Experiments on the Advantages and Limits of Using Conventional Friction Welding for Joining Dissimilar and Graded Materials

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Investigations concerning opportunities to apply the friction welding technique for joining dissimilar and graded materials are considered, starting from the advantages offered by this process in assembling parts for manufacturing equipments parts and automotive industry components. Experiments have been carried out on friction welding of heat treated 42CrMo4 with C45 steel and with the solution treated X6CrNiTi18–10 steel, as well as on joining copper with Al alloys. Metallographic observations and hardness measurements are performed in order to detail the peculiarities of the process of making joints that are difficult to obtain by conventional electric arc welding.

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INTRODUCTION

Friction welding is a technique that relies on thermomechanical processes, known to lead to significant structural changes in steels and other metallic materials [1], located at the interface of the joint. Several currently used types of friction welding are: stir, rotational, linear, and orbital welding. Nowadays friction stir welding (FSW) attracts most attention in the scientific world [2], with its significant opportunities for practical applications extended to a variety of materials, even steels [3]. FSW is a process that can be used to repair surface and near surface defects, and increase material strength. It is based on heating by friction and the subsequent plastic deformation of a workpiece placed between a rotating tool and the mating surfaces of the welded parts. The rotating tool is plunged in the material and then shifts along the joining line with a linear speed. The plasticized material is transferred beyond the tool, thus leading to the welded joint. FSW is a complex process, still under development for joining similar materials, and its complexity is reflected by thermomechanical modeling of phenomena. The following are the most relevant advantages of FSW [4]:

– subsequent machining is not necessary;

– lower energy requirement;

– welds of materials with different geometries can be made;

– long welding seams are possible.

However, the FSW process has also some limitations in contrast to conventional friction welding. They are:

– reduced number – so far – of the couples of materials that can be joined;

– specific requirements for clamping of workpieces;

– significant wear and cost of the rotational tool;

– difficulties in processing of the coated material;

– lower productivity for joints made in a single step.

Thus, rotational friction welding, also known as conventional friction welding, still keeps a significant segment among currently used techniques, while continuously expanding to include both similar and dissimilar materials [5, 6], thus offering substantial advantages compared to resistance and arc-welding techniques. The main characteristics of the joint, from the point of view of its constructive design, are related to the geometry of the weld. Dimensional coaxial or along the length misfits are significantly less than 0.5 mm, depending on the performances of the welding equipment.

Among the main aspects, concerning the friction-welded joints, are [7–9]:

– the expungement of the material initially in contact does not require pre-cleaning of the surfaces to be welded;

– the resulting mechanical strength is equal or higher than the one of the base material;

– the heated and mechanically affected zones are less extended and their mechanical characteristics less degraded;

– the microstructure of the joint plane shows a finer structure than the one of the base materials;

– an adequate forging expunges the overheated austenitic grains in the outer area and generates a grain refinement in the welded joint;

– the strength of the joint for dissimilar materials is at least equal to the lesser strength of the welded materials;

– there is no risk for decarburation of the steel parts to be welded.

The mechanical characteristics of the friction-welded joins are superior to the ones of the base materials, due to the favorable effects of the thermomechanical treatments during the process. In addition, the heat affected zone (HAZ) is less extended compared to that in other welding techniques, and the presence of segregations and porosities can be avoided in the joining plane.

The present work specifies the opportunities of application of the conventional friction welding process for joining similar, and especially, dissimilar materials. It also is an investigation on the welding behavior of nonferrous metals and alloys, which causes difficulties in making joints using the arc melting process.

A FRICTION WELDING APPROACH FOR INDUSTRIAL PROCESSES

According to the conventional friction welding process requiring rotation of the parts, the geometry of the components should show at least a contact surface with rotational symmetry. In principal, parts with solid and hollow sections can be welded, and depending on the rigidity of the walls, they can also be welded to flat surfaces. Figure 1 presents some of the geometries of the cross-section of the components that can be welded.

