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ADVANCED WELDING TECHNOLOGIES: FSW IN AUTOMOTIVE MANUFACTURING

ABSTRACT: The process of joining structural elements of a vehicle plays an important role in the development of new models in the automotive industry. Among the various technologies represented in the automotive industry, the friction stir welding (FSW) technology has been increasingly applied in recent times.

FSW provides high-quality welded joints, has high energy efficiency, relatively simple equipment, and the possibility of process automation. It is also the most environmentally friendly technology (no harmful fumes, harmful radiation, light flashes, or protective gas atmospheres), which is of great importance for the modern automotive industry. This automated friction welding process fits well with industries that have high-volume production, such as the automotive industry. Thanks to the application of this welding process, different, new, and more complex products have already been created in the automotive industry.

On the other hand, car manufacturers are increasingly working on the design of products made from mixed or hybrid materials, where it is necessary to combine and join completely different metals, such as the joining of steel and aluminium, in order to reduce the weight of their vehicles. With traditional welding methods, joining different metals was not possible. Additionally, the use of industrial robots enables the application of the FSW process for joining materials along complex joint line configurations, as well as joining sheets and plate materials in all welding positions.

This paper presents the basic principles of the FSW technological process. Then, all the technological components of this welding process are described. The physical essence of the process itself is based on the interaction of an appropriate tool with the base material. The rotation of the tool through the base material ensures the release of mechanical energy as a result of intense friction and mixing of the welded material. This mechanical energy is converted into heat, which heats the material in the joining zone, thus forming a continuous, high-quality weld. The paper presents examples of the application of FSW in the automotive industry by leading global manufacturers.

KEYWORDS: welding,friction stir welding, welded joint, automotive manufacturing, steel

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INTRODUCTION

Modern structures are increasingly required to meet high-quality standards, which demands faster and higher-quality welding processes. Today, efforts are being made globally to modernize and develop advanced welding methods, including Friction Stir Welding (FSW). This method falls under the category of pressure welding techniques. The FSW welding process is relatively simple, efficient, economical, environmentally friendly, and innovative [2]. Thanks to its excellent characteristics compared to other conventional welding methods, FSW is applicable in many industries.

Recently, there has been an increasing need for the use of lightweight metals and their alloys, especially aluminium and magnesium alloys, in the automotive and aerospace industries. In these industries reducing the weight of components is of great importance. For joining structural components made of these materials, resistance spot welding, laser spot welding, ultrasonic spot welding, and a special gas-shielded welding process (Cold Metal Transfer Spot Welding – CMTSW) are applied [3]. Among all the mentioned welding methods, resistance spot welding is currently the most commonly used process in the automotive industry, thanks to its high productivity [4]. More than 4,000 welded joints are necessary to form a single vehicle body and its related parts [5]. However, conventional resistance spot welding has disadvantages such as tool wear during joining, high thermal distortion, and sometimes weaker joint strength. Laser spot welding can result in defects such as porosity. Among other reasons, these challenges highlight the need for innovative welding processes.

Today, various variants of Friction Stir Spot Welding (FSSW) are being developed [1-4]. This paper presents the basic principles of the Friction Stir Welding process, with a focus on spot welding. Additionally, the paper highlights the application of this process in the automotive industry by well-known global brands.

Initially, vehicles were made from steel of a certain thickness. With the advancement of steel, the material's thickness has decreased, and today, very thin sheets (sometimes as thin as 0.5 mm) are used in car body manufacturing. Additionally, many steel parts are being replaced with parts made from lighter materials, reducing the vehicle's unnecessaryweight and increasing its payload capacity. Moreover, the reduced vehicle mass leads to lower fuel consumption, which directly contributes to environmental protection. Importantly, replacing materials and reducing thickness do not compromise passenger safety.

The group of materials that stands out the most in these tasks is high-strength steel. High-strength steels were developed in the late 19th century and are now widely used across all branches of mechanical engineering. They are characterized by favourable mechanical properties (strength and ductility) while maintaining good workability (forming, welding, etc.) [1, 2]. Today, even the processes for producing these steels are so advanced that their cost is often comparable to that of conventional low-carbon steels, yet with significantly better mechanical properties. The high strength of these steels results from the application of complex thermal, thermo-mechanical, and mechanical processing procedures. Consequently, the high strength allows for smaller cross-sectional dimensions of parts, reducing the amount of material used and the weight of structures. Regarding the vehicle production industry, the amount of advanced high-strength steel (AHSS) used in vehicle body production increases each year (Figure 1). Nowadays, high-strength steels are used in vehicles not only for body parts, but also for more critical components of cars [3, 16].

