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Robot-based Friction Stir Welding for E-mobility and General Applications

Abstract: There is a fast growing market for friction stir welding applications in many industrial areas of transportation where the focus is on light weight. Along with the aviation, railway vehicle and shipbuilding industries, the automotive industry is expecting a high growth rate over the coming years. Based on the advantages of the friction stir welding technology, such as excellent weld quality, high potential for saving and eco-friendly process, the market share for friction stir welding of automotive parts will also greatly increase. Following a general introduction to the friction stir welding process, a presentation of the tooling and expected quality of various types of joints will be given. Using examples from automotive manufacture, the requirements for component design for a variety of friction stir applications will be highlighted. Our process control and documentation system is the basis for the implementation of Industry 4.0 and ensures the required traceability, quality and data transparency. KUKA Industries has the experience and expertise to develop and implement cost-effective complete solutions with high process reliability. The benefits and special features of robot-based friction stir welding will be demonstrated with the aid of design concepts for production systems.

Keywords: Friction Stir Welding, FSW, automotive industry, FSW tooling, quality of joints

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General introduction to the Friction Stir Welding process

The friction stir welding process is a solid phase joining process in which the materials to be joined are not melted to form a weld pool. Rather, the parts being joined are “stirred” by means of a rotating tool in the plastic state below the solidus. A tool, consisting of a shoulder and a probe, are generally used to carry out friction stir welding. The welding probe is positioned centrally under the shoulder. The parts being joined are clamped firmly to the welding fixture. In the conventional process, shoulder and probe are rotated about their own axis and are pushed into the joint line between the two workpieces with a defined force. In addition, there are processes utilizing a fixed shoulder and rotating probe. Frictional heat is generated between the tool and the parts to be joined causing the material to plasticize. Thanks to the special design of the welding pin, the workpieces are joined before the softened material in the fusion zone solidifies again.

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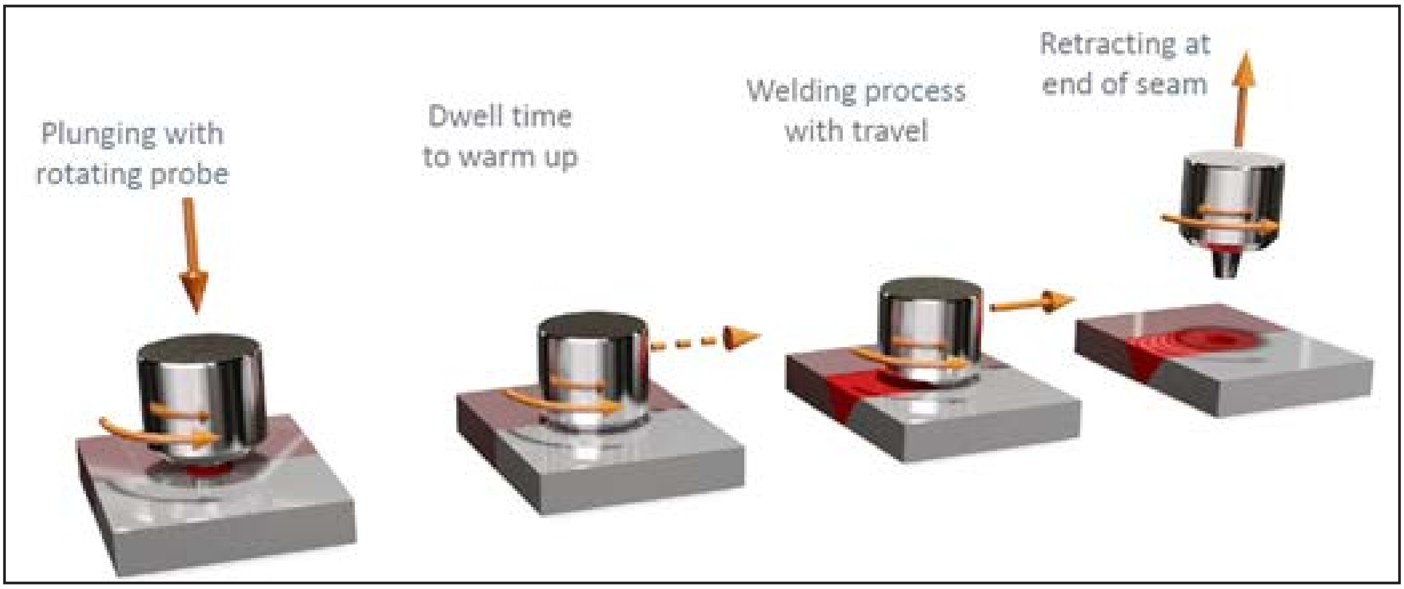