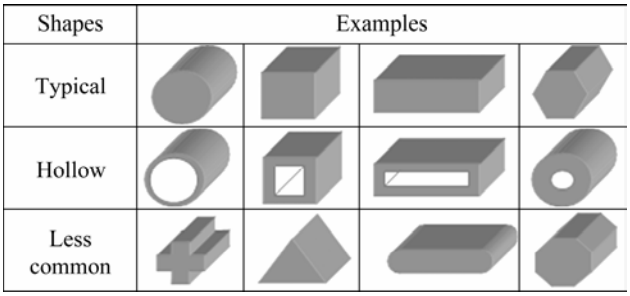


Fig. 1. Cross-section of weldable geometries.

The implementation of friction welding technology usually arises from a metallurgical need or has an economical justification, allowing the optimization of the technological process and the reduction of cost. Several applications of the conventional friction welding process are highlighted in Table 1.

On the other hand, the friction welding process is sometimes limited or more difficult to implement for materials that show inhomogenties and compositional gradients, especially in the joining plane [8–11]. Sometimes, depending on the couple of materials to be joined, post-welding treatments may be required. For joining dissimilar materials that are metallurgically incompatible, the formation of intermetallic compounds in the seam can be avoided by using intermediate layers.

The conventional friction welding process parameters (axial pressure, rotational speed, processing time) can be easily adjusted. They determine the initiation and the ending of the welding process, leading to high quality joints with reproducible properties. Beside those parameters, and in order to avoid cracking and fractures, supplementary precautions can be prescribed, related to preheating, cooling rates and subsequent heat treatments for tempering and stress relief. Compared to other welding techniques, friction welding is a solid-state process that does not require melting and offers relevant advantages related to the quality of the joint, the lack of additional materials, fluxes and protection gases. It is also economical, with such benefits as: lower energy consumption, reduced costs for surface preparation and subsequent machining, short welding times and high productivity, fewer human errors and no ecological risks.

EXPERIMENTAL DETAILS AND RESULTS

The friction welding experiments were performed using the equipment with the schematic principle and the practical solution depicted in Fig. 2. Structural observations of a dissimilar weld between heat treated 42CrMo4 low-alloyed steel and a C45 carbon steel are shown in Fig. 3.

The interface is an un-deformed plane – suggesting limited thermoechanical differences between the steels – that reveals the HAZ in each steel (Fig. 3a).

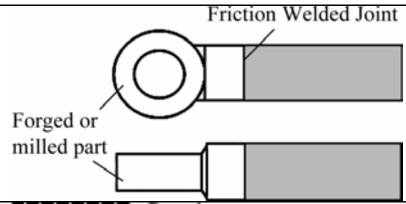
Experiments performed on joining stainless to mild alloyed or unalloyed steels are especially important for recipients operating under pressure. Mild alloys have a ferritic structure, while the Cr–Ni or Cr–Ni–Mo show an austenitic structure. Such joints are named „black-and-white” joints. A joint made out of the quenched–tempered 42CrMo4 and solution treated X6CrNiTi18-10 steels by friction welding was also subject to experiments. The main friction welding parameters for the “black-and-white” joint are: n = 2900 turns/min.; friction pressure 40 N/mm^2; upsetting pressure 45 N/mm^2; friction time 3.5 s ; deceleration time 0.09 s; upsetting time 3.2 s.

The results of the friction welding process are shown in Fig. 4. The hardness gradient across the joining plane is detailed in Fig. 5.

The difficulties arising in welding processes requiring melting are related to the significant microstructural differences. Thus, mild steels require preheating and cooling with a relatively low cooling rate of the joint and a subsequent tempering or annealing in order to reduce the stresses. On the other hand austenitic stainless steels are welded without preheating, the resulting joint needs to be rapidly cooled and in addition, for large equipments, the post-welding treatments can be performed only locally. Friction welding can be thus a solution to join such materials.