THE FRICTION STIR WELDING PROCESS

Friction Stir Welding (FSW), also known as "friction welding with a tool" is a modern technology for joining both similar and dissimilar materials, provided that the tool material can withstand the forging temperatures of the materials being joined. Aluminium alloys can be welded with high quality and relative ease using this process. Additionally, copper, titanium, and magnesium alloys, as well as steels, polymeric materials, and others, can also be welded using this method.

FSW is a simple process that involves the use of an appropriate tool. The tool needs to induce heat, which is generated as a result of friction between the tool surface and the base material.

FSSW is a newer process that has gained significant attention in the automotive and other industries [11]. It is a type of the FSW welding process, where a lap joint is created without melting the base material. The appearance of this welded joint is similar to that produced by resistance spot welding, which is used for joining car bodies. The diagrams of the FSW and FSSW processes are shown in Figure 1.

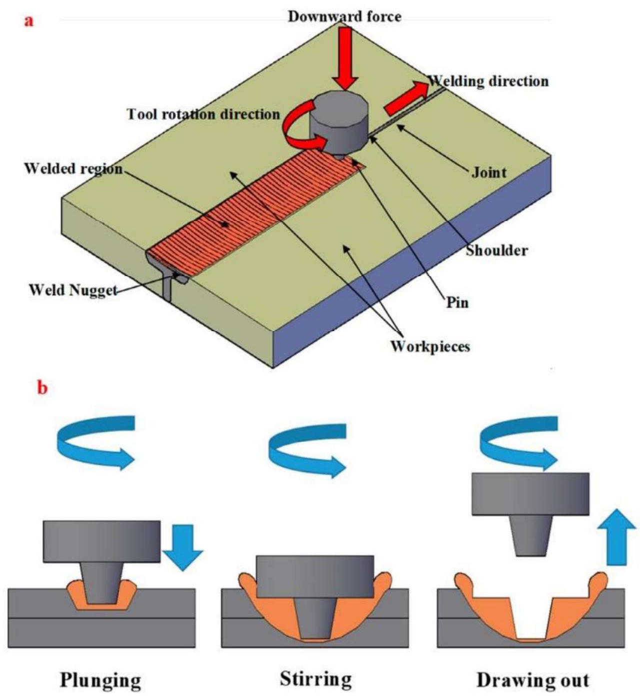

Figure 1 FSW process scheme (a), FSSW process stages (b) [8]

In friction stir spot welding, there is no linear movement of the tool, resulting in a localized spot weld in the lap joint of the base material or sheets. This process occurs continuously in three stages (Figure 1b). In the first stage, which involves the tool pressing into the material, the tool rotates around its axis and moves vertically downward, coming into contact with the base material where intense friction begins, releasing a large amount of heat. This heat softens the material, and the tool penetrates deeper into the material. In the second stage, the tool continues to rotate, and the mixing of the base materials occurs as the layers of the base material adjacent to the tool are pulled around the tool at high speed, leading to the mixing of the plasticized, softened material. In the third stage, the tool is withdrawn from the material, the material cools, and the joint is formed.

Due to the geometry of the tool, an exit hole remains. This problem has been addressed by applying a new variant known as Refill Friction Stir Spot Welding (RFSSW), or "spot welding with refill". RFSSW was patented at Helmholtz-ZentrumGeesthacht (HZG) in Germany in 2004. It is used in car bodies and the fuselage and wings of aircraft. This process uses a tool consisting of two rotating components – a probe and a tool body, which is concentrically assembled with a corresponding static clamping ring. The rotating elements have independent vertical movement, which ensures the creation of a weld without an exit hole after the tool is withdrawn [14]. The Refill FSSW process has two variants: an upsetting face and an upsetting probe.

In the process with an upsetting face, the face part of the tool enters the material during rotation. The process is synchronized, which leads to the redistribution of material, and the probe is withdrawn to create space for the excess material (phase 1 and phase 2, Figure 2), which is then used in the next step to fill the cavity (phase 3).

