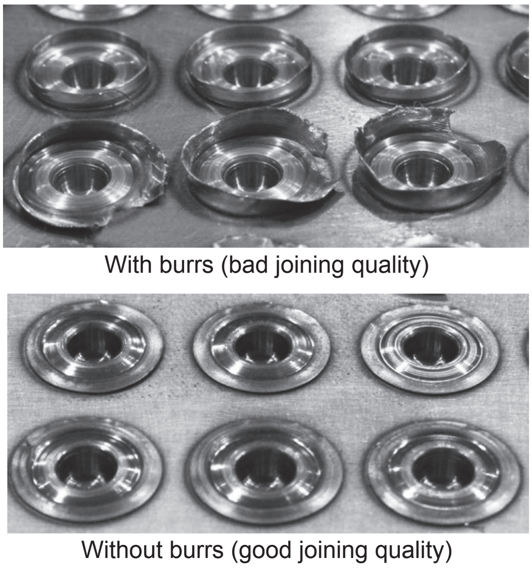



**Photo 5**. Exterior photos of the joined materials

To fulfill all necessary requirements, we developed a base material that has heat conductivity, hardness, and toughness appropriate for FSJ by optimizing the composition of the material as well as the WC particle diameter, thereby succeeding in simultaneously attaining high thermal crack resistance, high plastic deformation resistance, and high chipping resistance. Wear resistance was improved by ceramic coating the tool surface using physical vapor deposition (PVD).*5 When joining steel, the tool temperature reaches approximately 1,000°C, and thus a coating able to withstand oxidation at this temperature or above was needed. By adding a new element to the standard TiAlN coating widely used for cutting tools, we have developed a PVD coating for FSJ with both high hardness and an oxidation onset temperature of at least 1,100°C (**Table 2**).

**Table 2.** Film hardness and oxidation onset temperature of TiAlN and the developed coating

| | Film hardness (GPa) | Oxidation onset temperature (°C) |
|---|---|---|
| TiAlN | 32 | 850 |
| Developed coating | 36 | 1129 |

To reduce the load on the tool, we also explored the optimum conditions for lowering tool temperature by simulation using Abaqus finite element analysis software. Young's modulus, Poisson's ratio, heat conductivity, specific heat, specific gravity, coefficient of thermal expansion, yield strength, and coefficient of friction were used as the physical properties of the steel sheets and tool base material. **Figure 3** illustrates the results of simulating the tool temperatures in joining tests under Conditions 1 and 2. For the same joining time, the simulations show that the rise in tool temperature is smaller under Condition 2 compared to Condition 1. By selecting Condition 2, it was thus possible to lower the tool temperature during joining, minimize the probe wear and the oxidative wear of the shoulder.

Through the development work described above, the tool life, which was originally a mere several hundred spots, was improved to maintain a joint strength above the JIS-A-class minimum even after approximately 7,000 spots (**Figure 4**). Considering the fact that RSW

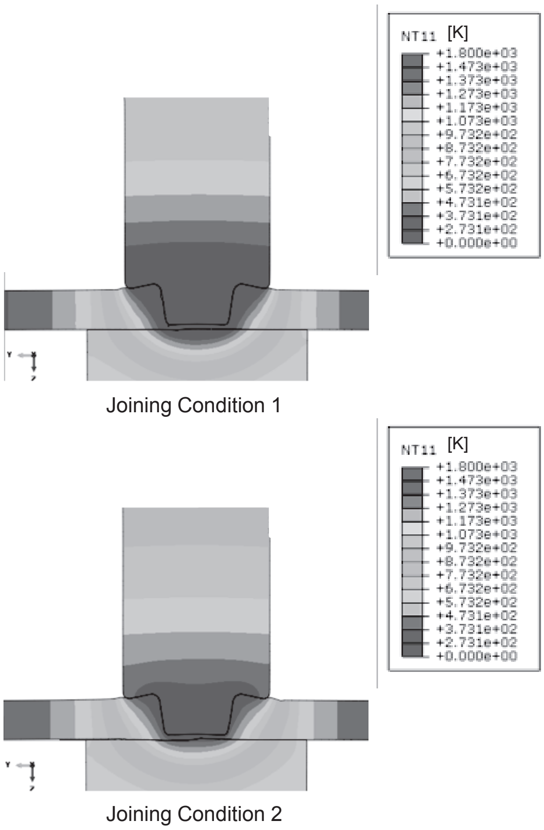



**Fig. 3**. Result of the simulation analysis

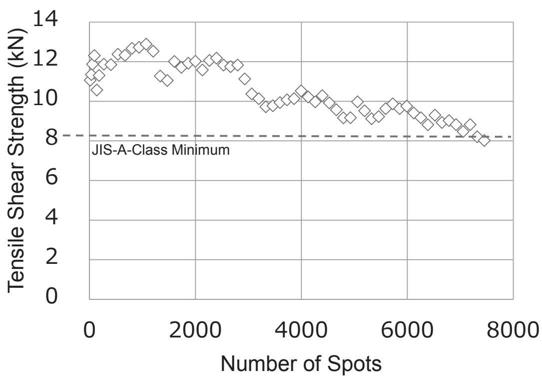



**Fig. 4**. Result of tool life evaluation in the joining of 980 MPa-class ultra-high tensile steel

requires dressing after approximately 200 to 300 spots and replacement of the electrode after 2,000 to 4,000 spots, we believe that the new FSJ tool is superior to RSW in both maintainability and cost performance.

## 6. Conclusion

FSJ is a ground-breaking new non-fusion joining technique able to join ultra-high tensile steel as well as different materials that cannot be joined using RSW. A suitable FSJ tool for 980 MPa-class ultra-high tensile steel was developed through improving the base material of the cemented carbide tool, enabling the simultaneous achievement of high thermal crack resistance, high plastic deformation resistance, and high chipping resistance. Furthermore, the development of the PVD coating, improvement of the tool shape, and optimization of the joining conditions raised the wear resistance of the tool, resulting in a tool with long tool life that maintains a joint strength of the JIS-A-class minimum up to approximately 7,000 spots. As increasingly higher tensile strength steel sheets are used for automobiles and the carbon content increases to a level that makes the use of RSW impossible, we believe that FSJ will have great potential. We will, therefore, continue to develop tools that responds to the need for increasingly high tensile strength automobile steel sheets.



### Technical Terms

∗1 Resistance spot welding: A technique for joining two metal sheets by pressing them together and passing a current through them in order to fuse the sheets using ohmic heat.

∗2 Laser beam welding: A technique for joining two metal sheets by locally fusing them using the heat of a laser beam and then waiting for the joint to solidify.

∗3 Cemented carbide: A hard material mainly composed of tungsten carbide (WC) that forms a hard phase and cobalt (Co) that forms a binding phase, widely used for cutting tools.

∗4 Tool steel: A kind of steel mainly used for metal processing tools.

∗5 Physical vapor deposition (PVD): A method for forming a film on the surface of a base material by vaporizing a metal at high temperature and relying on a physical reaction to form the film.

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