Fig. 1: Classic friction stir welding: process steps

Friction stir welding is an energy-efficient "Green Technology", which can contribute significantly to the reduction of costs and emissions during the manufacturing process. This results in long-lasting savings since no filler wire or shielding gas is needed for friction stir welding in contrast to fusion welding methods. Moreover, the protection against radiation and fume extraction systems frequently required when fusion welding is used are not necessary for friction stir welding. In particular, friction stir welding technology can make a valuable contribution to the efforts of the automotive industry to reduce the emission of CO_2 by vehicles and to develop manufacturing processes for lighter, emission-free vehicles.

Introduction to the Unique Features of Cars with Electric or Hybrid Drive

Sales figures for battery-driven electric cars ((B)EV) and hybrid vehicles (HEV) are rapidly increasing, since they are becoming more economical and less expensive due to the further development of key components such as energy storage systems. For automotive manufacturers this opens up a market potential which can be successfully exploited, provided that they are able to counteract unique features and limitations by appropriate adaptations of vehicle concepts and the manufacturing process in an economically viable way.

A hybrid drive is used in vehicles with internal combustion engines to improve efficiency and reduce fuel consumption. Numerous variations are manufactured for series-production vehicles. Only the variant "plug-in hybrid vehicle (PHEV)", in which the energy storage device can also be charged from a mains power supply, will be considered here. These vehicles are equipped with energy storage systems which allow longer distances, ranging from 60 to 80 km, to be travelled using the electric drive only. All-electric vehicles are characterised by the fact that they are heavier compared to vehicles with internal combustion engines and the energy storage device constitutes a substantial part of the weight and also of the costs involved.

Although electric vehicles demonstrate a higher degree of efficiency in the range between approx. 65 and 80% and some heavy components such as internal combustion engine, transmission and exhaust system can be dispensed with, the energy density is lower by a factor of 50 to 100 when compared to petrol-fuelled engines. This results in a large volume and a high weight, which must be safely accommodated in the vehicle. For a range of 400km commercially available energy storage devices have a weight of approx. 320kg. [1-3].

A further aspect in the design of electric vehicles is the unfavorable temperature behavior of the storage devices. At temperatures lower than 10°C the power output is reduced by the restricted mobility of the charge carriers. At temperatures above 30°C internal losses increase and aging processes accelerate. For these reasons, energy storage systems are integrated in cooling systems, equipped with electric heating systems or provision is made for air cooling. [4].

In addition, some manufacturers incorporate battery management systems (BMS), containing the power electronics, in the vehicle's cooling systems in order to control the very high currents which temporarily occur during acceleration or braking and to dissipate the heat loss. When cooling systems are used, these are either integrated directly into the housing or separate closed systems are used when installing battery modules.

Demands on Joining Technology from the Automotive Industry

What specific demands on the joining technology, with regard to vehicle concepts and the manufacture of components, do the unique features described above create? In this context, passenger cars have primarily been addressed; it is particularly difficult to develop a vehicle concept for them when compared to buses and commercial vehicles.

Bulky and heavy battery systems must be installed in plug-in hybrid and electric vehicles in such a way that they have a low center of gravity and restrict the passenger room and luggage compartment as little as possible. These systems must be securely mounted and be able bear the vehicle-specific loads over their life span. Furthermore, the systems must not impair the crash behavior and must take into account additional hazards, such as fire and environmental pollution in dangerous situations.

In the case of plug-in hybrid vehicles, the energy storage devices are usually located in the rear axle area under the back seats. The components of the Volvo V60 Hybrid are used here as an example. The housings for hybrid vehicle storage systems are usually made of die-cast aluminum. In order to guarantee temperature control, some manufacturers integrate cooling systems into the floor on which battery modules with a low thermal transition resistance are mounted. The difficulty in the manufacture of the storage housing lies in having to produce a closed, pressure-tight cooling circuit, which withstands the stress caused by the alternating pressure, causes low thermal deformation of the mounting surface and allows a permanent bonding of different aluminium alloys.

Fig. 2: Volvo V60 Hybrid electric motor on rear axle with battery pack

Here, the friction stir welding process has proven to be an optimum joining technology. The cooling circuit is closed by welding a base plate to the cast housing. For this purpose, an aluminium sheet of alloy EN AW 6000 has to be welded to a cast body of the EN AC 4000 class over a length of more than 10 m. Depending on the part design, the weld seams are executed in a meandering shape or as overlapping joints. The demands on weld seam quality are very high, in particular due to the requirements of the alternating pressure test with more than 200,000 pressure changes. In addition, the flatness of the mounting surfaces inside the housing should be less than 0.2 mm above that of the mounting surface, even after welding.