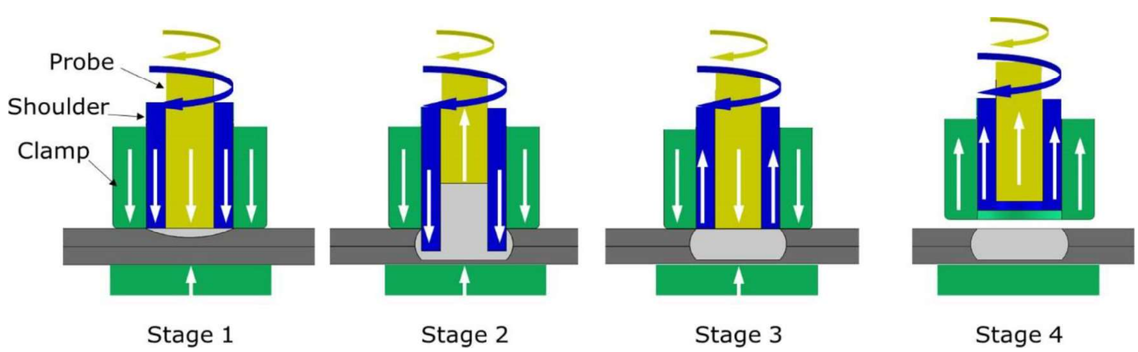

Figure 2 Schematic of the Refill FSSW process with indentation shoulder [10]

The process with an upsetting probe is similar. The internal part of the tool (the probe) rotates and enters the material, while the face is withdrawn to create space for the softened displaced material (phases 1 and 2, Figure 3), which then fills the exit hole in the next phase 3.

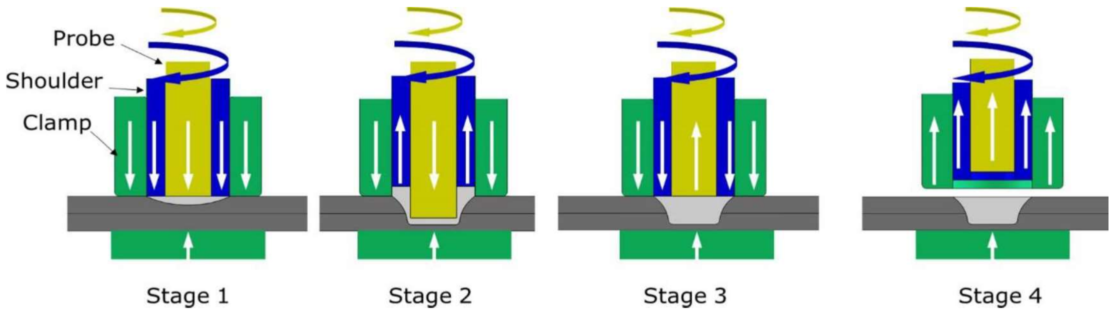

Figure 3 Schematic of the Refill FSSW process with an indentation probe [10]

CLASSIFICATION OF FSSW WELDING PROCESSES AND THE SFSSW PROCESS

Depending on the tool geometry, the complexity of the tool's movement, the type of materials being welded, and other factors, FSSW processes can be categorized into several variants. Some of these have been developed with applications in specific industrial fields, while others are still being refined and adapted to meet certain technical and other conditions to fulfil all requirements for a quality joint.

FSSW can be classified into the following methods:

- Friction Stir Spot Welding with a flat tool.
- Friction Stir Spot Welding with a profiled tool.
- Friction Stir Spot Welding with rotational tool movement (SFSSW).
- Friction Stir Spot Welding with intermediate layer mixing (IL-FSSW).
- Refill Friction Stir Spot Welding (RFSSW).
- Friction Stir Spot Welding with concave/convex tool.
- Projected Friction Stir Spot Welding (PFSSW).
- Friction Stir Spot Welding with a flat tool (FFSSW).

An important method is Friction Stir Welding with rotational tool movement – Swept FSSW, where the tool performs a complex rotational movement around its axis and along a corresponding circular path (Figure4).

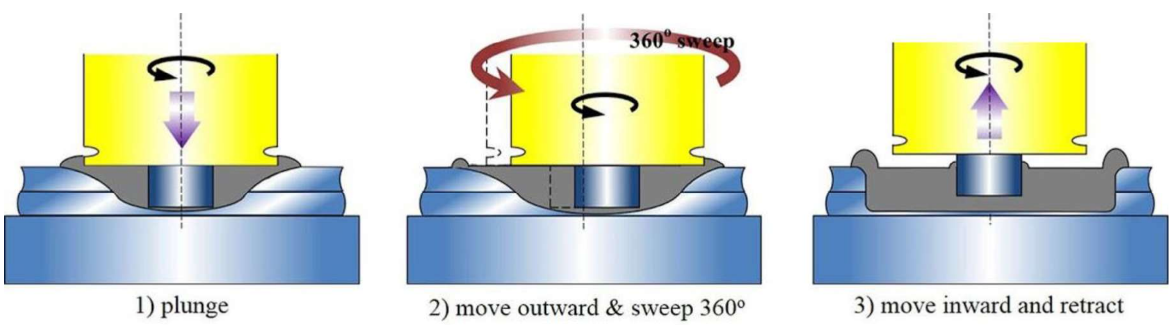

Figure 4 Scheme of the Swept FSSW welding procedure [6]