Another solution to join materials that are hard to be welded by melting techniques is the solution

Table 1. Examples of conventional friction welding applications

<table>
<tr><td>– Joining of forged/milled to laminate parts has the advantage of allowing the welding of complex parts with one axis of symmetry to other parts with a different axis of symmetry.</td><td>
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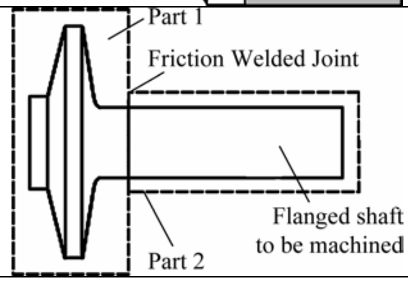
<tr><td>– Joining of parts with large cross-sectional variations that otherwise would lead to significant loss of materials in conventional machining as well as to high costs related to the tools and productivity. While forging can be a solution for mass production, it also implies additional costs for the molds. In addition, any dimensional shape change requires another mold. Thus, for particular geometry, the friction welding can be a solution, especially if different materials for the parts are preferred due to the in-service requirements.</td><td>
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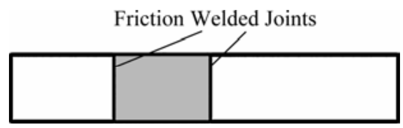
<tr><td>– Manufacturing functionally gradient parts, especially when only one element must provide high properties, are specific for expensive materials or components. The friction welding allows the use of a low-cost material for the parts that do not need special properties. Typical examples are drills and shafts made out of two or more materials.</td><td>
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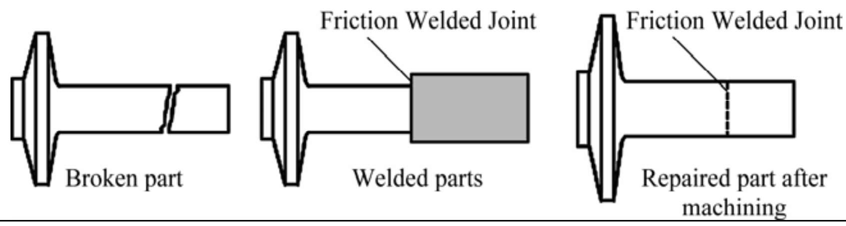
<tr><td colspan="2">– Repair by welding machine parts that accidentally get out of service, while the supply of replacements is slow or not possible, as is the case for older equipment.

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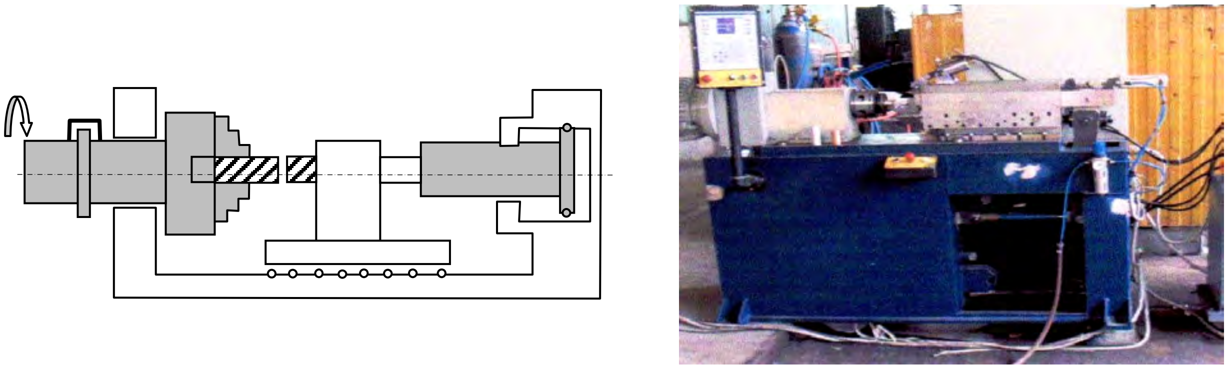
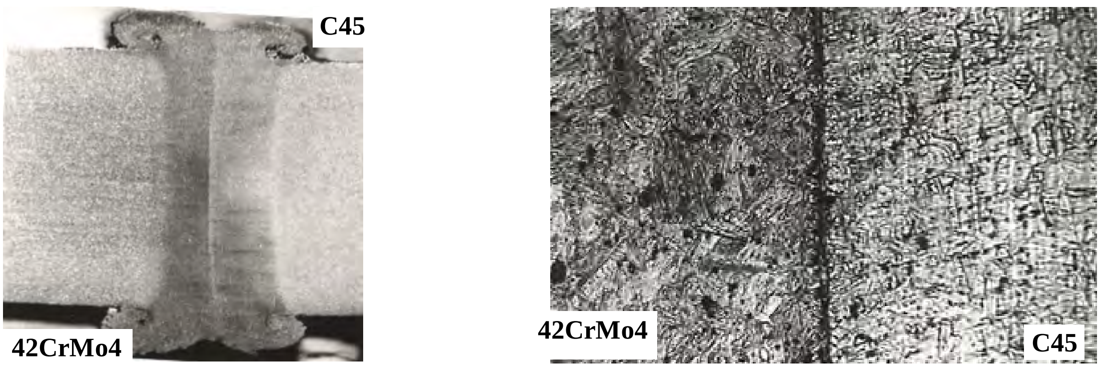