In some plug-in hybrid vehicles cast housings are also used, which are sealed with extruded plates, into which the cooling circuit can be integrated. The welding task consists of

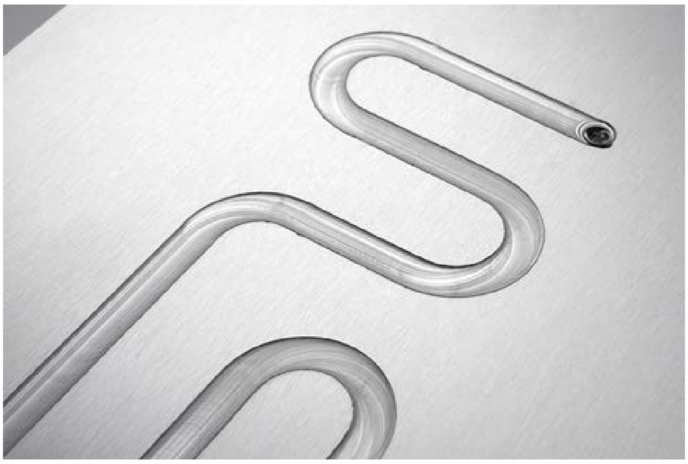

Fig. 3: Sample of a meandering seam

welding EN AW 5000 materials to EN AC 4000 alloys in various seam forms. In all-electric vehicles the housing for storage devices takes up a large area of the vehicle's underbody and is located between the axles.

Fig. 4: Battery pack in the Nissan Leaf

Some manufacturers have been installing the energy storage housings separately but more recent concepts show the integration of longitudinal beams into the storage housing of the vehicle. In order to ensure the required stiffness of the storage housings, these are produced either from frame sections with cross members, which are welded to an aluminum base plate or by using double-wall extruded sections welded together to form a base. In order to produce the complex connections of the front and rear sections of the vehicle economically, aluminum die-cast components are occasionally being employed today. The use of different aluminum alloys, the requirements for tightness and lowest possible distortion of the components due to heat input during welding lead to high demands on the joining technology for the storage housings.

The benefits of friction stir welding, when compared to conventional fusion welding techniques, are the excellent quality of the welds, the ability to join large cross-sections and the low heat input. However, the unique features of the friction stir welding process, such as the strong forces required and the dimensions of the gaps to be bridged, must also be taken into account when designing the components and production equipment.

Tooling Design and Expected Quality of Various Types of Joints for the Manufacture of Battery Packs

When manufacturing battery housings, various aluminum alloys must be welded as butt or overlap joints or as a combination of both forms. The seams must be leak-tight to seal cooling circuits and be able to reliably withstand the alternating pressure loads during the vehicle's service life. To this end, a large bonding cross-section and a well-mixed and compacted seam are required.

Another aspect which affects the choice of tooling and its design is the burr formation during the welding process and the resultant reworking required. The assembly of battery modules in battery packs imposes great demands on technical cleanliness with regard to metal particles and chips. Therefore, attention must be paid to burr formation and the presence of loose chips when planning the process and production system.

For the reasons given above, KUKA has decided to employ friction stir welding, using a fixed (stationary) shoulder (SSFSW), as the key process for welding the complex seams on storage and electronic housings. KUKA can only use this process, patented by ESAB, by contract with the licensor until the license expires in May

2018. How are the friction stir welding tools for welding with a fixed shoulder designed in principle? A significant design criterion is the diameter of the welding pin. A welding pin with as large a diameter as possible, for example 5 mm, should be utilized for welding metal sheets of 3 mm thickness. This ensures a wide bonding cross-section and a high degree of stability against the strong process forces of up to 2 kN in the advancing direction. The diameter of the welding probe should be smaller at the tip, i.e. taper conically, in order to facilitate penetration into the cold material. Furthermore, geometric features such as threads and flanks must be added, in order to perfectly mix the plasticized material.

The optimum design of the welding pin depends on the experience of the tooling designer and is part of the manufacturer's know-how. During process validation and determination of the ideal welding parameters, the welds will be analysed with the aid of micro-sections and various pin geometries used.

