# Critical assessment: friction stir welding of steels

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The level of activity in research on the friction stir welding of steels is dwarfed when compared with that on aluminium alloys. There are good reasons for this. The relative weakness of aluminium makes it ideally suited for a process which requires, at high strain rates, the permanent flow and mixing of material without melting. In contrast, there are in general no cost effective tools available for steel. The purpose of this article and the associated papers in this special issue of *Science and Technology of Welding and Joining* is to assess the state of the art, focusing on the knowledge base in the open literature.

**Keywords:** Friction stir welding, FSW, Steel

## Introduction

The astounding success of friction stir welding (FSW) in the context of aluminium alloys[1] has naturally stimulated exploration of its applicability to other materials such as steel, titanium, magnesium, nickel and copper alloys. Attempts have even been made to investigate it for the joining of polymers.[2] The process has clear advantages when it comes to welding dissimilar materials since the extent of mixing and solid state reaction between incompatible materials can be minimised; it is not surprising that this is an active field with much recent activity, for example.[3–7] Steels, however, represent by far the greatest opportunity for any new process given their undisputed prominence in structural applications. A part of this success must be attributed to the fact that the material is strong, versatile, cost effective and reliable.

These very factors make it difficult to apply FSW to steel. Figure 1 shows the typical temperature dependence of the strength of an aluminium alloy[8] compared with that of a steel.[9] It is apparent that the torment that an FSW tool would have to go through in the case of steel would be much greater than that for aluminium unless temperatures are achieved in excess of some 800°C; the steel must be sufficiently plasticised to permit the material flow to enable a sound weld to be fabricated. Cost effective tool materials which survive such conditions for extended service remain to be developed.

Because of the tool problems and the proliferation of cheaper and more effective methods for welding steels,[10] it remains doubtful that the process can have an impact on the joining of steels, certainly not in proportion to the quantities in production and use. Many niche applications are nevertheless being considered, for example, the friction stir spot welding of steel sheets for automotive applications.[11–14] The cost of making actual spot welds in the production of automobiles is a few cents of a dollar[15] and this is the level that friction stir spot welding would have to compete with, unless there are particular difficulties with specific steels (although it should be realised, the automotive industry would be reluctant to accept such steels).

In most studies, the steel being friction stir welded becomes locally red hot; the maximum temperature reached is less than 1200°C[16,17] and the time $\Delta t_{8-5}$ taken to cool over the range 800–500°C is ~11 s. Austenite will therefore form during the heating cycle and will subsequently transform during the cooling cycle. With few exceptions, only elementary mechanical properties have been characterised in studies of the FSW of steels;[10] most reports are limited to simple bend, tensile and hardness tests. For serious structural applications, it would be necessary to assess fracture toughness and other complex properties in much greater depth. Certainly, the early optimism[16,18] that FSW will become a commercially attractive method for the fabrication of ships, pipes, trucks, railway wagons and hot plate cannot come to fruition until this is carried out. Recent claims of success in the application of FSW to steels also do not seem to be well founded.[19] There has been work on the girth welding using FSW of X65 steel pipe using a boron nitride tool, where an almost uniform hardness distribution is obtained across the weld, with Charpy properties better than those of the parent material.[20]

The metallurgical transformations expected on the basis of cooling rates alone are unlikely to be significantly different from ordinary welds. However, because the peak temperatures achieved are smaller than in fusion welding, the austenite grain structure of the heat affected zone is expected to be finer. This would be beneficial in avoiding transformation to hard, detrimental phases. It has been argued that this would make it easier to weld high carbon equivalent steels.[10,21]

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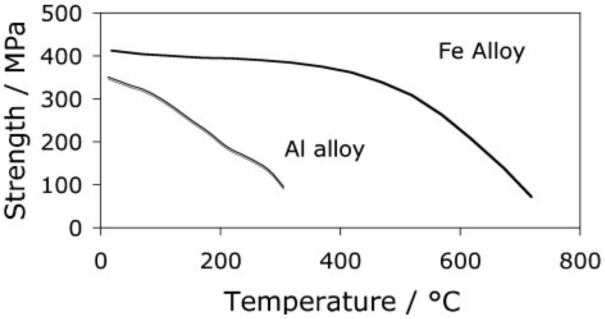

1 **Typical temperature dependence of hot strength of aluminium alloys and steels[8,9]**

Perhaps the orientation of research should be in finding areas like this where conventional techniques have disadvantages. Another possible area where FSW is claimed to have an advantage[22] is in the welding of duplex stainless steels when it is important to preserve the approximately equal austenite and ferrite phase fractions. Whether FSW offers a particular advantage over fusion welding is doubtful given that there are many kilometers of duplex stainless steel pipelines in service, having been fabricated using fusion welding processes.