This process is quite complex and can be divided into three phases (Figure 4). In the first phase, the rotating tool is pressed into the material and held briefly in the initial position. In the second phase, the tool moves away from the initial position and performs a circular movement counter clockwise along the circumference. The tool's movement diagram is shown in Figure 5 with a top-down projection. This movement allows the mixing of a larger amount of material in a wider mixing zone. In the final phase, the tool returns to the initial position, rotation ends, and the tool is withdrawn from the material.

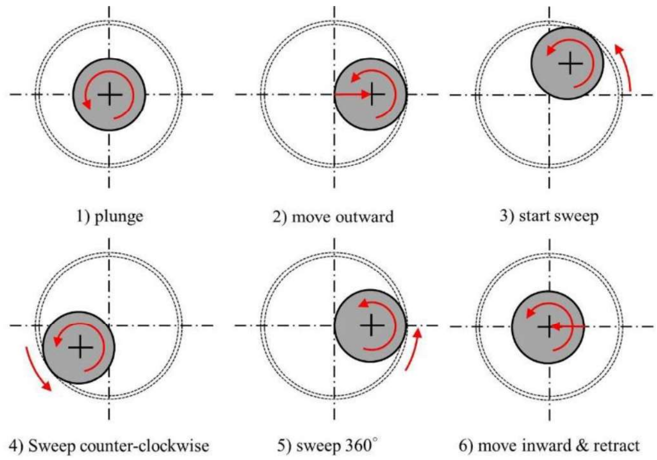

Figure 5 Path of tool movement in the Swept FSSW procedure [6]

The mechanical design of Swept FSSW welding is superior to the conventional FSSW process due to its larger mixing zone.

BASIC PARAMETERS OF THE PROCESS AND TOOL GEOMETRY

The mechanical properties and microstructure of welded joints largely depend on the welding parameters and tool geometry, which affect the heat generation due to friction and the material flow. Therefore, careful selection of welding parameters (Figure 6) is necessary to prevent defects such as voids, partial or incomplete bonds, and others [13]. Defects have great influence on the mechanical properties of the joint and affect the fracture mechanism.

Basic parameters of the friction stir spot welding process:

- Tool penetration depth (mm),
- Tool rotation speed (rpm),
- Tool shoulder immersion depth (mm),
- Dwell time **–** duration of immersion (s),
- Tool plunge rate (mm/min),
- Axial force applied to the tool (N).

All the mentioned parameters depend on the thickness of the base material, the type of materials being joined, whether the materials are the same or different, and other factors. The tool rotation speed is constant. The tool rotates at a constant defined speed and is designed to penetrate and join materials arranged in a lap configuration, prepared for friction stir spot welding. The tool penetration depth through the top and bottom plates significantly determines the overall quality of the joint. The thickness of the top and bottom plates is also a factor to consider.

Researchers [6-10] have analysed the impact of tool plunge depth, rotation speed, plunge rate, and dwell time on the mechanical properties of the joint as well as the microstructural properties of aluminium alloy (5042) used in the automotive industry. It was found, for example, that reducing the rotation speed from 1900 rpm to 900 rpm increased the length of the bonding layer [7]. For joints produced at higher tool rotation speeds (1900 rpm), the material flow was more vertical, i.e., more concentrated towards the surface of the joint, resulting in a slightly reduced bonding layer and a decrease in shear strength.

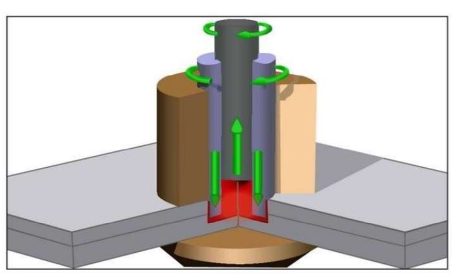

Figure 6 Tool model for FSSW in the joining process

The geometry of the tool, particularly the probe, has a significant impact on the process and the quality of the joint. It has a much greater influence on the welding regime compared to, for example, the tool rotation speed. The tool itself generally consists of three components: the clamping ring, the sleeve (shoulder), and the probe (pin or spindle) (Figure 7).