Along with the welding pin, the design of the shoulder plays a major role in the achievement of optimum welding results. In particular, the design of the shoulder is important for preventing the intrusion of softened material into the gap between welding pin and stationary shoulder. Alternatively, a safe transfer method for the penetrating material can also be chosen as a strategy for preventing the welding pin getting "welded" to the shoulder later when the material cools down.

Fig.5: Example of a simplified welding pin and shoulder geometry for tool with stationary shoulder (SSFSW tool)

Typical friction stir welding applications on battery housings for plug-in hybrid vehicles with integrated cooling

The battery housings for plug-in hybrid vehicles are usually produced as a die-cast component. If cooling circuits are to be integrated directly into the housing, this area must be subsequently closed by welding on an aluminum sheet. For this purpose, for example, a sheet made of an En-ac 6000 alloy, 3 mm thick, must be welded as an overlapping joint to the cast body, an En-ac 4000 alloy. The welding area is usually milled during machining of the cast body, so that the cast skin and irregularities in the contact surface pose no problem. The difficulty lies in designing the component in such a way that the minimum cross-section in the welding region of the cast body is sufficient to ensure ample rigidity also in the area of the cooling water connections.

For good heat transfer, the flatness of the mounting surfaces for the modules after welding is decisive for optimum cooling of the battery pack. For this reason, the housings in these areas must be supported in order to reduce distortion.

Weak points in components under pressure are the process-related exit holes at the end of each weld, caused by the tilt angle and the displaced material. Seam ends should therefore always be located outside the area under pressure. If this is not possible, or if additional weld seams need to be set for minimizing the surface under pressure, the end of the seam must be welded circumferentially by "closing in" the probe's exit hole.

Similar aspects of component design and similar welding tasks can also be found among the electronic components in hybrid and electric vehicles. Here, the components are usually smaller and the weld seams shorter, giving rise to different equipment concepts, since the cycle time per component is significantly lower.

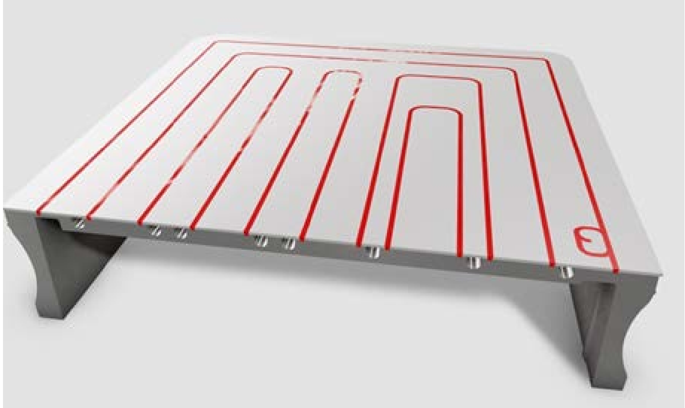

Fig. 6: Concept for a battery housing for hybrid vehicles

Typical friction stir welding applications on battery housings for electric vehicles

Where all-electric vehicles are concerned, the storage housings consist of extruded sections, welded together to create a frame structure by arc welding. Following machining of the seams in the welding area of the base, these frames are welded to a base sheet or base plate, consisting of several double-walled extruded sections, to form a liquid-tight housing by means of the friction stir welding process. The picture below shows two different basic concepts combined in a principle structure described in the following text.

When using a double-walled base plate, this must be welded from both sides from the individual extruded sections in a preliminary operation. In doing so, the geometric tolerances of the extruded precision profiles, as defined in Standard EN 12020-2, are to be observed. If welding of the profiles on the longitudinal edges is impossible due to the standard tolerances, then these profiles must be machined prior to welding. For example, when welding double-walled base plates of 12 mm thickness, a gap of 0.3 mm can be reliably welded at a penetration depth of approx. 4 mm using the stationary shouldered tool without a compaction defect occurring. When using a classic tool with a welding pin, 5 mm in diameter, and a shoulder with a diameter of 13 mm, the gap cannot be more than 0.5 mm at the most. The gap volume has a considerable influence on the interface at the bottom of the seam and must be taken into consideration when designing the components.

Fig.7: Concept for battery housing

It would not be practical to weld the base plate down through the full material thickness of 12 to 15 mm, since a very wide seam with a shoulder diameter in excess of 20 mm is required. The down forces necessary and the bonding cross-section of more than 10 mm cannot be achieved in the frame section since this is not compatible with the objective of a lightweight construction. Consequently, the base plate is mechanically machined in the bonding area and the hollow-chamber profiles welded to an external bar. Where cooling channels are integrated in the base plate, further mechanical processing steps are needed to be able to weld the profiles in a reliable and pressure-tight manner.