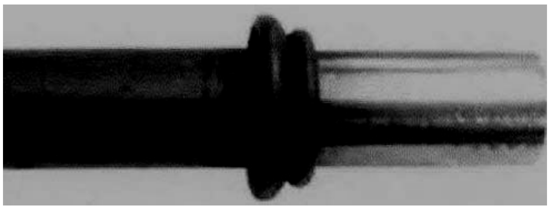
(a) (b)

Fig. 2. Details of the experimental process: (a) schematic representation of the process; (b) equipment for the process in (a).

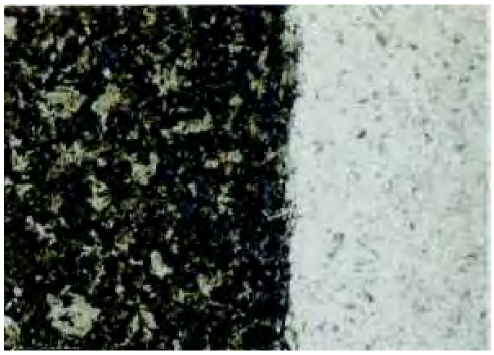


(a) (b)

Fig. 3. Details of the joining plane for a 42CrMo4 – C45 dissimilar steels joint: (a) macroscopic image, (b) microstructural aspects.



(a)



(b)

Fig. 4. Macroscopic image of the “black-and-white” joint and microstructure of the joining interface: (a) macroscopic image of the “black-and-white” joint, (b) microstructural details of the interface.

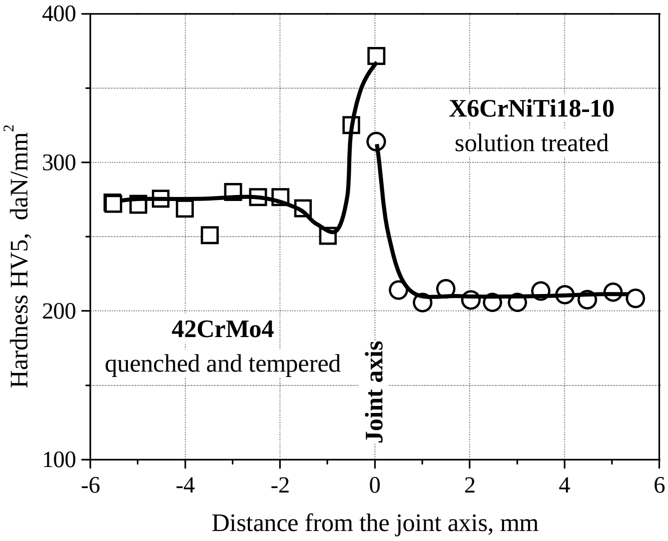


Fig. 5 .Hardness gradient across the interface of a “black-and-white” joint.

Fig. 6. Macrographic images of the Al ally/ Cu friction welded samples.