Figure 7 FSSW tool components: a) clamping ring, b) sleeve, c) pin [9]

Figure 8 shows the head of the FSSW tool in the robotic arm, the tool assembly, and the surface of the joint [15].

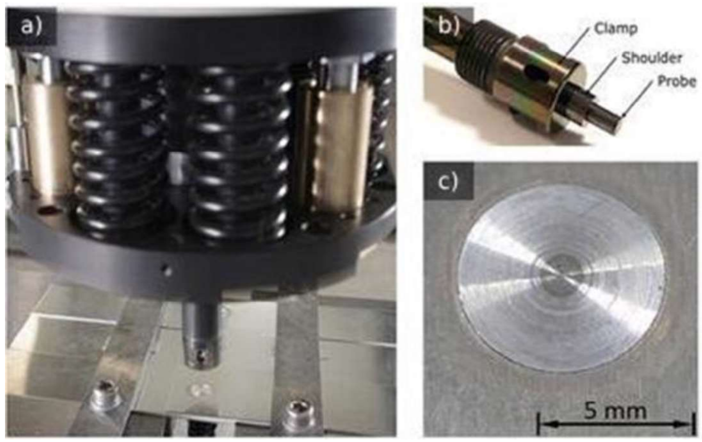

Figure 8 Robotic arm (a), tool (b), joint surface (c) [15]

APPLICATION OF FSW IN THE AUTOMOTIVE INDUSTRY

FSW welding is applied by several leading global automotive companies. The goal is to produce lighter vehicles, which reduce fuel consumption, increase load capacity, and decrease environmental pollution. This process is used in the production of engines and chassis, wheels, hydraulic components, body panels, truck cabs, fuel tanks, trailers, buses, airport vehicles, motorcycle and bicycle frames, as well as in the repair of aluminium components in cars, etc.

Since 2023, FSSW has been utilized by Mazda Motor Corporation and Kawasaki Heavy Industries, as well as in the assembly of aluminium hoods and rear doors of the PKS-8 sports car [11]. FSSW is also used by Toyota Motor, General Motors, Ford Motor, Fiat Chrysler Automobiles, and PSA Peugeot Citroen, among others.

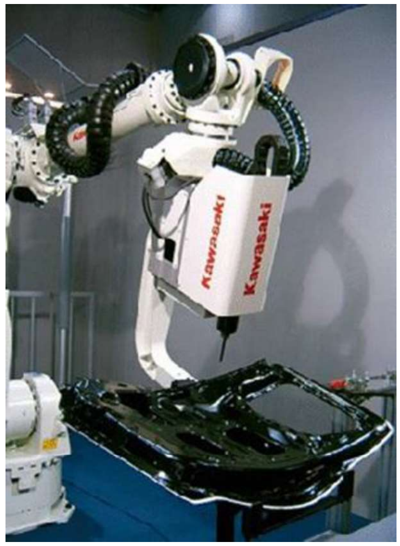

Figure 9 Example of FSW application in the automotive industry in Japan [12]

Figure 10 FSW at the Lincoln factory [11]

Figure 11 Application of FSW for rear doors on the Mazda RX-8 [11]

Specialized companies around the world manufacture and integrate FSW robots into automotive production lines, such as the German company Riftec in Geesthacht [11].

Figure 12 Automotive components connected using the FSW procedure of the German company Inpro [11]

All these examples, as well as many others in the public domain, demonstrate the growing demand for these advanced technologies.

CONCLUSION

The application of advanced welding technologies in the automotive industry is growing. Global trends in the automotive industry show an increasing need for higher quality, more efficient, cost-effective, and environmentally justified technologies. Researchers are working intensively on innovations in numerous methods that can replace existing conventional methods and be applied in technologically acceptable working conditions.

From a scientific perspective, all methods of the FSW process are very complex, and it is challenging to provide a comprehensive definition of them, as FSW is inherently a nonlinear process whose mathematical definition requires a series of analyses involving dynamic material flows and tool geometry. The complexity of the FSW process is reflected not only in the mechanical phenomena (friction between different materials, material flow, and mixing), but also in thermal, microstructural, and chemical processes. On the other hand, it involves the interaction between a solid body (the tool) and the plasticized, softened base material, so the analysis must include solid mechanics as well as fluid mechanics.

Thanks to their excellent characteristics (joint strength, hardness, material fatigue resistance, fracture resistance, etc.), FSW technologies are significantly applied not only in the automotive industry, but also in many other sectors. With the selection of optimal parameters, high-quality tools, and work devices, FSW provides excellent results and joints.

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