A more widespread concept for energy storage housings for all-electric vehicles is a frame section with additional struts which is sealed by means of a base plate. The friction stir welding process is employed to weld the base plate around the periphery such that it is sealed against liquids. The struts are also welded to the base plate, to absorb the weight of the battery: either MIG seams are welded after the base plate has been joined or friction stir welding is used to weld through the base plate into the struts to form an overlap joint. For this latter option attention must be paid that the seam end with the exit hole lies outside the leak tightness area.

A process-compatible design of the frame profiles in the welding area must be ensured for both the base plate and bottom section concepts. The stiffness of the profiles is one of a major factor, which is explained in more detail in the following. The frame sections with the side members are part of the vehicle's structure for most manufacturers and must be designed to meet the requirements for side crashes. In addition, the forces generated during the friction stir welding process must be taken into consideration for these frames and also for the transverse profiles. In order to achieve traversing speeds of around 1m/min, thereby enabling the required heat input into the joint line, a sufficiently high friction must be created. To do so, the friction stir weld tool must be pressed onto the surface of the components to be welded with a force ranging between 3.5 and 5 kN. This down force must be absorbed by all types of profiles in the welding area and by the clamping fixture without significant distortion.

The wall thickness in the welding area should also be defined to suit the process. It should be borne in mind that the material surrounding the welding pin becomes plasticized and therefore cannot contribute to rigidity and stiffness of the structure. If the welding pin is long enough to penetrate the profiled section by approx. 0.2 to 0.5 mm, then it must be assumed that the plasticised area, the thermo-mechanically affected zone, has a depth of approx. 0.4 to 0.8 mm. In practice, wall thicknesses of approx. 3.5 mm have been tried and proven where welding in the area of a profile edge is possible and represent a compromise between lightweight construction and stiffness when welding with high process forces. The beginnings and ends of the seams can cause distortion of the profiles at this wall thickness. These deformations can also result in superficial compaction defects. With profile thicknesses of 4.0 mm in the welding area and using 3 mm thick base plates, a reliable, safe seam without distortion can also be achieved in other profile areas.

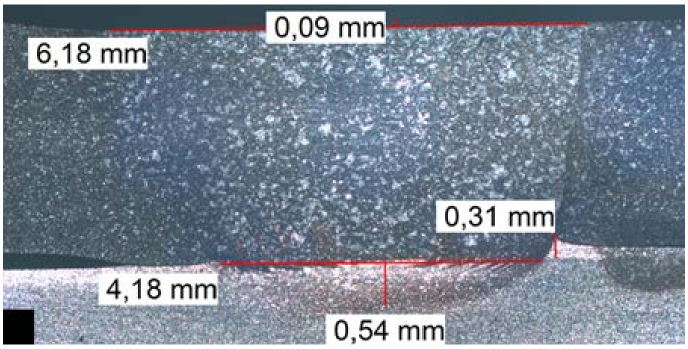

Fig. 8: Macro section through weld seam free from defects

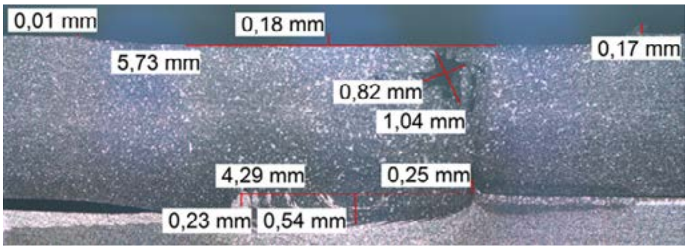

Fig. 9: Macro section through weld seam with compaction defect

Demands for Production Lines by the Automotive Industry

If one now considers the demands made by the automotive industry on the joining technology for the e-mobility sector and the advantages of the friction stir welding process for some of the main joining applications, then considerable market potential for production lines incorporating the friction stir welding process can be seen over the coming years. Along with the technological equipment needed to make use of the process as a safe and economical production method, however, the demands for transparency in the collection of quality data and traceability of the key process parameters must be fulfilled, with reference to each individual vehicle. With this in mind, Kuka has formed the basis for the integration of Industry 4.0 with their Process Control and Documentation system (PCD), which enhance our customers' production facilities.

The flexibility given by the use of a robot in two safe working areas and the possibility of integrating two robots, to share the welding task, into a friction stir welding line for large parts, allows Kuka to offer customized and cost-optimized production systems to the customer.

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