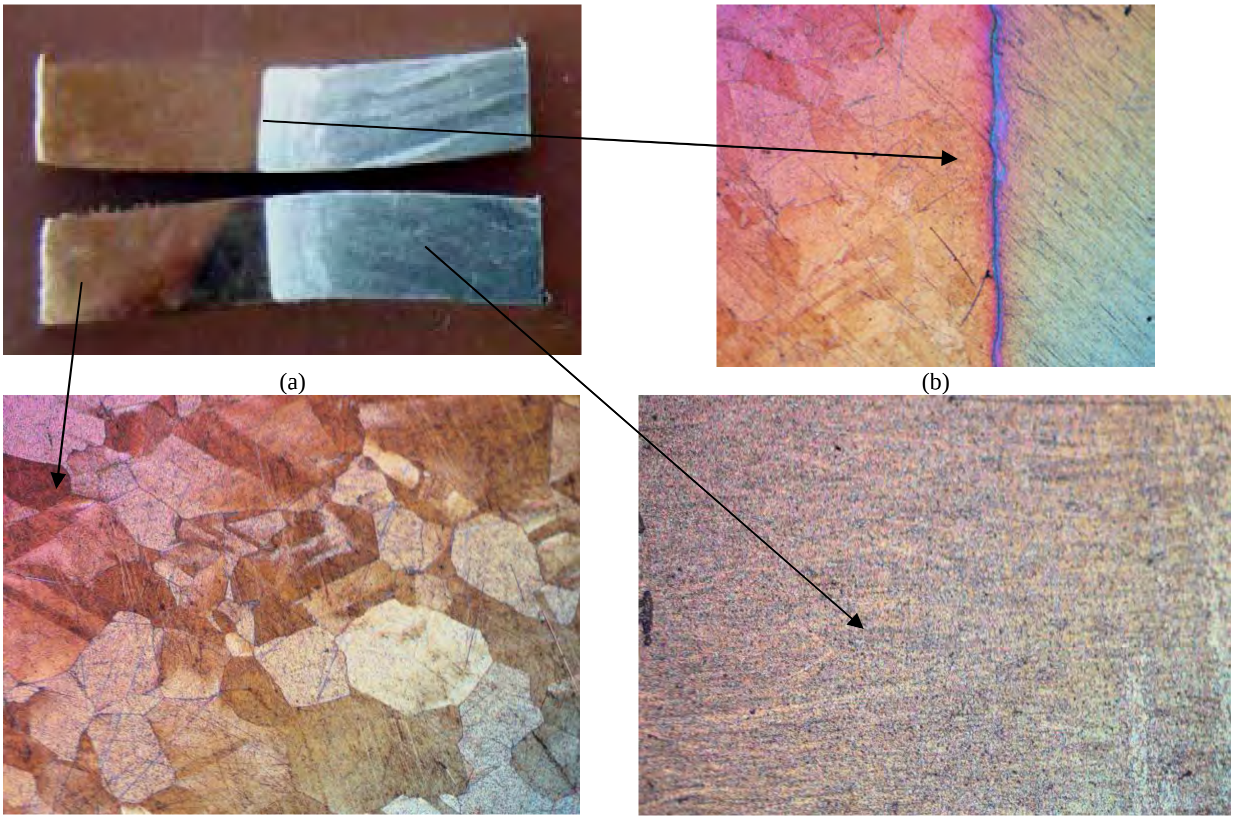
based on friction [6–8]. Several examples are the combination of materials, such as Al/Al, Al/Cu, Al/steel, Co/high alloyed steel. For materials that are hardened by heat treatments, the elimination of the burr is made immediately after welding, while the material is still hot.

Welding of Al and Cu and their alloys is difficult due to the following features: high oxygen intake, limited expansion coefficient, low fusion temperature, high fusion temperature of the oxides, low specific heat, high thermal conductibility. In welding techniques involving melting, the specific character of the process requires high temperature, low volume of the melt and the rapid formation of the seam, thus leading to chemical inhomogenities. To facilitate the evacuation of the gases that appear during welding, preheating is needed.