In view of these challenges, it is timely, in the present special issue of *Science and Technology of Welding and Joining*, to attempt to provide a commentary on research relevant to the FSW of steels. In commissioning the issue, the authors searched databases on relevant papers and solicited contributions from all those who could be contacted, to ensure comprehensive coverage and to avoid bias in the selection of authors. The contributions presented are from those who responded positively and were able to deliver manuscripts on time: the authors sincerely thank them all.

## Papers in this special issue

In recent years, numerical modeling of FSW has provided significant insight about the heat generation patterns, materials flow fields, temperature profiles, residual stress and distortion, and certain aspects of tool design.[23–25] Further work is needed for improved understanding of the role of tool geometry, understanding and prevention of defects, more rigorous model validation and inverse modelling capability.[10] Buffa and Fratini[19] have applied the method particularly to steels, with validation consisting of a comparison of the far field thermal profiles against published experimental data on austenitic stainless steel.[26]

This paper raises a few important issues. The model includes the calculation of the temperature distribution inside the tool. The question arises whether modelling work should, in the context of steels, focus now on the tool rather than the workpiece since the former is the limiting factor in all aspects of such welds. There is nothing in current models on the wear or fracture of such tools, whereas it is common knowledge that parts of the tool end up inside the weld, which is unlikely to be acceptable in any technologically critical weld. To do this would require constitutive relations to be developed for the tool material, together with fracture mechanics models and tribological models. Tribology is of course a two material problem, so any model would depend on both the properties of the steel and those of the tool (it is important also to recognise that the probe on the tool experiences compressive forces, torque and bending moments. It can as a result deform and experience cyclic stress because of its rotation).

The second general question regarding models is the extent to which they are validated. Is it sufficient validation to predict just the temperature profile away from the weld?[27]

The paper by Chung *et al.*[21] is an interesting approach for the welding of high carbon steels; it is based on previous work[28] on FSW where the peak temperature reached is within the two phase austenite and ferrite field. The advantage in intercritical welding is that the hardness profile across the joint is much more uniform than if the weld nugget becomes fully austenitic and then transforms into harder microstructures such as martensite, as was the case in an earlier report.[29] It is claimed that the method is successful because 25 cm long butt welds which were free of macroscopic defects were produced and failure in tensile tests occurred in the base metal. The question in all such work is whether this is sufficient evidence for such a joint to be technologically useful in a specific application (metal cutting tools, truck springs and clamps in the automotive industries are mentioned in the introduction to this paper).

Transformation induced plasticity (TRIP) assisted steels mostly have good properties for automotive applications[30,31] but their poor weldability has led some producers to design them out of their automobiles. Strong steels are good for weight reduction but a soft region is created in the heat affected zone of welds, leading to a reduction in formability.[32,33] The study by Miles *et al.*[34] used a polycrystalline cubic boron nitride tool to fabricate FSW joints in dual phase and TRIP assisted steels with success being defined by failure of a tensile test specimen in the region away from the weld or heat affected zone. It was possible to find conditions under which successful welds can be produced. Given that FSW in general is at its best for flat plates, it is possible that the process can be used in making tailored blanks,[35] assuming that the tooling costs can be justified.

The FSW of steels involves high temperatures; Ohashi *et al.*[36] found the base dual phase steel to suffer contamination with Si, N and O when friction stir spot welding using a silicon nitride tool. The contamination with oxygen could be mitigated using an argon shroud, and that from the tool (Si,N) by coating the tool with TiC and TiN. The life of the coating is not clear from this study.

There is a remarkable study reported by Lee and co-workers,[37] where a steel tool is used to make good joints between aluminium alloy sheet of 1 mm thickness and an underlying steel sheet. The tool does not have to be an exotic material because its penetration during friction stir spot welds did not exceed half the thickness of the aluminium. The underlying steel was never touched by the tool. Nevertheless, a mixed layer just 2 μm in thickness, formed at the aluminium/steel interface, with some intermetallic compound formation, resulting in a metallurgical bond between the dissimilar materials. Furthermore, shear tests demonstrated that with this configuration, it is possible to achieve properties similar to those when the steel is friction stir spot welded to itself. This study deserves further attention given the use of a inexpensive tool material and the need to join aluminium alloys to steel in the automotive industries.