An advantageous solution for joining such materials is friction welding. Figure 6 shows the experimental results obtained on friction welding of aluminum to pure copper.

The following welding parameters have been used during the welding experiments: n = 2900 rpm.; friction pressure: 30 N/mm^2; upsetting pressure 45 N/mm^2; friction time 3 s ; deceleration time 0.5 s; upsetting time 1.5 s.

The macroscopic aspect of the Cu/Al friction welded samples is shown in Fig. 7a, with microsco-



(a) (b) (c) (d)

Fig. 7. Macro and microstructural details of the Cu-Al alloy welded joint: (a) macroscopic image of the joint, (b) microscopic image of the joint plane, (c) microstructure of the copper part, (d) microstructure of the Al alloy part.

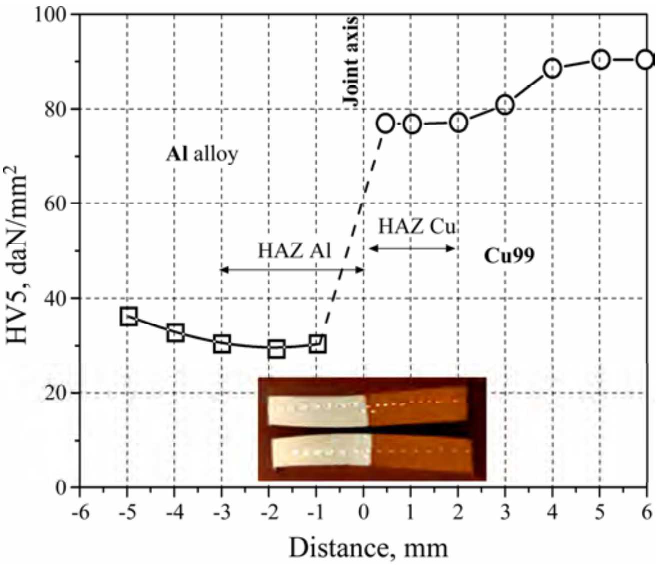


Fig. 8. Hardness gradient across the interface for the Al alloy–Cu friction welded joint.

pic details of the characteristic welded zones detailed in Figs. 7b-d. The microstructure reveals the formation of a free-defect joining zone, with metallic continuity and a microstructure typical for recrystallization with twins in the copper part. A pronounced grain refinement is observed in the Al alloy. Vickers hardness measurements (HV5) on both sides of the joining plane depicted in Fig. 8 reveal a softening of the thermomechanically affected zone, more expanded in the Al alloy as a result of its lower strength to plastic deformation.

CONCLUSIONS

Friction welding can lead to the optimization of the fabrication processes by reducing the costs related to use of materials and labor force. It also allows the fabrication of products with increased in-service performance. One of the advantages is that it allows joining materials dissimilar in terms of composition and/or heat treatment. The experiments carried out showed the possibilities to join 42CrMo4 with C45 steels and with the solution treated

X6CrNiTi18-10 steels, as well as to join copper with aluminum alloys.

The microstructure generated by friction welding across the joint plane favors a reliable assembly that in many cases cannot be obtained using other types of welding.

In addition, such friction welding processes, involving the fabrication of materials with functionally graded interface, are envisaged to be used as a way for developing graded actuators with combined properties of the constituting layers, a subject for further research activities to emerge from the present work.

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Реферат

Исследованы возможности применения сварки трением для соединения разнородных и калиброванных материалов, начиная с преимуществ, предоставляемых такой технологией при компоновке комплектующих для обрабатывающего оборудования и использования в автомобильной промышленности. Проведены эксперименты по сварке трением (при высокой температуре) 42CrMo4 со сталью марки C45, и со сталью X6CrNiTi18–10, обработанной раствором, а так же по соединению меди со сплавами Al. Осуществлен металлографический анализ и выполнены измерения твердости для уточнения особенностей процесса создания соединений, которые трудно получить традиционной электродуговой сваркой.