A study of the FSW of a solute rich precipitation hardened steel is reported by Weinberger *et al.*,[38] with high resolution characterisation of the structure and cross-weld tensile tests to assess properties. The welds were carried out using a W25Rh tool; there is a huge demand for the limited amount of rhenium available, primarily from the aeroengine industries because it enhances the creep strength of nickel superalloys. As a consequence, the costs of tools containing rhenium must become painful for anything other than specialised applications as time progresses. The preliminary work presented by Weinberger *et al.* does not justify the use of FSW for this class of steels.

Superaustenitic stainless steels, by virtue of their large Cr, Mo and N concentrations, have a particularly good pitting corrosion resistance[39] and there exist nickel based welding consumables with matching corrosion properties for fusion processes.[40] Chemical segregation during solidification can reduce corrosion resistance if a superaustenitic type welding consumable is used. Nevertheless, the heat from the fusion process can lead to the formation of intermetallic compounds in the heat affected zone, which then reduce the corrosion resistance there.[41] Sato *et al.*[42] attempted to overcome these difficulties using FSW in the hope that neither the segregation nor the intermetallic compound formation would occur with this process. A boron nitride tool was used to avoid the problems of tungsten ingress encountered in a previous attempt.[43] Unfortunately, FSW was not able to prevent the formation of intermetallic compounds in the heat affected zone to the detriment of corrosion resistance.

An adaptation of FSW is when the tool is used for processing the surface of a component by deformation.[44] Chen *et al.*[45] have speculated that surface deformation using friction stir may be useful in the repair of stainless steel components. Consistent with previous work on FSW of austenitic stainless steel,[46,47] $\sigma$-phase precipitation occurred in the processed layer.

Continuing on the theme of tools, the Bobbin design in which both the top and bottom surfaces of the weld are confined, has been used to join 8 mm thick samples of a '12Cr' steel.[48] Such steels are used typically in applications where the service temperature is in excess of 500°C and are normally supplied in severely tempered condition and given a subsequent stress relief heat treatment after fusion welding. The authors report producing sound welds which through the use of the Bobbin tool avoid the ingress into the weld of materials used to support the joint during conventional one sided FSW. Tensile tests were found to fail in the plate away from the weld, although this may not be surprising if the material there is softer; bend tests were also used. Once again, it is not clear whether these properties on their own are sufficient to reach the conclusion that successful friction stir welds have been produced, for example, the authors suggest that an excessive amount of ferrite observed in the weld zone might harm toughness.

## Summary

The papers presented in this special issue, together with published work, have contributed to the understanding of the FSW of steels. The fundamental problem is twofold. The definition of a tool is that it can be reasonably reused. This is not the case with any of the tool technologies available today for the FSW of steels. It is possible that a more sophisticated hybrid welding technique, in which a different heat source provides additional heating, may help reduce the demands on the tool material,[49,50] but anything that adds complexity must increase costs. The biggest problem in the industrial exploitation of FSW for steels is undoubtedly the development of a reliable, lasting and cost effective tool material and this is where the potential benefits in research could be large.

There are other difficulties, and claims of success may be premature given that the level of characterisation of mechanical properties is far less than that required in structural applications. The focus also must be on cost if real success is to be achieved, although this would be mitigated by the identification of critical problems which are not well addressed by established methods of joining steels.

The tendency has been to validate research by identifying problems with the fusion welding process. It must, however, be realised that the fusion process is in commercial use, but FSW for steels is not. Perhaps an emphasis in published work of difficulties with FSW would increase the rate of progress.

The authors have commented on the difficulties in FSW, which are easy to recognise, but it is useful to speculate on the more difficult task of how a vision for the future may be achieved, by focusing research on the issues which are 'show stoppers':

1. The identification of a joining problem for steel which cannot be tackled using conventional techniques. This will necessarily be a niche problem dealing with expensive components in order to justify costs. However, if this is successful, its adaptation by industry would stimulate other applications. One example which admittedly would need detailed analysis, is the joining of mechanically alloyed yttria dispersion strengthened iron based alloys[51] which are currently being investigated for the fusion research programme,[52] and for which there is no seriously useful joining technology available. These are expensive materials for an expensive but critically important application. Another clear example[53] is the underwater joining of steels, where FSW would have clear advantages over fusion welding. Underwater pipelines are extremely expensive to place in position and it is possible that the cost of tooling might then become tolerable.
2. The imaginative development of a tool material specifically suited to the problem, as in the paper by Lee *et al.*[37] For example, could the tool be designed so that any tool material which enters into the weld is benign? Perhaps the concept of a slowly consumable tool may then not be far fetched.

The editors invite comments on this subject for publication in *Science and Technology of Welding and Joining*.

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